

Valorization of polyphenol-rich extracts from *Oroxylum indicum* (L.) kurz outer stem bark as sustainable textile colourants: Comparison concerns selected GOTS 7.0 colour fastness criteria on effects of six mordants and pre-, meta- and post-mordanting techniques on dyeing properties

Siripan Metanawin¹, Apichart Sonthisombat^{1*}, Mahamasuhaimi Masae², Sumonman Niamlang³,
Jantana Sutdaen¹, Pannarai Rug-ngarn¹, Orathai Tangsirinaruenart¹, Tanapak Metanawin⁴,
Sarunya Puakpong⁵

¹ Department of Textile Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi.

² Department of Industrial Engineering, Faculty of Engineering, Rajamangala University of Technology Srivijaya.

³ Department of Material and Metallurgical Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi.

⁴ Department of Materials and Production Technology Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok.

⁵ Department of Home Economics, Faculty of Agriculture, Kasetsart University.

* Corresponding author.

Email address: apichart.s@en.rmutt.ac.th

Received: August 20, 2026 Revised: September 24, 2026 Accepted: September 25, 2026

Abstract

The Ban Kham Nang Ok weaving and agricultural community enterprise group in Nihkhom Kham Soi District, Mukdahan Province had the main issue of low light colour fastness of cotton yarns dyed with *Oroxylum indicum* (L.) Kurz. This study examined different mordant conditions to improve the colour fastness of the natural dye and to determine whether the resulting colours met the GOTS 7.0 colour fastness criteria. Greenish brown to khaki were received from those dyeing conditions. From FTIR analysis, it indicated that the bark contains polyphenolic compounds, including flavonoids, hydrolysable tannins, and other phenolic compounds. Pre-mordant copper sulphate, pre-mordant red lime, meta-mordant tamarind, meta-mordant red lime, and pre-mordant iron rust showed top five colour-intensity values respectively. When light, washing, rubbing, and perspiration fastness tests were considered together, post-mordant tamarind and post-mordant iron rust met the GOTS 7.0 colour fastness criteria. Individual colour fastness assessments showed that the post-mordant processes passed 126 out of 144 test results (87.5%), the meta-mordant processes passed 118 out of 144 tests results (81.9%), while the minimum pre-mordant processes passed 109 out of 144 results (75.67%). Selected mordanting conditions achieved light-fastness grades of 4 (fair) or higher, can improve this key limitation of the natural dyes for cotton. These findings identify practical mordanting routes for improving the fastness performance of naturally dyed textiles and support the development of products that comply with GOTS 7.0 colour fastness performance requirements.

Keywords: *Oroxylum indicum* (L.) kurz, Polyphenols, Mordant, GOTS (Global Organic Textile Standard) version 7.0

1. Introduction

Natural dyeing remains an important component of traditional textile production and local cultural heritage. However, practical use of naturally dyed yarns or fabrics is often constrained by variability in colour reproduction and colour fastness. Interviews with the leaders and members of the Ban Kham Nang Ok weaving and agricultural community enterprise indicated that yarns or fabrics dyed with locally available tree bark showed limitations, particularly in colour fastness to light, and that customers had raised concerns regarding the lack of standardization of the dyed textiles and related products. The community traditionally employed post-mordanting using locally available materials, including wood-ash alkaline solution, red lime, common salt, alum solution, eucalyptus leaves, clay-soil solution, mixtures of clay soil and wood-ash alkaline solution, and mud combined with eucalyptus leaf and stem solution. As these dyeing methods showed valuable wisdom and culture, different mordants and their mixtures can make some difference results varying lots by lots. Therefore, controlled dyeing processes should be considered as the quantities of barks and cotton fibres to improve reproducibility and shade consistency while the use of indigenous trees. *Oroxylum indicum* (L.) Kurz (as known as *Oroxylum indicum* (L.) Vent.) is a medium sized tree under the Bignoniaceae family with the height of eight to fifteen metre long [1–3]. They are distributed across the following countries: Thailand, India, Vietnam, Malaysia, Indonesia, Bhutan, and southern China [4]. In Thailand, “Peka” is called for this tree, and it has trumpet-like flowers and elongated seed pods [5]. The soft and spongy outer bark has colour varying from pale cream to light brown or greyish brown [1]. Previous studies have shown that *Oroxylum indicum* (L.) Kurz contains several bioactive flavonoids. Baicalin, baicalein,

and chrysin have been identified in extracts from seeds and tissue-cultured plants by HPLC [6], while Dinda et al. [7] reported approximately 50 flavonoids in the species. Baicalein, chrysin, and oroxylin A are among the major flavones reported in the stem and root bark [8]. The stem bark is therefore a relevant source of naturally occurring compounds with potential contribution to its extractable colour components. Extraction conditions influence the composition and yield of plant-derived extracts, and solvent-based extraction has been reported to recover higher amounts of some flavonoids than aqueous boiling [6–8]. Klinpikul et al. [9] investigated pigment extraction from *Oroxylum indicum* (L.) Kurz bark as one of six Thai plant materials selected on the basis of local availability and potential for natural dye production. Under boiling extraction conditions, the bark extract produced light- to dark-brown colouration, with a maximum reported extraction yield of $11.12\% \pm 0.06$ at 80 °C for 90 min [9]. This work shows the feasibility of extraction colourant from *Oroxylum indicum* (L.) Kurz bark; whereas the yield of extraction does not relate to dyeing performance, colour range, or fastness when applied to cotton. The dyeing behaviour of the bark still received limited systematic reports on its chemical constituents and extraction, especially the effects of mordants and mordanting techniques on colour fastness on cotton fibres have not been compared comprehensively. To the best of our knowledge, previous studies have not systematically evaluated *Oroxylum indicum* (L.) Kurz outer stem bark extract on cotton using multiple mordants applied through pre-mordanting, meta-mordanting, and post-mordanting while assessing colour fastness to light, washing, rubbing under dry and wet conditions, and perspiration under acidic and alkaline conditions. This gap restricts both reproducible application of this indigenous dye

source and evidence-based selection of mordanting conditions for practical textile production. The novelty of the present work lies in the systematic comparison of six mordants—red lime, alum, copper sulphate, tamarind, common salt, and iron rust solution—across three mordanting routes using a standardized *Oroxylum indicum* (L.) Kurz outer stem bark dyeing procedure for cotton. Rather than evaluating a single mordant or dyeing route, the study examines how mordant identity and the stage of mordant application affect the resulting colour shades and fastness performance within the same dye system. Hot-water extraction was selected as a simple and low-cost preparation method, and the dyeing procedures were controlled through defined measuring and weighing steps. The resulting yarns were evaluated for colour fastness to light, washing, dry and wet rubbing, and acidic and alkaline perspiration. Accordingly, the work contributes a reproducible experimental framework for comparing traditional and modified mordanting practices and identifies the range of colour and fastness responses achievable from a single locally available bark source without attributing these responses to mechanisms that were not directly measured. The environmental acceptability of mordants is also relevant to the practical adoption of natural dyeing processes. The Global Organic Textile Standard (GOTS) Version 7 . 0 , announced in March 2023 managed by Global Standard gemeinnützige GmbH, as outline requirements covered by subjects of organic textile processing, production chemicals, environmental management, and social criteria throughout the textile supply chain [10]. The use of metal-ion-based mordants is not strictly banned, while their application must have chemical approval from GOTS and must comply to relevant hazard-related requirements [10]. This distinction is particularly significant when comparing conventional salts, plant-

based mordants, and metal-based mordants. Therefore, this study presents experimental data on colour formation and colour fastness to assist in the selection of mordanting conditions, while noting that compliance with GOTS or other certification systems requires separate assessments based on the applicable chemical and processing criteria.

2. Materials and methods

2.1 Materials

The textile substrate used in this study was 100% cotton spun yarn with a yarn count of Ne 10/1. The cotton yarn was selected as the substrate for natural dyeing using an extract obtained from the outer stem bark of *Oroxylum indicum* (L.) Kurz. Prior to dyeing, the yarn samples were prepared in hank form to facilitate uniform contact between the yarn and the dye liquor during the dyeing and mordanting processes.

The outer stem bark of *O. indicum* (L.) Kurz was used as the natural source of colourants. The bark extract, which contains naturally occurring polyphenolic compounds, was prepared and subsequently applied to the cotton yarns using different mordanting procedures. Six mordants were investigated: red lime, alum, copper sulphate (CuSO_4), tamarind, common salt (NaCl), and iron rust solution. These mordants were selected to represent inorganic mordants and locally available natural or traditional mordant materials.

The effects of the six mordants on the dyeing properties of the cotton yarns were evaluated using three mordanting techniques: pre-mordanting, meta-mordanting, and post-mordanting. Cotton yarn dyed without mordant treatment was used as the control sample for comparison.

2.2 Preparation method of the mordants

The community enterprises typically use mordants such as clear lime water, saltwater, alum, and alkaline water—all of which are readily available in Mukdahan Province. For this study, six types of mordants were selected: red lime, alum, copper sulphate (CuSO_4), tamarind seed coats, common salt (NaCl), and an iron rust solution. The commercial-grade or locally sourced mordants were chosen because of actual community-level practices. The stainless-steel pot, a household electric stove and a 200-mesh (holes/inches) stainless-steel sieve. According to a community-based traditional recipe, the mordant solutions (red lime, alum, copper sulphate and common salt) were prepared as follows: each mordant material was mixed with water at a concentration of 50% (w/v). After thorough mixing, the mixtures were left undisturbed until the coarse, insoluble particles had settled. The clear supernatant was then carefully decanted and filtered twice through a 200-mesh stainless steel sieve.

The mordant solutions of red lime, alum, copper sulphate and common salt were prepared according to a community-based traditional recipe. Each mordant material was mixed with water at a concentration of 50% (w/v). After thorough mixing, the mixtures were allowed to stand undisturbed to permit coarse and insoluble particles to settle. The clear supernatant was then carefully decanted and filtered twice through a 200-mesh stainless-steel sieve. The resulting filtrates were used as the mordant solutions for subsequent dyeing experiments.

The mordants were categorized by condition: acidic (alum, CuSO_4 , tamarind, and iron rust), neutral (NaCl), and alkaline (red lime).

Mordant solutions of alum, red lime, CuSO_4 , and common salt were prepared by dissolving or dispersing the respective materials

in water at the specified concentrations. The prepared solutions were allowed to stand until coarse and insoluble particles had settled at the bottom of the containers. The clear supernatant was then carefully decanted and filtered twice through a 200-mesh stainless-steel sieve to remove residual suspended particles and other impurities prior to use in the mordanting process.

The tamarind mordant solution was prepared by soaking tamarind seed coats in water at the concentration of 20% (w/v) for 60 minutes and then squeezing the material while wearing rubber gloves to facilitate the release of water-soluble compounds. The resulting extract was allowed to settle and was then filtered twice through the same 200-mesh stainless steel sieve. The tamarind bio-mordant solution was freshly prepared and used within 24 hours to minimize microbial contamination and compositional changes during storage.

As traditional community wisdom, rusty nails or iron plates are dipped in water at the concentration of 20% (w/v) without the addition of acids or other chemicals at room temperature for 7 days. After that, the solution is carefully decanted and filtered twice through a 200-mesh stainless steel sieve to be used as an iron-rust mordant.

No nominal concentration is specified for this preparation, as its composition depends on the quantity of iron species naturally released from the rusted iron during the soaking process.

2.3 Extraction of dyes from the bark

The *Oronym indicum* (L.) Kurz outer stem bark was peeled off the bark from the tree between 6-8 a.m. or before sunshine based on the belief that harvesting at this time provides an adequate amount of dyestuff prior to the onset of photosynthesis. Then the bark should be used within 12 hours, the bark was chopped into approximately 2 × 2 cm pieces and washed three times with water to remove

adhering dirt and other surface impurities. Subsequently, 1,000 grams of the bark was immersed in 2,000 mL of water. The bark was submerged under water, and it was left in the room temperature for 48 hours. After 48 hours, the solution was boiled at 98 °C for 2 hours, after extraction, the extracted dye liquor was allowed to cool to room temperature and was filtered twice through a stainless-steel screen filter (200 mesh per inch) to remove residual bark particles and suspended matter which should be contaminated the textile materials. The filtrate, which exhibited a characteristic greenish brown to khaki colour, was collected and used as the natural dye solution for the subsequent cotton yarns dyeing experiments.

2.4 The dyeing methods (pre-mordant, meta-mordant, and post-mordant)

The effects of the six mordants on the dyeing properties of the cotton yarns were evaluated using three mordanting techniques as follows pre-mordanting, meta-mordanting, and post-mordanting. Cotton yarn dyed without mordant treatment was used as the control sample for comparison.



Figure 1 the illustration of natural dyeing methods. The figure was created with the assistance of ChatGPT (OpenAI) and subsequently reviewed and modified by the authors.

2.4.1 Pre-mordant dyeing method

The yarns were first treated with the mordant solution at a liquor ratio (L:R) of 1:20 (yarn solution) at 98 °C for 60 min under

continuous stirring. After mordanting, the yarns were allowed to cool to room temperature and were then rinsed twice with water. The mordanted yarns were subsequently dyed with the *Oroxylum indicum* (L.) Kurz bark extract at an L:R of 1:20 (yarn solution) at 98 °C for 60 min under continuous stirring. After dyeing, the yarns were rinsed with water and dried in the shade.

2.4.2 Meta-mordant dyeing method

For meta-mordanting, the mordant solution and *Oroxylum indicum* (L.) Kurz bark extract were applied simultaneously. The yarn: dye solution: mordant solution ratio was 1:10:10. The dyeing process was carried out at 98 °C for 60 min under continuous stirring. After treatment, the yarns were rinsed with water and dried in the shade.

2.4.3 Post-mordant dyeing method

For post-mordanting, the yarns were first dyed with the *Oroxylum indicum* (L.) Kurz bark extract at an L:R of 1:20 (yarn: dye solution) at 98 °C for 60 min under continuous stirring. The dyed yarns were then rinsed with water and subsequently treated with the mordant solution at an L:R of 1:20 (yarn: mordant solution) at 98 °C for 60 min. After mordanting, the yarns were rinsed with water and dried in the shade.

2.5 Evaluations with standard testing methods

2.5.1 FTIR analysis of natural solution extracts from *Oroxylum indicum* (L.) Kurz Bark.

FTIR was investigated using Perkin Elmer Frontier FTIR Spectroscopy. Spectra were recorded over the range of 4000–400 cm⁻¹ at a resolution of 4 cm⁻¹ with 32 accumulated scans. Background spectra were collected before each measurement and subtracted automatically using software. All measurements were conducted at room temperature.

2.5.2 Colour difference using spectrophotometer

The measurement of colour difference was carried out using a DataColor® spectrophotometer (Model Spectro 1050). The colour coordinates were determined according to the CIE L*a*b*, CIE L*C*h°, Colour Strength (K/S) value under illuminant D65 and 10° standard observer conditions. The measurements were performed using a d/8° with SCE mode and an aperture size of 8 mm. Ultraviolet light was excluded during measurement to eliminate the influence of optical brightening agents. Each sample was folded to obtain an opaque background and measured at five different positions. The reported values represented the mean of five measurements.

2.5.3 Colour fastness to light, washing, rubbing and perspiration

The colour fastness of the dyed yarns was measured in terms of standardized conditions, which are: ISO 105-B02:2014 (light), ISO 105-C01:1989 (washing) at

40 ± 2°C for 30 min, ISO 105-X12:2016 (rubbing), and ISO 105-E04:2013 (perspiration), using the Grey Scale of Assessing Change in Colour and Staining.

3. Results and discussion

3.1 FTIR analysis of natural solution extracts from *Oroxylum indicum* (L.) Kurz Bark

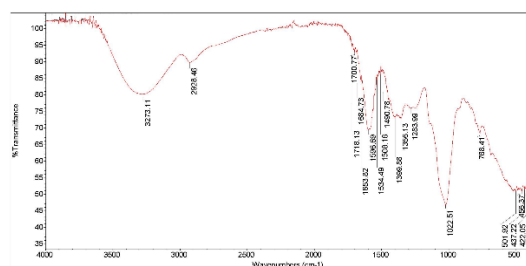


Figure 2 the FTIR spectrum of *Oroxylum indicum* (L.) Kurz bark extract solution investigated by Center of Research Innovation and Academic Promotion, RMUTT, Thailand

Table 1 Comparison of characteristic FTIR absorption bands of tannins with those observed in *Oroxylum indicum* (L.) Kurz bark, including typical ranges, typical peaks, possible chemical constituents, and relevant references.

Tannin Characteristic Peak	Typical Ranges (cm ⁻¹)	<i>Oroxylum indicum</i> (L.) Kurz Bark Typical Peaks (cm ⁻¹)	Possible chemical constituents	References
O–H stretching	3200–3500	3273.11	Phenolic compounds, tannin and polyphenols	[11] [12] [13] [14] [15]
C=O stretching	1720	1718.13	Digalloyl ester group, Hydrolysable tannin structure	[16]
C=O stretching	1700	1700.77	Gallic acid or Ellagic acid-related structures	[11] [16]
C=C/C=O conjugation	1650 and 1639–1665	1653.82	Flavonoid and polyphenolic structures	[11] [12]
Aromatic C=C stretching	1600–1620	1596.69	Aromatic tannins and flavonoids	[13] [14] [15]
Aromatic skeletal vibration	1500–1510	1508.16	Flavonoids, tannins, lignin-related structures	[11] [12] [17]
Phenolic O–H deformation	1395–1405	1399.88	phenolic compounds	[11] [12] [18] [19]

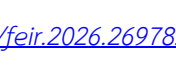
Tannin Characteristic Peak	Typical Ranges (cm ⁻¹)	<i>Oroxylum indicum</i> (L.) Kurz Bark Typical Peaks (cm ⁻¹)	Possible chemical constituents	References
C–O asymmetric stretching of Ether group	1260–1285	1283.99	Phenolic and flavonoid structures	[13] [14] [16]
C–O /C–O–C stretching	1000–1100	1022.51	Oxygenated polyphenolic structures	[11] [13] [14] [15] [18] [16]

From Table 1 and Figure 2, it presents the FTIR spectrum of *Oroxylum indicum* (L.) Kurz bark extract contains a variety of polyphenolic including flavonoids, hydrolysable tannins and other phenolic compounds [20].

3.2 Colour characteristics and colour strength

The colour characteristics of the dried dyed cotton yarns were evaluated using DataColour® Spectra 1050 spectrophotometer with the CIE standard Illuminant D65, and 10° standard observer.

Table 2 CIE L*a*b*, CIE L*C*h°, Colour Strength (K/S) value and colour obtained of textile yarns from the dyeing process with *Oroxylum indicum* (L.) Kurz barks without and with six mordants images from actual photographs of the dyed cotton yarns.

Samples/Mordants	Mordant Methods	L*	a*	b*	C*	h°	K/S	Colour obtained
White Cotton Yarn	Before dyeing	86.52	2.15	13.86	14.03	81.17	0.3560	
Controlled Sample	None	68.71	-1.60	23.58	23.63	98.87	3.1047	
Common Salt	Pre	65.33	2.90	16.27	16.53	79.90	4.3701	
	Meta	69.07	2.77	12.76	13.06	77.75	3.5631	
	Post	64.11	0.46	4.21	4.24	83.71	3.6843	
Copper-Sulphate	Pre	55.74	4.50	22.72	23.16	78.81	6.7564	
	Meta	67.73	3.02	11.52	11.91	75.32	3.6412	
	Post	65.65	1.73	8.76	8.92	78.84	3.7709	
Tamarind	Pre	64.92	3.96	9.43	10.23	67.24	3.8553	
	Meta	64.55	4.94	10.66	11.75	65.11	5.9469	
	Post	68.69	5.25	5.17	7.37	44.59	3.1381	
Iron Rust	Pre	66.75	3.13	20.31	20.55	81.23	4.4913	
	Meta	66.44	1.44	7.77	7.90	79.53	3.5882	
	Post	67.70	1.72	11.75	19.88	81.69	3.7205	

Samples/Mordants	Mordant Methods	L*	a*	b*	C*	h°	K/S	Colour obtained
Red Lime	Pre	60.37	2.44	25.39	25.51	84.51	6.1718	
	Meta	60.32	1.89	19.66	19.75	84.52	5.5047	
	Post	67.11	2.26	13.76	13.94	80.69	3.9481	
Alum	Pre	72.99	3.78	10.58	11.23	70.32	3.0293	
	Meta	67.02	0.06	19.53	19.53	89.23	4.3966	
	Post	73.55	2.98	7.80	8.35	69.10	2.8127	

From the colour strength (K/S) value, it revealed that the colour obtained from different mordants and techniques give different shade varying from greenish brown to khaki colour.

3.3 The results of colour fastness tests

The results of colour fastness test to xenon arc light (ISO105-B02: 2014 Method 3 Xenon-Arc Lamp (Exposure up to contrast of grey scale 4)), colour fastness to washing (at $40 \pm 2^\circ\text{C}$ for 30 min) (ISO 105-C01: 1989, Multifibre DW), colour fastness to rubbing (ISO105-X12:

2016), and colour fastness to perspiration (ISO 105-E04: 2013, MULTIFIBRE DW) were shown in Table 4-6.

3.4 Comparison concerns selected GOTS colour fastness criteria

The comparison concerns selected GOTS (Global Organic Textile Standard) Version 7.0 colour fastness criteria such as light, washing, rubbing and perspiration fastness tests [10] were compared against selected GOTS 7.0 technical-quality criteria.

Table 3 Technical quality parameters section of the GOTS 7.0 criteria for the colour fastness values in terms of light, washing, rubbing and perspiration testing of textile materials [10].

Parameter/Criteria	Light ^a	Washing ^b at 40°C		Rubbing ^c		Perspiration ^d			
		Colour Change	Colour staining Multifibre DW	Dry	Wet	Colour Change		Colour staining Multifibre DW	
						Acid	Alkali	Acid	Alkali
GOTS Version 7.0 March 2023	$\geq 3-4$	$\geq 3-4$	$\geq 3-4$	$\geq 3-4$	≥ 2	$\geq 3-4$	$\geq 3-4$	$\geq 3-4$	$\geq 3-4$

Note Test Methods are ^aISO 105 B02, ^bISO 105 C06 A1M (at 40°C), ^cISO 105 X12 and ^dISO 105-E04.

Table 4 Colour fastness to light and rubbing of cotton yarns dyed with *Oroxylum indicum* (L.) Kurz bark using different mordants and mordanting processes.

Mordants	Mordant methods	Light fastness	Rubbing fastness	
			Dry	Wet
Controlled sample	none	3	4-5	3
Common salt	Pre	4	4	2-3
	Meta	>4	3-4	2-3
	Post	<4	3	2-3

Mordants	Mordant methods	Light fastness	Rubbing fastness	
			Dry	Wet
Copper-sulphate	Pre	<4	3	2
	Meta	>4	3	2
	Post	4	3	2-3
Tamarind	Pre	4	4	2-3
	Meta	<4	3-4	3
	Post	>4	4	2-3
Iron rust	Pre	4	4	2-3
	Meta	4	4	2-3
	Post	4	4	2-3
Red lime	Pre	4	3-4	2-3
	Meta	4	3	2-3
	Post	4	2-3	2-3
Alum	Pre	<4	4	3-4
	Meta	>4	4	2-3
	Post	>4	4	3-4

Note Shaded cells indicate values that do not meet the acceptance criteria specified in the GOTS 7.0 colour fastness criteria.

Table 5 Colour fastness to washing cotton yarns dyed with *Oroxylum indicum* (L.) Kurz bark using different mordants and mordanting processes.

Mordants	Mordant methods	Colour change	Colour staining on multifibre DW					
			Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Controlled sample	None	2	4-5	4-5	4-5	4-5	4-5	4-5
Common salt	Pre	4-5	4	4	4-5	4-5	4-5	4-5
	Meta	3	4-5	4-5	4-5	4-5	4-5	4-5
	Post	3-4	4-5	4-5	4-5	4-5	4-5	4-5
Copper-sulphate	Pre	3-4	3	3	3-4	3-4	4	4
	Meta	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	Post	4-5	2	2-3	1-2	1-2	2-3	2
Tamarind	Pre	3	4-5	4-5	4-5	4-5	4-5	4-5
	Meta	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	Post	4-5	4-5	4-5	4-5	4-5	4-5	4-5
Iron rust	Pre	2	4-5	4-5	4-5	4-5	4-5	4-5
	Meta	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	Post	4-5	4-5	4-5	4-5	4-5	4-5	4-5
Red lime	Pre	1-2	3-4	3-4	4	4	4	4
	Meta	1-2	4	4	4-5	4-5	4-5	4-5
	Post	2	4-5	4-5	4-5	4-5	4-5	4-5
Alum	Pre	1-2	4-5	4-5	4-5	4-5	4-5	4-5
	Meta	4-5	4	4	4	4	4-5	4-5
	Post	4-5	4-5	4-5	4-5	4-5	4-5	4-5

Note Shaded cells indicate values that do not meet the acceptance criteria specified in the GOTS 7.0 standard.

Table 6 Colour fastness to perspiration of cotton yarns dyed with *Oroxylum indicum* (L.) Kurz bark extract using different mordants and mordanting processes under acidic and alkaline conditions.

Mordants	Mordant methods	Conditions	Colour change	Colour staining on multifibre DW					
				Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Controlled sample	None	Acid	2-3	4	4	3	4	4	3-4
		Alkaline	3-4	3-4	3	3	3-4	4	3
Common salt	Pre	Acid	4	3-4	3	3	3-4	3-4	3-4
		Alkaline	4-5	3-4	3	3-4	3-4	3	3
	Meta	Acid	4	3-4	3-4	3-4	3-4	3-4	3-4
		Alkaline	3-4	3-4	3	3	3	3	3-4
	Post	Acid	4-5	4	3-4	3-4	4	4	4
		Alkaline	4	4	3-4	4	3-4	3-4	4
Copper-sulphate	Pre	Acid	3-4	3-4	3-4	3-4	3-4	3-4	4
		Alkaline	3	3-4	3-4	3-4	3-4	3-4	3-4
	Meta	Acid	4	4	3	3	3	3	3
		Alkaline	4-5	4	3-4	3-4	3-4	3-4	3-4
	Post	Acid	3	4	4	4	4	4	3-4
		Alkaline	4	3-4	3	3	3	3-4	3
Tamarind	Pre	Acid	4	4	3-4	3-4	4	4	4
		Alkaline	3	3-4	2-3	3	3	3	3-4
	Meta	Acid	4	4	3-4	3-4	4	4	4
		Alkaline	3-4	4	3	3-4	3-4	3-4	3-4
	Post	Acid	4-5	4	4	4	4	4	4
		Alkaline	4	4	3-4	3-4	3-4	3-4	4
Iron rust	Pre	Acid	3	4	3-4	3-4	4	4	4
		Alkaline	4	3-4	3	3-4	3-4	3-4	3-4
	Meta	Acid	3-4	4	4	4	4-5	4-5	4-5
		Alkaline	4	3-4	3	3-4	3-4	3-4	3-4
	Post	Acid	3-4	3-4	4-5	4	4	4	4
		Alkaline	4	4	3-4	4	4	4	4
Red lime	Pre	Acid	2-3	3-4	3-4	3-4	3-4	3-4	3-4
		Alkaline	3	3	3	3	3	3	3
	Meta	Acid	1-2	3-4	3-4	3-4	3-4	4	4
		Alkaline	3	3	2-3	3	3	3	3
	Post	Acid	4	4	4	4	4	4	4
		Alkaline	4	4	3-4	3-4	3-4	3-4	3-4
Alum	Pre	Acid	4	4	4	4	4-5	4-5	4-5
		Alkaline	4	3-4	3-4	3-4	3-4	3	3-4
	Meta	Acid	1-2	4	4	4	4-5	4	4-5
		Alkaline	3	4-5	4-5	4-5	4-5	4-5	4-5
	Post	Acid	1-2	4	4-5	4	4-5	4	4-5
		Alkaline	2	4	4	4	4-5	4-5	4-5

Note Shaded cells indicate values that do not meet the acceptance criteria specified in the GOTS 7.0 standard.

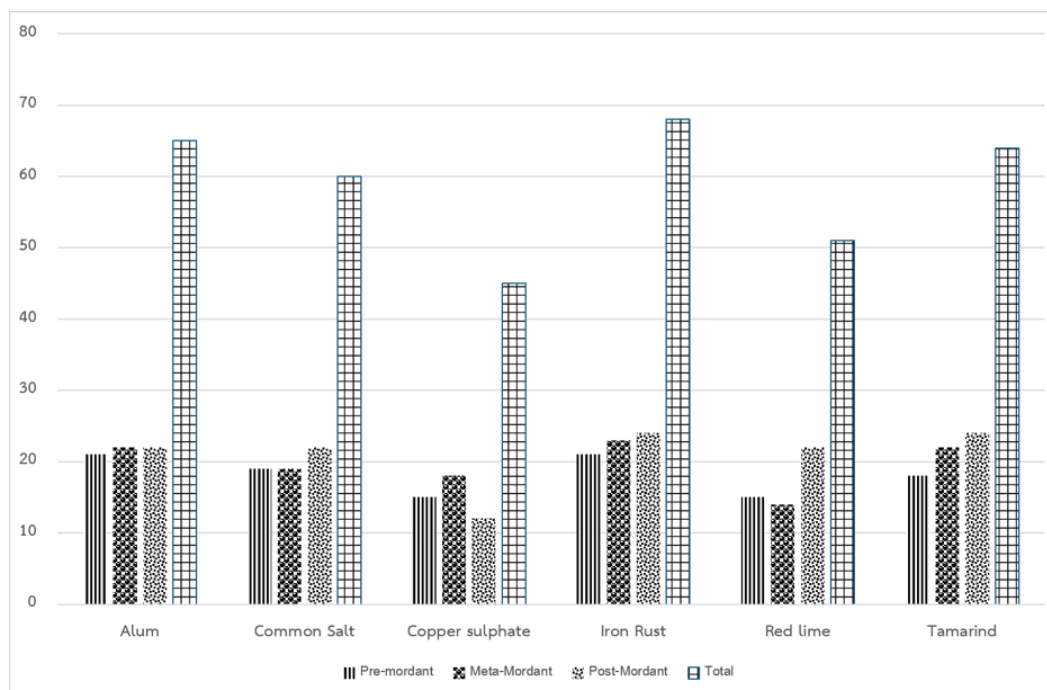


Figure 3 Comparison of the numbers of samples meeting the selected GOTS 7.0 colour fastness criteria for light, rubbing, washing, and perspiration among the six mordants.

1. From Fourier transform infrared (FTIR) spectroscopy, it was shown that the stem bark of *Oroxylum indicum* (L.) Kurz contains a variety of polyphenolic compounds, including, hydrolysable tannins (containing numerous numbers of hydroxyl (-OH) groups), and other phenolic compounds, which contribute to its suitability for natural dyeing processes with metal ion mordants such as Fe^{3+} , Fe^{2+} , Cu^{2+} , Al^{3+} ions.

2. The colour strength (K/S) value revealed that the colour obtained from different mordants and techniques give different shade varying from greenish brown to khaki colour. The highest colour intensity (K/S) value (in descending order) was obtained with pre-mordant common salt > meta-mordant alum > pre-mordant iron rust > meta-mordant red lime > meta-mordant tamarind > pre-mordant red lime > pre-mordant copper-sulphate respectively give colour intensity of 6.7564, 6.1718, 5.9469, 5.5047, 4.4913, 4.3966 and 4.3701 respectively whereas the post-mordant

alum gives lowest (paler shade) colour strength (K/S) value of 2.8127 compared to those of no mordant controlled sample (3.1047). Recent references suggested that the colour strength (K/S) received from various substances as $\text{Fe} > \text{Cu} > \text{Al} > \text{Ca}$ respectively [21-26]. These results cannot directly compare because of differences in concentration of the mordant and mordant techniques.

3. The experimental results showed that the no mordant sample still does not pass the light fastness grade <4 (less than fair) and washing fastness equals to grade 2 (poor) and perspiration fastness equals to grade 2-3 (poor to fair). After the treatment of mordants and mordanting techniques, it was shown that two processes (post-mordant tamarind and post-iron rust) give a benefit for the Ban Kham Nang Ok group as it represents a significant breakthrough that overcomes previous limitations as light fastness grade 4 or higher of products which usually only achieving grade 1-3 for natural dye dyeing in the rural Thailand's

textile industry. This allows global fashion brands to use them in everyday wear and outdoor apparel, reducing product returns due to fading and the products can be used for longer lifespan thus this can reduce textile waste in landfills. Also, GOTS 7.0 products must be free from hazardous chemicals and heavy metals. Passing GOTS 7.0 confirms that the dyeing process is eco-friendly for aquatic ecosystems thus it does not rely on toxic mordants (such as chromium or cadmium), making it safe for wearers and non-allergenic and protects the health of workers in dyehouse. The advantages of GOTS 7.0 give a chance to create a competitive advantage in the global sustainable fashion market (European and American). Also passing GOTS 7.0 is an opportunity to step on the "high-performance sustainable materials" which means sustainable transformation from handicrafts to luxury and green brand name [27].

4. From the six mordants and three mordant processes, it can be individually pass each colour fastness values (light, rubbing, washing and perspiration), compared to the GOTS 7.0 colour fastness criteria, are ranked as follows: iron rust (Fe^{3+} or Fe^{2+}) > alum (Al^{3+}) > tamarind > common salt (Na^+) > red lime (Ca^{2+}) > copper sulphate (Cu^{2+}) that these can pass GOTS 7.0 from 68, 65, 64, 60, 51 and 45 samples/techniques respectively. The four mordants (Cu^{2+} Al^{3+} Fe^{2+} or Fe^{3+} and tamarind) show acidic conditions and common salt shows neutral condition whereas red lime mordant gives alkaline conditions which may not be suitable for the natural dye exhaustion on cellulosic fibres. The effect of acidic conditions on adhesion to cotton depends on the source of flavonoids and other chemicals present in the dye bath. Compared to cotton, adhesion to cotton fibres is reduced, but other fibres such as wool and polyamide perform well in acidic conditions (pH 2.5 – 4.5) [28] Protonated flavonoids can be easily diffused into the

swollen cellulose structure and bonded the cellulose via hydrogen bonding [29]. The main mechanism as the pH moves toward neutral condition (pH 7), this protonates competition relaxes; therefore, it allowed more dye molecules to bind effectively to the yarn and fabric, resulting in higher colour yields [28]. The effect of neutral conditions is compatible with many extracts from flavonoids and at pH 7 also maximum dye uptake and colour strength. The effect of alkaline conditions is significantly deteriorated by causing electric repulsion (deprotonation) with the fibre surface [28].

5. Across the individual tests, the post-mordant processes pass 126 out of 144 test conditions (87.5%), the meta-mordant processes pass 118 out of 144 test conditions (81.9%), whereas the pre-mordant process passed 109 out of 144 test conditions (75.67%), indicating that these methods promote more effective natural dye bonding to cotton fibres. As the reference [24], it suggests that post-mordant process provides the highest wash fastness and light fastness among the three techniques due to physical entrapment whereas meta-mordant process trend to give surface deposition, resulting in lower rubbing fastness, lower wash fastness [24].

4. Conclusions

Oroxylum indicum (L.) Kurz outer stem bark was successfully applied as a natural dye source for cotton, with mordant type and mordanting sequence strongly affecting colour shade, colour strength, and fastness performance. FTIR results indicated hydroxyl- and phenolic-containing functional groups consistent with polyphenolic constituents, although specific dye-mordant coordination structures cannot be established from FTIR alone. The highest colour strength was obtained with pre-mordant common salt (K/S = 6.7564), followed by meta-mordant alum (6.1718) and pre-mordant iron rust (5.9469), whereas post-mordant alum produced the

lowest value (2.8127). The no-mordant sample showed light fastness below grade 4, washing fastness of grade 2, and perspiration fastness of grade 2–3, while post-mordant tamarind, post-mordant iron rust, meta-mordant iron rust, and pre-mordant common salt achieved light-fastness grades of 4 or higher.

Across the individual tests, the post-mordant processes pass 126 out of 144 test conditions (87.5%), the meta-mordant processes pass 118 out of 144 test conditions (81.9%), whereas the pre-mordant process passed 109 out of 144 test conditions (75.67%), indicating a modest overall advantage under the conditions studied. The results demonstrate that systematic control of mordant chemistry and application sequence can broaden the achievable colour range and improve specific fastness properties of *Oroxylum indicum*-dyed cotton. The GOTS 7.0 colour fastness criteria were used to benchmark the dyed yarns not to claim certification as the GOTS 7.0 certification must be considered in chemical usage, environmental and supply chain assessments. The results of this finding were intended to provide a basis for improving the consistency and practical use of this locally available bark dye in cotton dyeing.

5. Acknowledgements

The authors thank National Research Office (NRO) Thailand through Rajamangala University of Technology Thanyaburi (RMUTT) for the financial support provided. The authors sincerely thank Associate Professor Dr. Sommai Pivsa-Art, President of RMUTT and Dr. Sirikorn Maneerin, President of the Community College Institute Council, Ministry of Higher Education, Science, Research and Innovation Thailand for their supports throughout this research. The authors thank the Baan Kham Nang Oak Weaving Community Enterprise Nikhom Kham Soi District Mukdahan Province Thailand for sharing valuable information and knowledge of

the traditional Phu Thai ethnic group for natural dyeing process using tree bark and for supplying the bark used in this study. The authors thank the Central Laboratory Facility (or Central Instrument Facility), Rajamangala University of Technology Thanyaburi (RMUTT), Thailand, for providing the FTIR analysis service. Further, the author thanks Pisit Intergroup Co., Ltd., Bangkok, Thailand for the DataColor® spectrophotometer and technical assistance with colour measurements.

6. References

- [1] Deka D, Kumar V, Prasad C, Kumar K, Gogoi B, Singh L, Srivastava R. *Oroxylum indicum*—a medicinal plant of North East India: An overview of its nutritional, remedial, and prophylactic properties. *Journal of Applied Pharmaceutical Science*. 2013;3(Suppl 1):104-12.
- [2] Harminder, Singh V, Chaudhary AK. A review on the taxonomy, ethnobotany, chemistry and pharmacology of *Oroxylum indicum* vent. *Indian J Pharm Sci*. 2011;73(5):483-90.
- [3] Joshi N, Shukla A, Nailwal TK. Taxonomic and phytomedicinal properties of *Oroxylum indicum* (L.) Vent: A wonderful gift of nature. *J Med Plants Res*. 2014;8(38):1148-55.
- [4] Nik Salleh NNH, Othman FA, Kamarudin NA, Tan SC. The biological activities and therapeutic potentials of baicalein extracted from *Oroxylum indicum*: a systematic review. *Molecules*. 2020;25(23):5677.
- [5] Sharma K, Devi T, Singh O, Singh T. *Oroxylum indicum* Vent: A review on its phytochemical and pharmacological profile. *Asian J Chem*. 2022;34(3):459-72.
- [6] Rojsanga P, Bunsupa S, Sithisarn P. Flavones contents in extracts from *Oroxylum indicum* seeds and plant tissue cultures. *Molecules*. 2020;25(7):1545.

- [7] Dinda B, SilSarma I, Dinda M, Rudrapaul P. *Oroxylum indicum* (L.) Kurz, an important Asian traditional medicine: from traditional uses to scientific data for its commercial exploitation. *J Ethnopharmacol.* 2015;161: 255-78.
- [8] Hari Babu T, Manjulatha K, Suresh Kumar G, Hymavathi A, Tiwari AK, Purohit M, Madhusudana Rao J, Suresh Babu K. Gastroprotective flavonoid constituents from *Oroxylum indicum* Vent. *Bioorganic & Medicinal Chemistry Letters.* 2010;20(1): 117-20.
- [9] Klinpikul N, Dittapohn S, Nakyai W, Keawbankrud W. Optimization of eco-friendly mordant- assisted extraction and stability of natural pigments from six plant species for pressed paint development. *Trends in Sciences.* 2025;22(9):10316.
- [10] Global Standard gemeinnützige GmbH. Global Organic Textile Standard (GOTS): version 7.0. Stuttgart: Global Standard gemeinnützige GmbH; 2023.
- [11] Stuart BH. *Infrared Spectroscopy : Fundamentals and applications.* Chichester: John Wiley & Sons; 2004. Available from: <https://digital.casalini.it/9780470011133>.
- [12] Socrates G. *Infrared and raman characteristic group frequencies: tables and charts.* 3rd ed. Chichester: John Wiley & Sons; 2001.
- [13] Silverstein RM, Webster FX, Kiemle DJ. *Spectrometric identification of organic compounds.* 7th ed. Hoboken (NJ): John Wiley & Sons; 2005.
- [14] Ricci A, Olejar KJ, Parpinello GP, Kilmartin PA, Versari A. Application of fourier transform infrared (FTIR) spectroscopy in the characterization of tannins. *Applied Spectroscopy Reviews.* 2015;50(5):407-42.
- [15] Silva K, Galindo Gomes JE, Moreira KA, Lima R, Guzzo PL, de Andrade Silva DK, Hernández EP. Chemical and functional consistency of condensed tannins from *anadenanthera macrocarpa* at different collection sites. *ACS Omega.* 2026;11(8): 13199-211.
- [16] Tondi G, Petutschnigg A. Middle infrared (ATR FT-MIR) characterization of industrial tannin extracts. *Industrial Crops and Products.* 2015;65:422-8.
- [17] Nada A-AMA, El-Sakhawy M, Kamel SM. Infra- red spectroscopic study of lignins. *Polymer Degradation and Stability.* 1998;60(2):247-51.
- [18] Coates J. Interpretation of infrared spectra, a practical approach. In: Meyers RA, editor. *Encyclopedia of analytical chemistry.* Chichester: John Wiley & Sons; 2000. p. 10815-37.
- [19] Falcão L, Araújo MEM. Application of ATR–FTIR spectroscopy to the analysis of tannins in historic leathers: The case study of the upholstery from the 19th century Portuguese Royal Train. *Vibrational Spectroscopy.* 2014;74:98-103.
- [20] Boeriu CG, Bravo D, Gosselink RJA, van Dam JEG. Characterisation of structure-dependent functional properties of lignin with infrared spectroscopy. *Industrial Crops and Products.* 2004;20(2):205-18.
- [21] Kasprzak MM, Erxleben A, Ochocki J. Properties and applications of flavonoid metal complexes. *RSC Advances.* 2015;5(57):45853-77.
- [22] Uddin MG. Extraction of eco-friendly natural dyes from mango leaves and their application on silk fabric. *Textiles and Clothing Sustainability.* 2015;1(1):7.
- [23] Mira L, Fernandez MT, Santos M, Rocha R, Florêncio MH, Jennings KR. Interactions of flavonoids with iron and copper ions: a mechanism for their antioxidant activity. *Free Radic Res.* 2002;36(11):1199-208.
- [24] Kamali Moghaddam M, Ghanbari Adivi M, Tehrani Dehkordi M. Effect of acids and different mordanting procedures on color characteristics of dyed wool fibers using

- eggplant peel (*Solanum melongena* L.). Progress in color, Colorants and Coatings. 2019;12(4):219-30.
- [25] Tharawatchruk W, Janma S, Panthuwat W, Pitakrajpong S, Sassa-deepaeng T, Pranamornkith P. Study on a potentiality of plant aqueous extracts as natural dye fixatives in traditional dyeing processes using natural indigo from *Strobilanthes cusia* (Nees) Kuntze. Journal of Science and Agricultural Technology. 2025;6(1):1-10
- [26] Koçak ED, Altay P, Tektaş Çelikkanat Ö, Ofloğlu T. The effect of different mordants on natural dyeing of cotton, viscose and lyocell fabrics with pomegranate bark extracts. Journal of Textile Engineering & Fashion Technology Research. 2022;8(6):185-9.
- [27] Krywalski-Santiago J. Navigating sustainable transformation in the fashion industry: The role of circular economy and ethical consumer behavior. Journal of Intercultural Management. 2024;16(3):5-36.
- [28] Ivanovska A, Gajić IS, Lađarević J, Milošević M, Savić I, Mihajlovski K, Kostić M. Sustainable dyeing and functionalization of different fibers using orange peel extract's antioxidants. Antioxidants. 2022;11(10):2059.
- [29] Jabar JM, Oluwasina OO, Agunloye OM, Akinmoladun AC, Akande OA, Ojo ET, Olojuolawe HO. Brazilian Plume (*Justicia carnea* L.) Leaf Wine-Colored Extract for Natural Dyeing of Mordant-Functionalized Cellulosic Fabric: Color Strength, Coordinates, and Fastness. Chemistry. 2025;7(1):23.