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Evaluation of the Colour Fastness Properties of *Bixa orellana*-Dyed Silk Using CIELab Analysis

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ABSTRACT

The application of plant-derived dyes in textiles is often limited by inadequate colour stability, particularly under ultraviolet exposure. This study evaluated the effects of four mordants: potassium aluminium sulphate $KAl(SO_4)_2$. $12H_2O$), copper (II) sulphate ($CuSO_4$), iron (II) sulphate $FeSO_4$ and sodium metasilicate (Na_2SiO_3) on the colour stability of silk dyed with bixin extracted from *Bixa orellana* seeds. Bixin concentrations of 10, 20, 30 g/L were applied to silk using the post-mordanting method, and the treated specimens were evaluated under dark, visible light and UVA exposure conditions. Colour stability was assessed using CIELab parameters, including yellow intensity (b*), colour saturation (s) and total colour difference (ΔEab), supported by Pearson correlation and principal component analysis. Under dark conditions, $KAl(SO_4)_2$. $12H_2O$, combined with 30 g/L bixin, produced the lowest degradation, recording 27.53% in b* and 43.05% in colour saturation. Under UVA exposure, $FeSO_4$ combined with 20 g/L bixin demonstrated the best relative performance, with degradation values of 72.70% for b* and 82.38% for colour saturation. In contrast, Na_2SiO_3 exhibited the poorest overall UVA stability, with degradation reaching 98.91% for b* and 98.64% for colour saturation. Nevertheless, ΔEab values ranging from 36.02% to 57.04% after seven days indicated substantial perceptible colour changes across all treatments. The dataset was suitable for multivariate analysis (KMO = 0.783; Bartlett's X^2 = 7363.286, df = 10, p < 0.0001), while the first two principal components explained 94.87% of the total variance. Overall, mordant effectiveness was dependent on the exposure condition; KAl $(SO_4)_2$. $12H_2O$ was more effective

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under dark storage, whereas $FeSO_4$ provided comparatively better protection against IVA induced degradation. However, the high degradation and ΔEab values demonstrate that *Bixa Orellana* dyed silk remains unsuitable for prolonged UVA exposure without additional UV-protective finishing or improved stabilisation strategies.

Keywords: Bixa orellana, bixin pigment, CIELab analysis, colour stability, mordants, natural dyes, silk, textile colouration, UVA degradation

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INTRODUCTION

Bixa orellana has gained attention as a potential natural dye because it produces bright, biodegradable, and non-toxic colours, making it suitable for environmentally responsible dyeing practices (Cuong & Chin, 2016). However, maintaining colour stability under challenging environmental conditions, especially prolonged exposure to UV radiation, remains a significant challenge. The results of this study illustrate that selecting the appropriate mordant is essential to achieving better colour retention while minimising the ecological footprint of the dyeing process. The data also reveal a saturation effect, where higher dye concentrations produce a more uniform and more protective colour layer that resists fading more effectively. However, the use of large amounts of dye carries financial and environmental implications, indicating the need for carefully optimised dyeing strategies, especially in industrial-scale applications (Kalapriya & Gurumalesh Prabu, 2020).

Known for its lustre and luxurious handle, silk is highly receptive to natural dyes due to its protein-based fibre structure (Lee et al., 2010). In most natural dye systems, colour fastness is enhanced by mordants, which help to attach dye molecules to the fabric and strengthen their resistance to degradation (Swamy, 2020). Increasing environmental awareness has encouraged the exploration of more sustainable mordant practices that can enhance dye performance without causing undue ecological damage (Burkinshaw & Kumar, 2009; Vankar, 2017).

In this study, the colour fastness of silk dyed with *B. orellana* was evaluated under exposure to light, complete darkness, and UVA radiation. CIELab measurements were used to track the colour behaviour under each condition. The investigation focused on the effects of potassium alum ($KAl(SO_4)_2$), iron (II) sulphate ($FeSO_4$), copper (II) sulphate ($CuSO_4$), and sodium metasilicate (Na_2SiO_3) as mordants on the resulting colour parameters. Overall, this study aims to provide practical insights that support the development of more sustainable and effective natural dye applications for silk textiles. It is hoped that the findings contribute practical insights into sustainable and effective natural dye application on silk textiles.

MATERIALS AND METHODS

The *Bixa orellana* seeds used in this study were obtained from the Authentic Vietnamese Market, Vietnam, while the silk was sourced from Gulati's Silk House, Kuala Lumpur, Malaysia. The chemicals used were sodium hydroxide (NaOH), ethyl acetate, potassium aluminium sulphate ($KAl(SO_4)_2{\cdot}12H_2O$), iron(II) sulphate ($FeSO_4$), copper (II) sulphate ($CuSO_4$), sodium metasilicate (Na_2SiO_3), and distilled water. The principal equipment comprised a centrifuge, rotary evaporator, glass slides, fluorescent-light source, UVA source and CIELab colourimeter.

Extraction and Preparation of Dye Concentration

5 grams of powdered *Bixa orellana* seeds were mixed with 30 mL of NaOH and maintained at room temperature for 30 minutes. The pigment was subsequently extracted with 30 of ethyl acetate. The extraction was repeated two to three times until no further colour was transferred into the solvent. The combined ethyl acetate fractions were centrifuged at 8000 to10 000 rpm for 5 minutes and concentrated using a rotary evaporator at 40 °C, 75-100 rpm qnd 300 mbqr to obtain a slurry-like extract. Aliquots of 0.5, 1.0 and 1.5 g of the concentrated extract were separately diluted in 50 mL ethyl acetate to prepare dye concentrations of 10, 20 and 30 g/L, respectively.

Fabric Preparation

The silk fabric was cut into standardised strips measuring 1 cm x 5 cm. The specimens were labelled according to dye concentration, mordant treatment and exposure condition. Three replicate specimens were prepared for each treatment.

Mordant Preparation and Dyeing Procedure

Four mordants were evaluated: $KAl(SO_4)_2{\cdot}12H_2O$, $FeSO_4$, $CuSO_4$, and Na_2SiO_3. The potassium aluminium sulphate solution was prepared by dissolving 70 g of the compound in 1 litre of distilled water, stirring for 5 minutes and allowing the solution to clarify. The $FeSO_4$, $CuSO_4$, and Na_2SiO_3 solutions were prepared separately by dissolving 5 g of each compound in 1 litre of distilled water to obtain homogeneous solutions. While the silk specimens were immersed separately in the 10, 20 and 30 g/L dye solutions at room temperature for 60 minutes with complete submersion to promote uniform dye uptake. Following dyeing, the specimens were treated with one of the prepared mordant solutions using a post-mordanting technique. The concentrations of 10, 20 and 30 g/L therefore refer to the bixin dye solutions rather than the mordant solutions. Unmordanted specimens were retained as controls (Mongkholrattanasit et al., 2013; Sarker et al., 2020).

Dark and Light Exposure of the Dyed Fabric

For the light and dark storage test, the dyed specimens were affixed to glass slides and maintained at room temperature for four weeks. Dark storage specimens were protected completely from light, whereas light-exposed specimens were placed 30 cm from a fluorescent light source at an illuminance of 3,100 lux. CIELab measurements were recorded at baseline and on days 1, 7, 14, 21 and 30 using a CS-10 digital colourimeter (manufactured in China using a Japanese-made sensor)

UVA Exposure of the Dyed Fabric

The dyed specimens were mounted on glass slides and positioned upright at approximately 10 cm from the UVA source with a wavelength of 365 nm. The recorded illuminance at the specimen position was 5,500 lux, and the experimental setup is shown in Figure 1. The specimens were exposed at room temperature for seven consecutive days and evaluated daily. All treatments were tested in triplicate, and CIELab readings were recorded before exposure and after each daily exposure interval using a CS-10 digital colourimeter (manufactured in China using a Japanese-made sensor)

Colour Stability Evaluation

Colour stability was evaluated using the CIE 1976 L* a* b* colour system. The L* coordinate represents lightness from black (0) to white (100); positive and negative a* values represent red and green directions, respectively. The spatial relationships among the L*, a* and b* coordinates are illustrated in Figure 2. Colour saturation (s), yellow

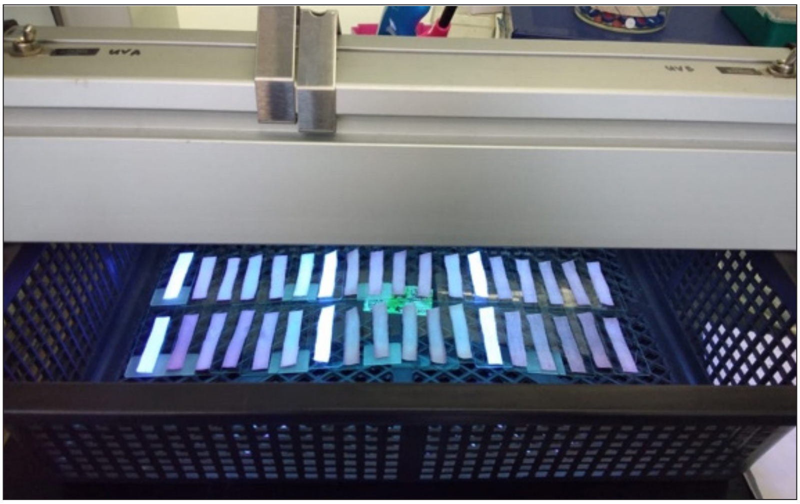

Figure 1. Experimental setup for UVA exposure of Bixa Orellana-dyed silk specimens

intensity (b*) and total colour difference (ΔEab) were used to assess colour retention and degradation (Othman, 2009). $\Delta E^*ab = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]}$. Where ΔL*, Δa* and Δb* represent the differences between the initial and post-exposure colour coordinates. In this study, colour difference was used to assess the stability of the pigment particles. A ΔE* value < 1.0 indicates that no perceptible colour difference is observed, whereas values < 2.0 indicate only a slight difference. Values < 3.5 represent a noticeable colour difference, while values < 5.0 indicate a clearly perceptible difference. A ΔE* value > 5.0 signifies that the two colours are distinctly different (Latos-Brozio & Masek 2020; Melgosa et al., 2013). Degradation (%) = $[(X_0 - X_t)/X_0] \times 100$, where X_0 is the initial b* or s value, and X_t is the corresponding value after the specified exposure period. The reported values were calculated from the mean of three replicate specimens.

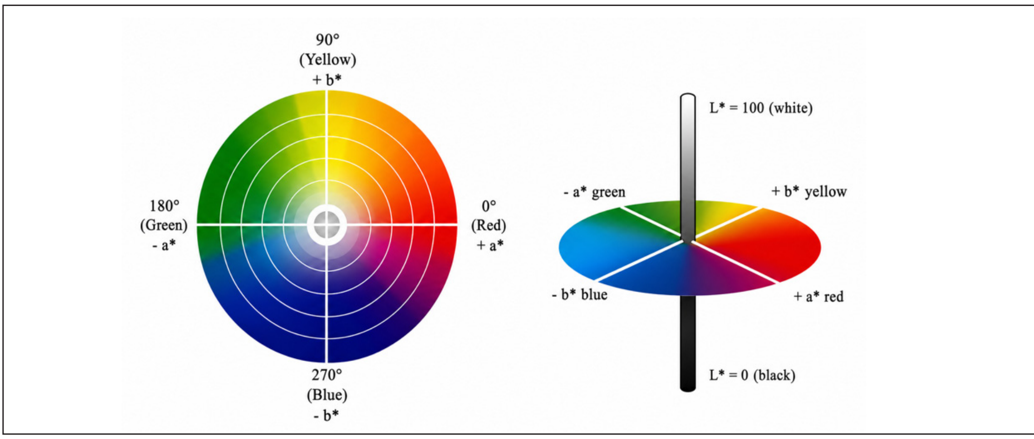

Figure 2. CIELab colour space (Earl et al. 2016)

Statistical Data Analysis

The triplicate colour measurements were summarised using the mean, standard deviation and variance. Data from the light and dark tests were evaluated at the scheduled weekly intervals, whereas the UVA exposure data were evaluated daily. The statistical analyses were conducted using XLSTAT- Basic + 2024 (Addinsoft/Lumivero, France). The dataset was normalised, and potential outliers were assessed at $\alpha = 0.05$ using the Grubbs and Dixon tests (Coucke et al., 2012). Differences between treatment means were evaluated by analysis of variance (ANOVA), followed by Tukey's post-hoc test at $\alpha = 0.05$. Where required, the data were transformed using centring, standardisation, scaling, Pareto or logarithmic procedures before the normality and sampling adequacy assessments were repeated. Sampling adequacy for principal component analysis (PCA) was evaluated using the Kaiser-Meyer-Olkin (KMO) test. KMO values were interpreted as inadequate (<0.5), mediocre (0.5-0.7), good (0.7-0.8), very good (0.8-0.9) and excellent (>0.9); only values exceeding 0.5 were accepted for PCA (Ismail et al., 2021). Bartlett's test of sphericity was used to determine whether the correlation matrix was suitable for factor analysis. Pearson correlation analysis was then applied to evaluate the relationships among dye concentration, b*, s, ΔE*ab and exposure time. PCA was used to reduce the dataset into principal components, and the cumulative variance and factor loadings of PC1 and PC2 were examined to identify the variables that contributed most strongly to the colour changes.

RESULT AND DISCUSSIONS

Analysis of Mordants on Colour Stability Under Light and Dark Conditions

Figure 3 and Table 1 compare the percentage degradation of the yellow coordinate (b*) and saturation (s), together with the final colour difference (ΔE*ab), for silk dyed with bixin at 10, 20 and 30 g/L after four weeks under visible-light and dark-storage conditions. Under visible light, all treatments showed substantial losses in b* and saturation (s).

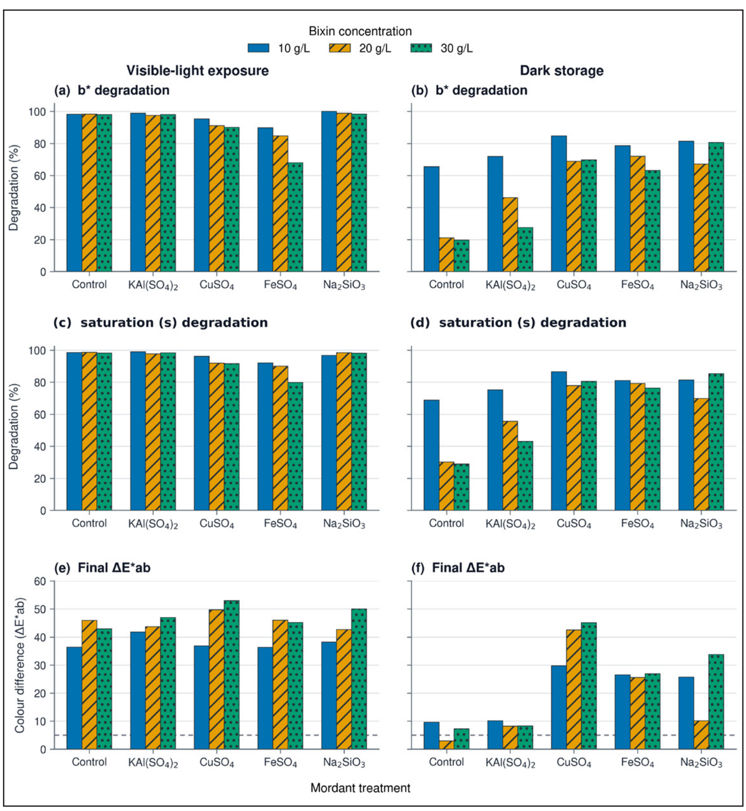

Figure 3. Degradation of b* and saturation (s) and final ΔE*ab for *Bixa orellana* dyed silk at pigment concentrations of 10, 20 and 30 g/L after four weeks: (a0 b* under visible light, (b) b* in dark storage, (c) saturation (s) under visible light, (d) saturation (s) in dark storage, (e) ΔE*ab under visible light and (f) ΔE*ab in dark storage. The dashed line in panels (e) and (f) marks ΔE*ab = 5.0

Table 1
Degradation of b and saturation (s) and final ΔE*ab for bixin dyed silk after four weeks under visible light and dark storage*

Colour response	Treatment	Value / Pigment concentration (g/L)					
		Visible light			Dark storage		
		10	20	30	10	20	30
Saturation degradation, s (%)	Control (unmordanted)	98.53	98.61	98.26	68.88	30.13	28.94
	$KAl(SO_4)_2$	98.94	97.81	98.29	75.21	55.66	43.05
	$CuSO_4$	96.18	91.96	91.62	86.51	77.91	80.53
	$FeSO_4$	92.06	90.05	79.82	81.05	79.29	76.39
	Na_2SiO_3	96.80	98.46	98.12	81.37	69.90	85.30
Yellow-coordinate degradation, b* (%)	Control (unmordanted)	98.25	98.30	98.00	65.49	21.13	19.63
	$KAl(SO_4)_2$	98.85	97.54	97.95	71.89	46.15	27.53
	$CuSO_4$	95.34	91.21	90.08	84.74	68.88	69.72
	$FeSO_4$	89.82	84.77	67.99	78.56	71.97	63.13
	Na_2SiO_3	100.00	98.84	98.29	81.43	67.19	80.66
Colour difference, ΔE*ab	Control (unmordanted)	36.39	45.93	42.90	9.59	2.97	7.21
	$KAl(SO_4)_2$	41.75	43.71	46.93	10.13	8.19	8.25
	$CuSO_4$	36.84	49.68	52.95	29.71	42.55	45.12
	$FeSO_4$	36.33	45.98	45.16	26.49	25.57	26.90
	Na_2SiO_3	38.18	42.66	50.05	25.69	10.11	33.76

Note. Degradation (%) = [initial value – final value] x 100 for b* and saturation (s). ΔE*ab is an absolute colour difference value, not a percentage

Among the mordanted samples, $FeSO_4$ at 30 g/L produced the lowest degradation (67.99% for b* and 79.82% for saturation (s)), whereas Na_2SiO_3 produced consistently high losses, including 100.00% degradation of b* at 10 g/L.

Under dark storage, degradation was lower than under visible light for most treatments. Among the mordanted samples, $KAl(SO_4)_2 \cdot 12H_2O$ at 30 g/L recorded the lowest degradation (27.53% for b* and 43.05% for saturation (s)). The control at the same concentration showed lower degradation (19.63% for b* and 28.94% for saturation (s)). Therefore, the advantage of $KAl(SO_4)_2 \cdot 12H_2O$ applies only within the mordanted treatments.

At week 4, ΔE*ab values under visible light ranged from 36.33 ($FeSO_4$, 10 g/L) to 52.95 ($CuSO_4$, 30 g/L). As all values exceeded 5.0, the final colours were clearly distinguishable from their initial colours. These high values indicate a substantial and rapid loss of the original pigment colour, reflecting poor colour stability under visible light exposure. Under dark storage, ΔE*ab ranged from 2.97 (control, 20 g/L) to 45.12 ($CuSO_4$, 30 g/L). All mordanted samples showed distinct colour changes (ΔE*ab = 5.0), indicating considerable pigment colour degradation, whereas the control value 2.97 represented only a noticeable colour difference.

Analysis of UVA Exposure on Colour Stability of Silk Fabric

Figure 4 and Table 2 present the endpoint results following the recorded 24-hour UVA exposure and daily colour monitoring through Day 7. Substantial degradation was observed across all treatments. Among the mordanted samples, $FeSO_4$ at 20 g/L showed the lowest degradation, recording 72.70% for b* and 82.38% for saturation (s). In contrast, Na_2SiO_3 exhibited very high degradation, reaching 98.91% for b* at 10 g/L and 98.64% for saturation (s) at 30 g/L.

On Day 7, ΔE*ab values ranged from 36.02 to 57.04. $FeSO_4$ recorded the lowest ΔE*ab at each pigment concentration with values of 36.02, 44.96 and 50.31 at 10, 20 and 30 g/L, respectively, whereas the highest value of 57.04 was recorded for $KAl(SO_4)_2 \cdot 12H_2O$ at 30 g/L. All endpoint E*ab values exceeded 5.0, demonstrating clearly distinguishable colour changes and substantial pigment fading. Although $FeSO_4$ at 20 g/L provided the greatest relative colour retention under UVA exposure, degradation remained above 70% for b and 80% for saturation (s), indicating that none of the mordants completely prevented UVA induced colour deterioration.

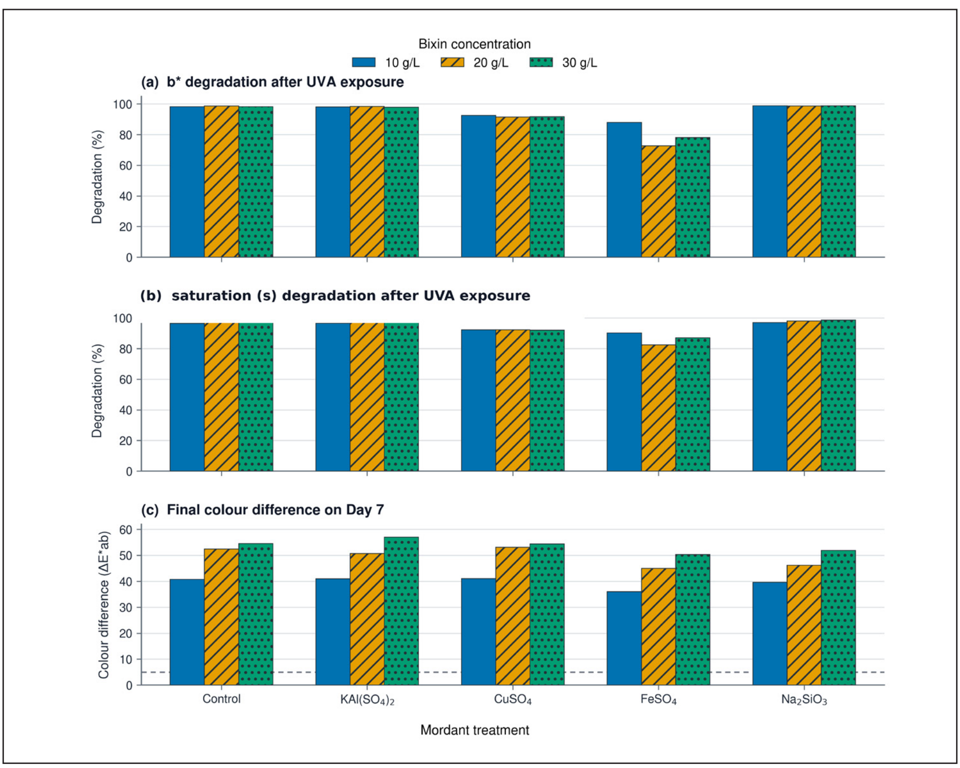

Figure 4. Degradation of b* and saturation (s) and final ΔE*ab for *Bixa orellana* dyed silk monitored through Day & following the recorded 27-hour UVA exposure: (a) b* degradation, (b) saturation (s) degradation and (c) ΔE*ab on Day 7. The dashed line in panel (c) marks ΔE*ab = 5.0

Table 2
Degradation of b and saturation (s) and final ΔE*ab for bixin dyed silk monitored through Day & following UVA exposure*

Colour response	Value / Pigment concentration (g/L) Treatment	10	20	30
Saturation degradation, s (%)	Control (unmordanted)	96.48	98.68	98.33
	$KAl(SO_4)_2$	96.63	98.29	98.25
	$CuSO_4$	92.18	92.21	91.95
	$FeSO_4$	90.20	82.38	87.05
	Na_2SiO_3	96.99	97.98	98.64
Yellow-coordinate degradation, b* (%)	Control (unmordanted)	98.27	98.79	98.24
	$KAl(SO_4)_2$	98.08	98.30	97.80
	$CuSO_4$	92.44	91.51	91.77
	$FeSO_4$	87.85	72.70	78.09
	Na_2SiO_3	98.91	98.74	98.84
Colour difference, ΔE*ab	Control (unmordanted)	40.74	52.41	54.53
	$KAl(SO_4)_2$	40.96	50.69	57.04
	$CuSO_4$	41.07	53.08	54.40
	$FeSO_4$	36.02	44.96	50.31
	Na_2SiO_3	39.63	46.19	51.86

Note. The specimens were recorded in 24 hours of UVA exposure followed by daily colour monitoring. Degradation (%) was calculated for b* and saturation (s); ΔE*ab is an absolute colour difference value

Multivariate Data Analysis

The factors affecting the stability of bixin pigments on silk textiles and chromaticity changes were assessed using multivariate data analysis, or MDA. The adequacy of the sample factor analysis was confirmed by the Kaiser-Meyer-Olkin (KMO) test, which yielded a value of 0.783, exceeding the minimum threshold of 0.5, and Bartlett's test of sphericity was significant (X2 = 7363.286, df = 10, $p < 0.0001$), confirming that the correlation matrix was suitable for PCA (Ismail et al., 2021) as shown in Table 3.

The Pearson matrix showed a strong positive correlation between b* and saturation (s) ($r = 0.979$). ΔE*ab was strongly negatively correlated with b* ($r = 0.891$) and saturation (s)

Table 3
Kaiser-Meyer-Olkin Test and Bartlett's Test of Sphericity for Chromaticity changes of bixin pigment on fabric

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.783
Bartlett's Test of Sphericity	Chi-square (Observed value)	7363.286
	DF	10
	p-value (Two-tailed)	< 0.0001

(r = -0.883). Exposure time was negatively correlated with b* (r = -0.903) and saturation (s) (r = -0.889) but positively correlated with ΔE*ab (r = 0.869). Thus, increasing exposure time was associated with loss of yellowness and saturation and with a larger overall colour difference as shown in Table 4.

Principal component analysis (PCA) retained two components with eigenvalues greater than 1. PC1 explained 74.24% of the variance and represented the colour retention versus degradation axis; b* (0.981) and saturation (s) (0.977) loaded positively, whereas ΔE*ab (-0.943) and exposure time (-0.949) loaded negatively. PC2 explained 20.64% of the variance and was dominated by pigment concentration (loading = 0.995). Together, PC1 and PC2 explained 94.87% of the total variance, as shown in Tables 5 and 6. Because the analysis was pooled across three fabrics, the components should not be interpreted as silk-specific effects.

DISCUSSION

This study demonstrates the potential of *Bixa orellana* (annatto) as a natural colourant for silk, supporting more sustainable and environmentally conscious textile practices. The CIELab system was used to examine how the dyed silk responded under different

Table 4
Pearson correlation matrix of chromaticity changes of bixin pigment on fabric

Variables	CONC	b	S	ΔE	t
CONC	1				
b	0.093	1			
S	0.176	0.979	1		
ΔE	0.062	-0.891	-0.883	1	
t	0.000	-0.903	-0.889	0.869	1

Table 5
Eigenvalues, cumulative variance, and factor loading (FL) of different parameters for colour changes of bixin pigment on fabric

Variables	F1	F2
Conc (concentration)	0.076	0.995
b* (yellow intensity)	0.981	0.029
s (saturation)	0.977	0.113
ΔE (chromaticity)	-0.943	0.148
t (time)	-0.949	0.078
Eigenvalue	3.712	1.032
Variability (%)	74.236	20.638
Cumulative (%)	74.236	94.874

Table 6
Summary of multivariate analysis

Test/Parameter	Value/category	Interpretation
Kaiser-Meyer-Olkin (KMO)	0.783	Data adequate for factor analysis (good category)
Bartlett Test of Sphericity	X^2 =7363.286=10, p<0.00001	A correlation matrix is suitable for PCA
Pearson Correlation	b*-s=0.979 b*- ΔE=0.869 ΔE-t=0.903 s-t=-0.891	Strong positive correlations (b* & s; b* & ΔE); strong negative correlations (ΔE & t; s & t)
Eigenvalue (PC1, PC2)	PC1=3.71 PC2=1.03	Both components exceed the eigenvalue threshold of 1
Cumulative Variance	PC1=74.24% PC2=20.63% Total=94.87%	Two principal components explain almost all data variation
Factor Loadings (FL)	All variables FL>0.75	All variables contribute significantly to colour variations

conditions in both the presence and absence of light and UVA radiation. Silk, a natural protein-based fibre, is highly compatible with plant-derived colours and commonly used in high-quality textiles. These findings serve to clarify how natural dyes interact with silk, which is critical for creating dyeing procedures with less effect on the environment (Che & Yang, 2022; Yusuf et al., 2017).

In dark storage, $KAl(SO_4)_2$ was the most effective mordant in preserving colour stability. This indicates that each mordant works more effectively under different conditions. However, the mordants all showed a clear colour change under light exposure, with ΔE* values exceeding 5.0. Such behaviour implies that the changes were readily noticeable, which highlights the tendency of the mordants to fade when exposed to light. This is a known weakness of many natural dyes (Chakraborty et al., 2025; Ibrahim et al., 2010). In this study, all the mordants showed a noticeable colour change (ΔE* > 5.0) under prolonged light exposure, indicating that *Bixa orellana*-dyed silk fabric does not exhibit long-term stability under typical lighting conditions. This result aligns with earlier work showing that natural dyes, especially carotenoid dyes such as bixin, are moderately prone to photo-oxidation and fading when exposed to light (Othman, 2009; Sant'Anna et al., 2013).

The importance of mordants in increasing the durability of colour on textiles of natural dyes is well-documented (Burkinshaw & Kumar, 2009; Vankar, 2017). In this study, $FeSO_4$ was the most effective mordant for maintaining colour stability under both light and UVA exposure, particularly at the highest concentration of 30 g/L. This result aligns with previous studies indicating that iron-based mordants tend to improve colour retention in natural dyeing, possibly due to their ability to form strong bonds with dye molecules and fibres (Mongkholrattanasit et al., 2016; Swamy, 2020). The remarkable efficacy of $FeSO_4$

in this study is likely linked to its ability to stabilise the bixin pigment sourced from *Bixa orellana*, which is renowned for its vulnerability to light and UV radiation (Shahid-ul-Islam et al., 2016). $FeSO_4$ can create more stable dye-fibre-mordant complexes due to its sulphate groups, which can efficiently link the metal centres and dye molecules via robust hydrogen bonds and coordination interactions. Moreover, the redox-active Fe (II) entities can promote dynamic ligand-to-metal charge transfer, enhancing the stability, lightfastness, and dye retention of the complexes relative to other mordants (Inouchi et al., 2026; Roy Maulik, 2019). Although $FeSO_4$ offered slightly greater protection than the other mordants, the aggregate colour loss remained significant and, in many cases, exceeded 70%. This pattern is consistent with previous findings showing the susceptibility of natural dyes, particularly carotenoid pigments such as bixin, to photooxidation under UV light, which ultimately leads to decreased colour stability (Othman, 2009; Sant'Anna et al., 2013).

Na_2SiO_3, in contrast, consistently exhibited the lowest stability in all the tested conditions. This result is consistent with previous research indicating that sodium metasilicate is generally less effective as a mordant for natural dyes due to its poor binding affinity to fibres (Burkinshaw & Kumar, 2009). Exposure to UVA increased the fading effect, and reductions in yellow intensity and saturation were clearly observed across all the mordants tested. The diminished efficacy of sodium metasilicate as a mordant is attributed to its elevated alkalinity and pH-dependent polymerisation, leading to the formation of large aggregates of less reactive silicates that fail to bond with fibres and dyes as effectively as traditional metal mordants. Moreover, its feeble coordination interactions with cellulose hydroxyl groups and the potential for fibre degradation owing to its corrosive nature diminish its effectiveness in dye fixation and colour retention (Jamaludin et al., 2025). The interaction of Na_2SiO_3 with molecules is lower than that of standard metal mordants, leading to insufficient dye fixing and colour fastness. The effectiveness also depends on the ionic strength of the solution and on competing ions (Rahman & Karacan, 2022; Kon'kova et al., 2021).

Since no mordant can completely stop the degradation process, the use of additional treatments, including UV-blocking finishes or the addition of antioxidant agents, could help to increase pigment stability for longer periods. From a practical perspective, these findings suggest that *Bixa orellana* dyes on silk are suitable for indoor or low-light applications, such as scarves, interior upholstery, or ceremonial clothing, where there is limited UV exposure. Besides, the silk proteins, mainly fibroin and sericin, possess reactive groups including hydroxyl, carboxyl, and amine functionalities (Phasayavan et al., 2026). The carboxyl and amine functional groups are essential for binding metal ions, forming stable complexes by coordination bonding. Metal cations such as Mg^{2+}, K^{+} and Ca^{2+} can engage with silk proteins, generally leading to gelation or alterations in structure by coordination with the negatively charged moieties of the protein (Zhou et al., 2025). Metal mordants primarily interact with the functional groups of silk protein, particularly carboxyl and amino groups, to create stable complexes and alter the structure and properties of silk protein.

The dye's poor resistance to sunlight needs to be improved if it is to be used for outdoor products. One possible solution is to explore the use of natural bio-mordants or encapsulation methods to boost colourfastness while maintaining eco-friendliness (Burkinshaw & Kumar, 2009; Vankar, 2017). The vulnerability of carotenoid pigments like bixin to photooxidation mostly arises from their long chain of conjugated double bonds, rendering them highly reactive and unstable in the presence of light and oxygen; yet this characteristic is advantageous for their colouration and antioxidant functions. This results in rapid degradation, fading of hue, and diminished biological activity (Enayati et al., 2023). Bixin is regarded as the inaugural cis-carotenoid and an apocarotenoid that may modify its stability and light sensitivity. In addition, carotenoids exhibit significant instability when exposed to light and oxygen, leading to photooxidation and the deterioration of the pigments (Cortez et al., 2017).

This study generates important information on the shelf life of annatto at different levels. The findings revealed that a higher concentration (30 g/L) contributed slightly to the stability of the dye, particularly with $FeSO_4$ and $KAl(SO_4)_2$ mordants. The potential of *B. orellana* to generate bright colours, its biodegradability, and its non-toxicity render it a suitable candidate for eco-friendlier approaches to dye production (Cuong & Chin, 2016). Nevertheless, the related issues (from colour fastness to environmental factors, and especially exposure to UV radiation) remain a major challenge. These findings highlight the importance of selecting the right mordant to optimise colour stability while reducing the environmental impact of the dyeing process. Reactive oxygen species (ROS) generated from UVA radiation can oxidise pigment molecules such as melanin and synthetic dyes, resulting in their destruction or alteration (Lawrence et al., 2022). Oxidative stress is a main cause of pigment degradation, because reactive oxygen species can change the chemical structure of the pigments and cause their discolouration or transformation (Bouider et al., 2024). The rate of pigment degradation was greatly increased by the inclusion of photocatalysts (TiO2, SnO2, etc.) under UVA irradiation, which leads to higher production of extra reactive oxygen species (ROS) and acceleration of photodecomposition processes (Bokhari et al., 2022). The data also showed the existence of a saturation effect, whereby the use of higher quantities of dye helped to increase the level of protection on the fabric surface and subsequently reduce the rate of fading. However, these factors must be considered along with aspects such as the cost and environmental implications, thus emphasising the need to optimise dyeing techniques for large-scale production purposes (Kalapriya & Gurumalesh Prabu, 2020).

Although this study lays a solid foundation for using *Bixa orellana* as a textile dye, future studies should include other fastness tests, such as washing, perspiration, and rubbing, which are important for real-life applications. Dye concentration is a fundamental factor influencing colour intensity in textiles; nevertheless, its impact is influenced by fibre characteristics, fabric composition, and dying parameters. A realistic maximum for colour depth exists due to fibre saturation, and over this threshold can adversely affect product quality and environmental sustainability (Chakraborty et al., 2025; Li et al., 2009). Testing on other fabrics, such as cotton, wool, and polyester, will also help in applying these findings more widely. In addition, the integration of additional protective treatments, such as UV-blocking or antioxidant finishes, could further improve the fastness of natural dyes in outdoor applications. Further studies should also test the fastness to washing and rubbing of *Bixa orellana*-dyed fabrics, with these factors being important for the practical everyday use of textiles (Yusuf et al., 2017). As emphasised by Alegbe & Uthman (2024), testing on a wide range of fabrics is important to understand the full potential of natural dyes in modern textile applications.

CONCLUSION

This study on the colour fastness of silk dyed with *Bixa orellana* (annatto) using CIELab analysis showed that although this dye is biodegradable and has strong colour, it has no long-term stability under environmental stress. Of the mordants tested, $FeSO_4$ gave the best results, especially at a high dye concentration of 30 g/L, with better colour retention under light and UVA exposure. $KAl(SO_4)_2$ performed well in dark storage, while Na_2SiO_3 performed the worst, with high colour loss under all conditions. However, all the mordants showed obvious colour changes ($\Delta E^*>5.0$), with more than 70% fading under UVA. This indicates that no mordant could completely protect the dye. Thereafter, the use of more dye might slightly improve the short-term stability. Based on the resistance, future studies should test UV blocking treatments or natural bio-mordants, as well as study the dye resistance to washing and rubbing.

Although *Bixa orellana* has potential as a natural dye, it is easily affected by UV radiation and fades when exposed to light. This indicates the need for further improvement in mordanting techniques or the development of a protective layer. Although $FeSO_4$ showed better colour fastness, the overall durability of the dye was still limited, indicating that additional treatments such as UV barrier finishes or the use of natural bio-mordants could improve its performance for practical applications. Although this study provides valuable insights into the colourfastness of silk dyed with *Bixa orellana*, some limitations need to be considered. The scope of this study was limited to exposure to light and UVA radiation, so future research should include other forms of environmental stress, such as washing, sweating, and rubbing, which are important for real-world applications. Furthermore, conducting tests on diverse fabric types, such as cotton, wool, and synthetic materials, would facilitate the wider applicability of the results. Further studies should also explore the optimisation of the dyeing process, including the use of different extraction methods and concentrations of *Bixa orellana*, to further improve colourfastness and enhance the sustainability of natural dyes in textile manufacturing.

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