Journal of Fiber Bioengineering and Informatics 18:3 (2025) 263–274
Cite as: Y. Komonsilichok et al.
doi:10.3993/jfbim00299

Optimising Natural Dyeing of Cotton with Butea Monosperma through Anodic Pretreatment and Eco-Friendly Auxiliaries

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Abstract

This study investigates the combined effect of anodic pretreatment and varying auxiliary formulations on the dyeing performance of cotton fabric using a natural dye extracted from Butea monosperma flowers. While past studies have examined the role of mordants and pH modifiers in natural dyeing, limited attention has been given to how auxiliary systems interact with electrochemically modified fabrics to influence colour yield and fastness performance. This research addresses that gap by evaluating how anodically pretreated cotton responds to common dyeing auxiliaries—sodium chloride (NaCl), potassium aluminium sulfate (alum), sodium carbonate (Na_2CO_3), and calcium oxide (CaO)—in terms of shade development, chromatic richness, and durability.

Using the CIE Lab colour system, significant colour variations were observed across all treated specimens (2–7) compared to the salt-only control (specimen 1). ΔE values ranged from 12.49 to 19.95, with the highest chromatic shift seen in the NaCl + alum sample, which produced a vivid orange hue with enhanced redness and yellowness. Combinations of alum and alkalis yielded deeper, more saturated shades, while alkali-only formulations produced earthier tones with moderate lightness. These outcomes highlight the synergistic effect of anodic surface activation and auxiliary chemistry on improving dye-fibre interactions.

Fastness tests, conducted according to ISO 105-C10 and ISO 105-X12 standards, revealed moderate washing durability (colour change ratings of 3 to 4) and good rubbing fastness (ratings up to 4). Specimens treated with mordants and alkalis generally exhibited improved fixation and reduced staining, whereas anodic treatment enhanced surface adhesion of the dye.

This study demonstrates a promising, low-impact approach to improving natural dye uptake and fastness on cotton fabric by integrating anodic pretreatment with accessible auxiliary systems. The findings support the development of sustainable, decentralised dyeing processes using locally available plant waste, with particular relevance for rural craft and textile communities seeking eco-friendly alternatives to synthetic dyes.

Keywords: Butea monosperma, natural dyeing, anodic pretreatment, cotton fabric, dye auxiliaries, colour fastness, sustainable textiles, rural textile innovation

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Sep. 2025

1 Introduction

In many tribal and rural communities, seasonal tree shedding generates significant amounts of unmanaged organic waste, often devoid of economic value. A prominent example is the Butea monosperma tree, abundantly found across Thailand. Its bright orange-red flowers fall in large quantities during blooming seasons, creating piles of biomass that, while visually striking, remain largely unutilized. The accumulation of these flowers not only demands labour-intensive cleanup but also contributes to environmental clutter. However, this overlooked biomass presents a unique opportunity for sustainable innovation, particularly in low-resource regions with limited access to industrial dyeing inputs and infrastructure [1].

This study builds on earlier work that proposed a value-added approach to this floral waste by extracting natural dye from Butea monosperma flowers for cotton fabric dyeing. The prior experiment explored how different dyeing auxiliaries—such as sodium chloride (NaCl), alum (potassium aluminium sulfate dodecahydrate), sodium carbonate (Na_2CO_3), and calcium oxide (CaO)—influenced shade development and fastness, without relying on conventional chemical pretreatments [2]. By focusing on simple, locally accessible methods, the process aligned with decentralised and eco-conscious dyeing practices that could support artisanal textile production in tribal areas.

While previous studies have examined Butea monosperma as a natural dye source [3,4], there is limited research on optimising dye–fibre interactions using advanced yet sustainable techniques. Notably, electrochemical pretreatment—specifically anodic activation of cotton—has shown promise in improving the affinity between cellulosic fibres and natural dyes by altering fibre surfaces and enhancing dye uptake [5,6]. However, its combined effect with dyeing auxiliaries on shade development and fastness has not yet been systematically explored in Butea monosperma.

To expand on the original study's findings, this new set of experiments applies anodic electrochemical pretreatment to cotton fabric before dyeing under identical dye-bath conditions. The aim is to evaluate how this pretreatment step, in conjunction with the previously tested auxiliaries, influences colour strength, shade uniformity, and fastness properties. The electrochemical treatment is conducted under controlled anodic conditions to enhance reactive sites on the fibre surface, thereby promoting stronger interactions with the natural dye molecules.

The core objective of this investigation remains focused on shade development—specifically, how variations in auxiliary type and concentration, when combined with electrochemical pretreatment, affect the depth, vibrancy, and consistency of the resulting dyed shades. These effects are quantitatively assessed using the CIE Lab colourimetric system and standard fastness tests to determine wash and rubbing resistance.

This integrated approach not only strengthens the scientific foundation for natural dyeing with Butea monosperma but also offers a potential pathway for improving product quality in heritage textile crafts. The culturally significant role of Butea monosperma in Indian traditions [1] further adds value to this work, opening avenues for regional identity reinforcement and potential Geographical Indication (GI) recognition for naturally dyed textiles in Thailand. Ultimately, the research seeks to bridge environmental sustainability, cultural preservation, and economic empowerment in rural communities.

2 Materials and Methods

2.1 Materials

The primary textile substrate used in this study was 100% plain-weave cotton fabric, selected for its compatibility with natural dyeing processes and responsiveness to surface modification techniques, such as electrochemical activation [5]. Before any treatment, the fabric was scoured to remove waxes, pectins, and residual impurities that could interfere with dye uptake, thereby ensuring uniform and efficient dye absorption.

The natural dye source was the flower of Butea monosperma (commonly known in Thai as TongKwaw), widely distributed across the India Subcontinent and Southeast Asia. The flowers were collected after natural abscission, aligning with the study's objective of converting floral waste into value-added resources. These were then shade-dried to preserve pigment integrity and stored in airtight containers until dye extraction.

The aqueous extract obtained from the dried petals is rich in flavonoid compounds, primarily butin, butin, and coreopsin - classified as chalcone and flavone derivatives [3,7]. These bioactive pigments contribute significantly to the yellow-to-orange colouration observed in dyed fabrics. While carotenoids may also be present in trace amounts, their lower water solubility and thermal instability make them less prominent in hot-water extraction [8]. The presence of flavonoids in the extract was confirmed by the ferric chloride test, which yielded a characteristic green colour, indicating the presence of phenolic functional groups [9].

Unlike the previous phase of this research [2], the cotton fabrics used in this extended experimental set underwent electrochemical pretreatment under anodic conditions before dyeing. This surface modification step is known to enhance the reactivity of cellulosic fibres, thereby facilitating stronger dye–fibre interactions and improved dye uptake [5,6]. Photographic documentation of the Butea monosperma tree, its flowering branches, and a close-up of the flower used in this study is presented in Fig. 1.



Fig. 1: *Butea monosperma* (commonly known as TongKwaw or Palash or Flame of the Forest).

2.2 Preparation of Natural Dyestuff

A total of 0.5 kg of dried *Butea monosperma* flowers was used as the raw material for dye extraction. The flowers were immersed in 20 litres of tap water at room temperature and left to

soak for 12 hours to facilitate optimal pigment release. Following the soaking period, the mixture was filtered using a fine fabric to separate the solid residues from the liquid extract. Only the clear filtrate obtained was used in the subsequent dyeing procedures. The detailed steps of the dye extraction process are shown in Fig. 2.



Fig. 2: Preparation of natural dyestuff from *Butea monosperma* flowers.

2.3 Electrochemical Pretreatment

The cotton fabric underwent electrochemical pretreatment under anodic conditions using a solution containing 10 mL/L of polyethylene polyamine (PEPA). The treatment was carried out at a liquor ratio of 20:1 and maintained at a temperature of 50 °C for 10 minutes. Upon completion, the fabric was removed from the solution and passed through a laboratory padder to ensure uniform squeezing, adjusting the moisture content to approximately twice the fabric's dry weight.

2.4 Dyeing Procedure

The PEPA-pretreated cotton fabrics were dyed using the extracted Butea monosperma dye liquor at a material-to-liquor ratio (LR) of 1:30. The dyeing process was conducted at boiling temperature (approximately 100 °C) for 45 minutes, with continuous stirring to promote uniform dye uptake. A total of seven fabric samples were prepared, each treated with a different combination of dyeing auxiliaries to evaluate their influence on shade development and colour characteristics.

The first sample, serving as the control, was dyed with the natural dye extract and 10 g/L of sodium chloride (NaCl). The second sample included a combination of 10 g/L NaCl and 3 g/L of alum (potassium aluminium sulfate dodecahydrate). The third sample was treated with 10 g/L NaCl and 3 g/L sodium carbonate (Na_2CO_3), while the fourth sample was dyed with 3 g/L calcium oxide (CaO) alone. The fifth sample received a mixture of 10 g/L NaCl, 3 g/L alum, and 3 g/L sodium carbonate. The sixth sample was dyed with a combination of 10 g/L NaCl, 3 g/L alum, and 3 g/L calcium oxide. Finally, the seventh sample included 10 g/L NaCl, 3 g/L calcium oxide, and 3 g/L sodium carbonate. The full formulation details for each sample are summarised in Table 1.

After completion of the dyeing and initial drying stages, all fabric samples underwent a standardised post-dyeing wash protocol to remove unfixed dye molecules. Each specimen was first rinsed under continuous tap water to remove surface-adsorbed dye, then washed in a mild non-ionic detergent solution to assist in the desorption of loosely bound dye components. This was

Table 1: Auxiliary combinations used for dyeing PEPA-pretreated cotton fabric with Butea monosperma extract

Sample No.	Auxiliary combination
1 (control)	10 g/L Sodium chloride (NaCl)
2	10 g/L NaCl + 3 g/L Alum (Potassium aluminium sulfate dodecahydrate)
3	10 g/L NaCl + 3 g/L Sodium carbonate (Na_2CO_3)
4	10 g/L NaCl + 3 g/L Calcium oxide (CaO)
5	10 g/L NaCl + 3 g/L Alum + 3 g/L Sodium carbonate
6	10 g/L NaCl + 3 g/L Alum + 3 g/L Calcium oxide
7	10 g/L NaCl + 3 g/L Calcium oxide + 3 g/L Sodium carbonate

followed by multiple rinses with tap water to ensure the removal of residual detergent and dye. The washed samples were subsequently air-dried under ambient laboratory conditions before colourimetric analysis and fastness testing.

2.5 Colour Evaluation and Fastness Testing

The colour attributes of the pretreated and dyed cotton fabrics were analysed using a CI6x Spectrophotometer (X-Rite, USA) in the CIE Lab colour space, with a D65 illuminant and a 10° observer. Measurements were taken at four random locations on each sample to ensure reproducibility, and the mean values of L* (lightness), a* (red-green coordinate), and b* (yellow-blue coordinate) were recorded for comparative analysis. Colour fastness properties were assessed according to established international standards. Washing fastness tests were conducted based on ISO 105-C10, modified to simulate mild domestic laundering at 40 °C for 30 minutes. Both colour change and staining on multifiber DW fabric were evaluated, with results graded on a scale of 1 (poor) to 5 (excellent). Rubbing fastness was determined according to ISO 105-X12 under both dry and wet conditions. The degree of staining on standard crock cloth was rated on a grey-scale, with scores ranging from 1 (poor) to 5 (excellent).

3 Results

3.1 Colour Evaluation

The objective of this evaluation was to examine how anodically pretreated cotton fabrics responded to different dyeing formulations incorporating various auxiliary agents, with a focus on their influence on final shade, chromatic intensity, and colour uniformity. Particular attention was given to variations in CIE Lab parameters—lightness (L*), red–green (a*), and yellow–blue (b*)—which quantitatively reflect the fabric's visual characteristics, including hue, depth, and saturation. These measurements are essential for optimising natural dyeing processes that integrate electrochemical pretreatment, thereby enabling improved reproducibility and the identification of formulations that deliver consistent, commercially desirable results. Furthermore, analysis of total colour differences (ΔE values) among samples provided insights into how auxiliary agents

interact with anodically treated substrates to influence dye uptake and fixation. The visual differences in shade among the dyed fabric samples produced under varying auxiliary conditions are illustrated in Fig. 3.

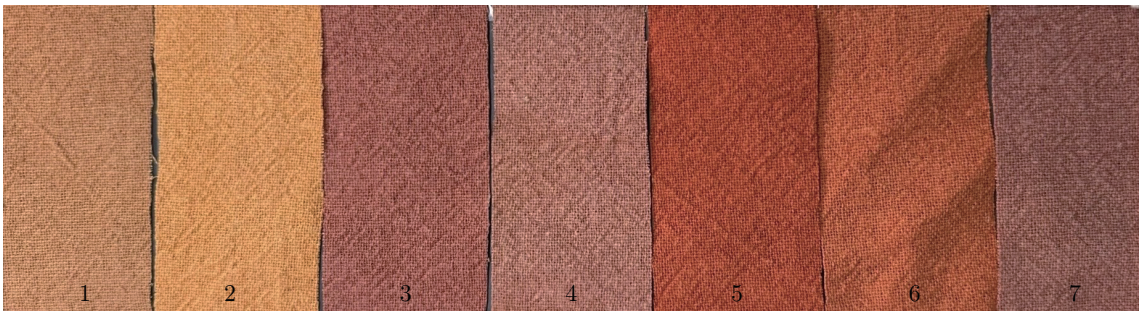

Fig. 3: Dyed cotton fabric specimens pretreated under anodic conditions and dyed with Butea monosperma extract using different auxiliary combinations.

Table 2 presents the results of the colour evaluation of the anodically pretreated cotton fabrics dyed with Butea monosperma extract, labelled Samples 2-7. Sample 1, dyed only with sodium chloride, served as the control for comparative analysis. Colour measurements were conducted using the CIE Lab colour space, which defines colour in three dimensions: L* (lightness), a* (red–green), and b* (yellow–blue). Each fabric specimen was measured at four random locations to account for potential variation in dye distribution, and average values were recorded to ensure consistency. The total colour difference (ΔE) for each sample was calculated using the CIE76 formula (Eq. (1)), comparing the chromatic deviation of each auxiliary-treated sample with that of the control. These ΔE values provide a quantitative basis for evaluating how different auxiliary combinations applied to anodically treated fabric influence final shade, hue shift, and colour intensity. A visual comparison of the CIE Lab coordinates across all samples is illustrated in Fig. 4, which presents a radar chart of L*, a*, and b* values, highlighting differences in lightness and chromaticity among the treatments.

$$\Delta E = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* + a_1^*) + (b_2^* - b_1^*)^2} \tag{1}$$

Where: L_1^*, a_1^*, b_1^* = CIELAB values of the reference sample (control fabric)

L_2^*, a_2^*, b_2^* = CIELAB values of the test sample

ΔE = perceptual colour difference between the two samples

The results of the CIE Lab colour evaluation (Table 2), supported visually by the radar chart in Fig. 4, indicate that all anodically pretreated cotton fabrics dyed with Butea monosperma extract (Samples 2–7) exhibited clear and perceptible colour differences compared to the control sample (Sample 1), which was dyed using sodium chloride alone. These variations reflect the influence of different auxiliary agent combinations on shade depth, chromaticity, and brightness.

Among the treated fabrics, Sample 2—prepared with sodium chloride and alum—exhibited the highest lightness (L = 67.00) and the greatest colour difference (ΔE = 18.50), indicating a visually brighter and more vibrant appearance. Its elevated a* (26.01) and b* (50.95) values, as highlighted in the radar plot, reflect a strong shift towards red and yellow hues, producing a vivid, luminous orange tone that clearly stands apart from the control and other treatments.

Samples 3 and 4, treated with sodium chloride combined with sodium carbonate and calcium oxide, respectively, showed moderate ΔE values (15.35 and 12.49), with lower L* and reduced b*

Table 2: CIE Lab colour values (L*, a*, b*) and total colour difference (ΔE) of anodically pretreated cotton fabrics (Specimens 2–7) dyed with Butea monosperma extract using different auxiliary combinations. Specimen 1 (dyed with NaCl only) served as the control for ΔE calculations. Values represent the average of four measurements per sample

Fabric	L*		a*		b*		ΔE		Interpretation
	mean	SD	mean	SD	mean	SD	mean	SD	
1	57.64	0.52	19.58	0.32	36.67	0.36	–	–	Baseline: medium-light orange-yellow
2	67.00	0.59	26.01	0.72	50.95	1.10	18.50	1.05	Brightest and warmest; vivid reddish-yellow
3	52.61	0.22	23.91	0.33	22.56	0.18	15.35	0.26	Darker shade; more red, less yellow
4	56.95	0.32	22.25	0.56	24.21	0.43	12.49	0.75	Slightly darker; muted yellow, enhanced red
5	49.70	0.61	37.07	0.35	41.69	0.38	19.95	0.69	Deepest and most saturated; rich orange
6	55.54	0.47	35.64	0.23	42.45	0.40	17.32	0.89	Darker, highly chromatic red-orange
7	55.07	0.69	22.14	0.32	20.74	0.78	16.09	0.80	Muted and dull; less yellow, earthy tone

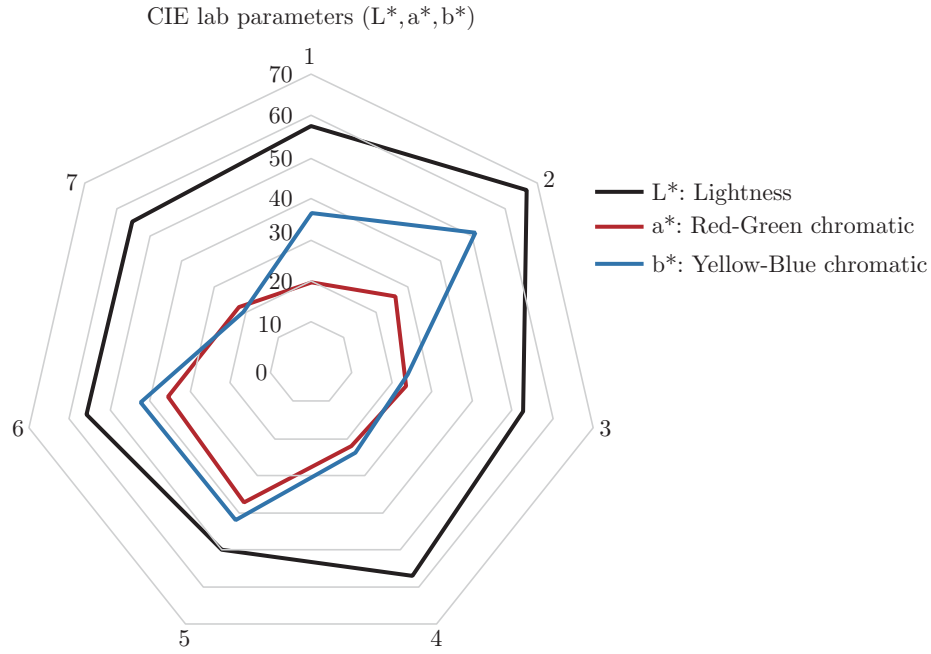

Fig. 4: Comparison of CIE L*, a*, and b* values among seven sample groups. The radar chart reveals a shift in brightness and chromaticity across treatments.

values. These shifts correspond to darker, more muted colours with earthy tones, as the reduced yellow contribution and relatively low lightness produce a more subdued appearance than in brighter samples.

In contrast, Samples 5 and 6, incorporating ternary mixtures of sodium chloride, alum, and either sodium carbonate or calcium oxide, produced some of the richest and most intense orange shades, with ΔE values of 19.95 and 17.32. Despite their lower lightness, both samples exhibited

high a* and b* values, suggesting strong red and yellow chromatic content that contributes to their vivid, saturated appearance. This is clearly depicted in the radar chart, where these samples occupy prominent positions along both the a* and b* axes.

Sample 7, treated with a combination of sodium chloride, calcium oxide, and sodium carbonate, yielded a noticeable colour change ($\Delta E = 16.09$) and presented moderate lightness with comparatively lower yellow (b) values*, aligning more closely with Samples 3 and 4. This produced a darker, less vibrant orange tone, suggesting that without alum, the chromatic saturation was comparatively reduced.

Overall, both the numerical data (Table 2) and the visual trends shown in Fig. 4 demonstrate that the type and combination of auxiliary agents used during anodic pretreatment significantly impact the final colour outcomes. Formulations containing alum, particularly in ternary blends, enhanced lightness and chromatic richness, resulting in more vivid and appealing hues. In contrast, the use of sodium carbonate or calcium oxide alone tended to produce deeper, duller shades with lower yellowness. These findings underscore the importance of auxiliary selection in modulating dye performance and provide valuable insights for optimising sustainable dyeing processes using natural extracts such as Butea monosperma.

3.2 Colour Fastness Tests

To evaluate the functional performance of the anodically pretreated cotton fabrics dyed with Butea monosperma extract, colour fastness tests were conducted under standardised conditions. Washing fastness was assessed using a modified ISO 105-C10 protocol, simulating mild domestic laundering at 40 °C for 30 minutes. Rubbing fastness was measured in accordance with ISO 105-X12, under both dry and wet conditions. These evaluations are crucial for assessing the durability of the natural dye on the electrochemically pretreated cotton substrate and for evaluating the potential for colour fading or transfer during typical use.

The subsequent section presents and analyses the fastness ratings of all fabric samples (specimens 1-7), emphasising the effects of various auxiliary combinations—including alum, sodium carbonate, and calcium oxide—on dye fixation and overall fabric performance.

Table 3 summarises the washing and rubbing fastness results for the dyed fabrics. Washing fastness scores reflect the resistance of the dye to fading and staining during laundering, whereas rubbing fastness scores indicate the dye's tendency to transfer under friction in both dry and wet states. Comparison of these results provides insight into which auxiliary treatments, when combined with anodic pretreatment, optimise dye adherence and enhance the practical durability of naturally dyed cotton fabrics.

The washing fastness, assessed according to ISO 105-C10, varied among fabric samples dyed with Butea monosperma extract under different auxiliary treatments. The control fabric (specimen 1), treated only with sodium chloride, showed a relatively good colour change rating of 3/4 and cotton staining of 2-3, indicating moderate dye retention but some dye transfer during laundering.

Specimen 2, containing sodium chloride and alum, showed a slightly lower colour change rating of 3 and similar staining on cotton at 2/3, suggesting a minor reduction in wash durability compared to the control. Specimens 3 and 4, treated with sodium carbonate and calcium oxide, respectively (both combined with sodium chloride), exhibited washing fastness ratings comparable

Table 3: Washing and rubbing fastness ratings of anodically pretreated cotton fabrics dyed with Butea monosperma extract using different auxiliary combinations (specimens 1–7)

Fabric	ISO105 C10		ISO105 X12	
	colour change	colour staining	Wet rubbing	Dry rubbing
1	3/4	2/3 (cotton)	3	4
2	3	2/3 (cotton)	3	3/4
3	3/4	3 (cotton)	3	4
4	3	3 (cotton)	3	4
5	4	3 (cotton)	3	4
6	3/4	3/4 (cotton)	3	4
7	3/4	3/4 (cotton)	3	3/4

Note: the colour fastness ratings in this table are based on the ISO grey scale (ISO 105 standards), which ranges from 1 to 5: 5 = No change or staining (Excellent), 4 = Slight change or staining (Good), 3 = Noticeable change or staining (Moderate), 2 = Significant change or staining (Poor), 1 = Severe change or staining (Very Poor)

to or slightly better than the control, with colour change at 3/4 and cotton staining at 3. This implies enhanced dye fixation with these alkaline auxiliaries.

Specimen 5, combining sodium chloride, alum, and sodium carbonate, demonstrated the highest washing fastness, with a colour change rating of 4 and a staining rating of 3, indicating improved resistance to fading and dye transfer during washing. Specimen 6 (sodium chloride, alum, and calcium oxide) also performed well, showing a colour change of 3/4 and staining improved to 3/4 on cotton, suggesting balanced dye fixation. Specimen 7, with sodium chloride, calcium oxide, and sodium carbonate, showed similar washing fastness to specimen 6, with colour change at 3/4 and staining rated 3/4, reflecting moderate improvement in durability.

Rubbing fastness, tested under ISO 105-X12, was generally strong across all specimens. Dry rubbing ratings were consistently high, mostly at 4, indicating minimal dry dye transfer and good adhesion to the cotton surface under normal handling. Wet rubbing fastness showed more variability, with most specimens rated at 3 to 4. Specimens 1 and 3, for example, achieved the highest wet rubbing fastness rating of 3, while specimens 2 and 7 showed slightly lower ratings (3/4), reflecting minor dye transfer under moist conditions. Overall, the rubbing fastness results indicate good resistance to friction, making the fabrics suitable for everyday use with a low risk of colour loss from rubbing.

In summary, the washing fastness results suggest that the combination of sodium chloride, alum, and sodium carbonate (specimen 5) offers the most effective dye fixation and durability during laundering. Alkaline agents such as sodium carbonate and calcium oxide (specimens 3, 4, 6, and 7) contribute positively to wash fastness, enhancing dye-fibre interactions and reducing staining. However, alum alone or in combination without adequate alkaline support may slightly reduce washing fastness. Rubbing fastness results were generally satisfactory across all treatments, with better performance in dry conditions than in wet conditions.

These findings emphasise the importance of carefully selecting auxiliary combinations to optimise both colour intensity and fastness in natural dyeing processes, thereby supporting sustainable textile applications using Butea monosperma flower extract.

4 Discussion

The findings of this study provide valuable insights into the dyeing behaviour of Butea monosperma flower extract on anodically pretreated cotton fabric, emphasising not only technical aspects but also broader sustainability goals. The seasonal shedding of Butea monosperma flowers in tribal and rural areas generates substantial organic waste, which typically accumulates in public spaces and is often considered an environmental burden rather than a resource [2]. Without effective utilisation strategies, this biomass remains an untapped asset that neither benefits the environment nor supports local economies.

Transforming this floral waste into natural dye products offers a dual benefit: alleviating environmental pressures while fostering circular economy principles. Natural dyes derived from such biomass offer an eco-friendly alternative to synthetic dyes, which are commonly associated with toxicity and water pollution concerns [3]. Moreover, this approach enables small-scale, decentralised textile dyeing enterprises to utilise readily available local resources. By enhancing dye uptake and fastness through electrochemical pretreatment and auxiliary combinations, this work opens new avenues for income generation within tribal communities traditionally engaged in handloom weaving and natural crafts [4].

This research advances understanding of how anodic electrochemical pretreatment, combined with an auxiliary agent, influences the shade development and fastness characteristics of Butea monosperma dyes on cotton fabric. The study contributes not only to the scientific knowledge of enhanced natural dye applications but also supports sustainable rural entrepreneurship by promoting resource recovery, value addition, and preservation of indigenous practices [10-12].

Analysis of the CIE Lab colour data (Table 2) showed that all auxiliary-treated samples (specimens 2-7) exhibited significant colour differences ($\Delta E > 12.4$) compared to the control (specimen 1, dyed with NaCl only). Specimen 2 (NaCl + alum) had the highest colour difference ($\Delta E = 18.50$), characterised by markedly elevated redness ($a = 26.01$) and yellowness ($b = 50.95$), resulting in a vivid, bright orange shade. This enhancement is consistent with alum's known capacity to form coordination complexes with flavonoid-based natural dyes, intensifying hue and chromaticity [3,7]. Similarly, specimens 5 and 6, combining alum with alkaline modifiers (sodium carbonate and calcium oxide), displayed strong colour shifts and increased chromatic richness ($\Delta E = 19.95$ and 17.32), indicating a synergistic effect of mordant and pH modification on dye uptake and fixation [2,5].

Specimens 3 and 4, treated with sodium carbonate and calcium oxide, respectively, without alum, showed moderately large colour differences ($\Delta E = 15.35$ and 12.49), exhibiting darker but less saturated tones. These alkaline auxiliaries likely enhance dye solubility and promote cellulose fibre swelling by elevating bath pH, thereby modifying the binding environment of the flavonoid dye molecules [5,9]. Specimen 7, which combined calcium oxide and sodium carbonate, produced a balanced shade with moderate saturation ($\Delta E = 16.09$), indicative of stable dyeing conditions under alkaline pH [12].

These colour development trends align with previous findings, which show that alum mordanting improves the brightness and fixation of natural dyes [3,7]. At the same time, alkaline auxiliaries facilitate dye uptake by adjusting bath pH and promoting fibre swelling [4,5,9]. The application of anodic pretreatment further enhances these effects by modifying cotton surface properties and increasing dye affinity without the need for synthetic chemicals [10,12]. Collectively, these results demonstrate the potential of combining anodic pretreatment with auxiliary agents to customise

natural dyeing outcomes using underutilised floral biomass, thereby supporting eco-friendly textile colouration [11].

Washing fastness results (Table 3) indicated moderate durability across most samples, with colour change ratings of 3-4, reflecting reasonable resistance to dye loss during laundering. The control fabric (specimen 1) showed moderate wash fastness (colour change 3/4, staining 2/3), consistent with typical natural-dye behaviour on cellulose fibres [6]. Specimens 5 and 6, involving alum and alkaline combinations, exhibited the best washing fastness (colour change 4 and 3/4; staining 3 to 3/4), suggesting that the synergy of mordants and pH modifiers enhances dye fixation on cotton [2,5]. Specimens 3 and 4 (alkaline only) also demonstrated satisfactory wash fastness, whereas specimen 2 (NaCl + alum) had somewhat lower washing durability, highlighting the critical role of auxiliary combination in fixation efficiency.

Rubbing fastness ratings were generally good for all samples under both dry and wet conditions (ratings 3–4), indicating strong resistance to dye transfer through friction. This suggests that anodic pretreatment combined with auxiliaries improves surface dye adhesion, enhancing practical usability despite moderate wash fastness [10].

The observed moderate wash fastness concurs with known challenges in natural dyeing, as flavonoid compounds primarily bind to cellulose via weak hydrogen bonding and van der Waals forces, making them prone to leaching during washing [6,7]. While anodic pretreatment likely increases dye uptake by altering cotton surface characteristics, it does not establish covalent bonding. Future studies could explore the use of bio-mordants, such as tannins or chitosan, which form stronger dye-fibre interactions, or crosslinking agents, such as citric acid, that improve wash durability through covalent ester linkages [6,13]. These strategies could enhance fastness while maintaining the sustainability of the dyeing process.

5 Conclusion

This study demonstrated that anodic pretreatment combined with various auxiliary agents significantly affects the dyeing performance of cotton fabrics with natural dyes extracted from Butea monosperma flowers. The use of mordants such as alum and alkaline modifiers such as sodium carbonate and calcium oxide notably influenced both the colour outcomes and the fastness properties. Alum-containing combinations produced brighter, more vivid shades, while alkaline auxiliaries improved dye uptake by altering the dye bath pH and fibre swelling. Anodic pretreatment enhanced dye affinity by modifying the cotton surface, resulting in improved colour depth without synthetic chemicals.

Fastness testing revealed moderate washing durability across samples, with the best performance observed in fabrics treated with combined mordant and alkaline auxiliaries. Rubbing fastness was generally good, indicating strong surface dye adhesion and practical usability. Despite improved dye fixation from these treatments, natural dye binding remains primarily non-covalent, limiting wash fastness.

Future research should explore bio-mordants and crosslinking agents to strengthen dye-fibre bonding and enhance wash durability while maintaining eco-friendly processing. Overall, the findings highlight the potential of integrating anodic pretreatment with optimised auxiliary formulations to develop sustainable, vibrant, and functional natural dyeing processes using floral waste, thereby contributing to greener textile colouration solutions.

Acknowledgement

The authors gratefully acknowledge the collaborative support between Rajamangala University of Technology Lanna (RMUTL) and Rajamangala University of Technology Thanyaburi (RMUTT) in the successful completion of this research project. This study was made possible by integrating RMUTL's deep-rooted knowledge of Northern Thai culture and traditional textile craftsmanship, particularly in the use of locally sourced natural dyes and handcrafted fabric production, with RMUTT's technical expertise in material testing, colour evaluation, and scientific analysis.

This partnership exemplifies the synergy between cultural heritage and modern research, promoting sustainable innovation while preserving the traditional way of life. The authors would like to express their sincere thanks to both institutions for their shared commitment to advancing community-based, eco-friendly textile practices in Thailand.

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