Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

Evaluation of the Strength of Natural Dyeing from Teak Wood Extract on Traditional Weaving Yarn

Ismadi, Soesanto, Tjetjep Rohendi Rohidi, Syakir, Bandi Sobandi, Moh. Fathurrahman, Dedy Sartono

How to cite: Ismadi, Soesanto, Rohidi TR, Syakir, Sobandi B, Fathurrahman M, Sartono D. Evaluation of the Strength of Natural Dyeing from Teak Wood Extract on Traditional Weaving Yarn. Textile & Leather Review. 2025; 8:326-348. https://doi.org/10.31881/TLR.2025.003

How to link: https://doi.org/10.31881/TLR.2025.003

Published: 11 April 2025

Evaluation of the Strength of Natural Dyeing from Teak Wood Extract on Traditional Weaving Yarn

ISMADI[1*], SOESANTO[1], Tjetjep Rohendi ROHIDI[2], SYAKIR[1], Bandi SOBANDI[3], Moh. FATHURRAHMAN[1], Dedy SARTONO[4]

[1]Universitas Negeri Semarang, Sekaran, Gn. Pati, Semarang 50229, Central Java, Indonesia

[2]Universitas Dian Nuswantoro, Jl. Imam Bonjol 207, Semarang 50131, Central Java, Indonesia

[3]Universitas Pendidikan Indonesia, Jl. Dr. Setiabudi 229 Bandung 40154, West Java, Indonesia

[4]Universitas Negeri Yogyakarta, Jl. Colombo 1 Karang Malang, Caturtunggal, Depok, Sleman, Yogyakarta 55281, Daerah Istimewa Yogyakarta, Indonesia

*ismadiunnes@students.unnes.ac.id

Article

https://doi.org/10.31881/TLR.2025.003

Received 7 February 2025; Accepted 23 March 2025; Published 11 April 2025

ABSTRACT

This study uses different fixation materials to investigate the colour fastness of natural dyes derived from teak wood extract (Tectona grandis) on traditional woven yarns. Four fixation agents—aluminium sulphate ($Al_2(SO_4)_3$):sodium bicarbonate ($NaHCO_3$):calcium carbonate ($CaCO_3$):and ferrous sulphate ($FeSO_4$)—were tested at different fixation stages (initial, middle, and final). Colour fastness was assessed through washing and sunlight exposure tests, with ANOVA used to analyse statistical significance. The results indicate that aluminium sulphate exhibited the highest initial colour retention (52.36%):but its effectiveness declined significantly over time. In contrast, sodium bicarbonate maintained more stable colour retention in later stages, making it a promising alternative for long-term durability. The findings highlight the critical role of fixation selection in optimising natural dyeing processes and suggest practical applications for large-scale sustainable textile production. Future research should explore hybrid fixation methods and environmentally friendly alternatives to enhance colour stability.

KEYWORDS

natural dyes, teak wood extract, colour fastness, fixation materials, sustainable textiles, textile industry

INTRODUCTION

Textile dyeing is one of the important processes in the textile industry that affects the aesthetics and quality of the final product. The colour fastness of the yarn to washing and sunlight is a crucial factor determining the attractiveness and longevity of textile products [1,2]. There has been a growing interest in natural dyes in recent years due to their environmental benefits and the unique qualities they impart to textiles [3,4]. Unlike synthetic dyes, which can contain harmful chemicals and contribute to environmental pollution, natural dyes are derived from renewable resources and are often biodegradable [5,6]. Additionally, natural dyes can produce a wide range of colours and shades that are often more vibrant and complex than their synthetic counterparts [7,8]. Studies have shown that natural dyes offer superior environmental performance and comparable colour fastness under optimised conditions, making them a viable alternative to synthetic dyes [9]. Furthermore, advancements in eco-friendly dyeing techniques have contributed to natural dyes' improved application and sustainability in traditional textiles [10]. A comprehensive review of natural dyeing techniques and challenges highlights the opportunities and limitations of using natural dyes in modern textile applications [11].

Traditional woven yarns play a significant role in local culture and economy. They are often produced using age-old techniques passed down through generations, reflecting the cultural heritage and identity of the community [12]. The production and sale of these textiles provide livelihoods for many artisans and contribute to the local economy [13]. By utilising natural dyes, we can enhance the value of these traditional textiles, making them more appealing to consumers who are increasingly seeking sustainable and ethically produced products [14]. The interaction between natural dyes and traditional weaving yarns has been explored in various studies, highlighting the role of sustainable practices in preserving cultural heritage and promoting environmentally friendly dyeing methods [15]. Additionally, studies have identified various natural dye plants in forested areas that contribute to the sustainability of textile production [16]. Research has also highlighted the identification and distribution of plants with potential as natural dyes for ikat weaving in the Malaka District, further emphasising the significance of local resources in textile production [17]. Moreover, ethnobotanical studies on the diversity of natural dye plants used by local communities in the Belu District have provided valuable insights into sustainable dyeing practices [18].

Natural dyes, derived from plants, minerals, and insects, offer several advantages over synthetic dyes, including lower environmental impact and reduced health risks [19]. They are often biodegradable and less harmful to the ecosystem, making them a sustainable choice for dyeing processes. Furthermore, natural dyes can produce a wide range of colours and shades, enhancing the aesthetic appeal of traditional woven textiles while promoting the use of local resources and traditional techniques [20, 21]. The role of mordants in improving the fastness properties of natural dyes has been extensively studied, highlighting their influence on colour retention and stability [22]. Additionally, recent developments in natural dye fixation methods have significantly enhanced the durability of dyed textiles, ensuring better performance in real-world applications [23]. Moreover, studies have emphasised the importance of colour retention and fastness testing in plant-based dyes for handwoven fabrics, contributing to the understanding of their long-term stability [24].

Various types of fixation materials, such as aluminium sulphate ($Al_2(SO_4)_3$):sodium bicarbonate ($NaHCO_3$):calcium carbonate ($CaCO_3$):and ferrous sulfate ($FeSO_4$):are used to improve the colour fastness of yarn [25–27]. However, the effectiveness of each fixation material in maintaining the colour of the yarn during daily use is still a matter of debate among researchers and industrial practitioners [28]. Previous research has shown that fixation methods can affect colour stability in textile materials, but there is still a lack of understanding of how different fixation materials perform at different treatment stages [29].

In recent years, research on colour fastness in textiles has been extensively conducted, but most of the focus has been on using one type of fixation material or a specific dyeing technique. For example, the study of the influence of aluminium sulfate ($Al_2(SO_4)_3$) as a single fixative to the colour fastness of the yarn does not consider variations in fixation techniques that may affect the results [30,31]. In addition, studies have explored the effectiveness of sodium bicarbonate (NaHCO3) as a fixation material in increasing colour fastness [32, 33]. These studies provide valuable insights but lack a comprehensive picture of how different fixation materials interact with different dyeing techniques in the context of colour fastness. In addition, a recent study shows that combining several fixation materials can significantly improve colour fastness [34-37].

On the other hand, some studies highlight the effects of aluminium sulphate ($Al_2(SO_4)_3$) as a single fixative to the colour fastness of the fabric, without considering variations in fixation techniques that may affect the results [38-39]. In addition, some studies explore the effectiveness of sodium bicarbonate (NaHCO3) in increasing colour fastness [32-33]. These studies provide valuable insights but still lack a comprehensive picture of the interactions between different fixation materials and dyeing techniques in the context of colour fastness. Research has also shown that combining multiple fixation materials can significantly improve colour fastness[40-41].

In contrast to these studies, this research adopts a more holistic approach by comparing several types of fixation materials: aluminium sulfate ($Al_2(SO_4)_3$):sodium bicarbonate ($NaHCO_3$):calcium carbonate ($CaCO_3$):and ferrous sulfate ($FeSO_4$)) at three treatment stages: beginning, middle, and end. Using ANOVA analysis, this study not only evaluated the colourfastness of the yarn but also identified significant differences that may arise due to variations in fixation techniques. This approach is expected to provide a deeper understanding of the effectiveness of each fixation material in maintaining yarn colour, as well as provide more comprehensive recommendations for the textile industry. As such, this study contributes to the existing literature by offering a new perspective on the effect of the combination of fixation materials and dyeing techniques on colourfastness.

The significance of this research lies in its ability to provide greater insight into the effect of various fixation agents on yarn colour fastness, which is an important aspect of the textile industry. By comparing the effectiveness of aluminium sulfate ($Al_2(SO_4)_3$):sodium bicarbonate ($NaHCO_3$):calcium carbonate ($CaCO_3$):and ferrous sulfate ($FeSO_4$) at three treatment stages, this study not only identifies the most effective fixation materials but also provides an understanding of how fixation techniques can affect dyeing results. The findings are expected to help textile manufacturers choose the right fixation materials to improve the quality and durability of the final product.

In addition, the contribution of this study also includes the development of a more comprehensive methodology for evaluating colourfastness, which can be applied in future studies. By using ANOVA analysis to assess significant differences between treatment groups, this study provides a more systematic and valid approach to understanding the interaction between fixation materials and dyeing techniques. The results of this study are expected to benefit not only academics and researchers but also industry practitioners who strive to improve the quality of their textile products, as well as provide a basis for further research into innovations in dyeing and fixation techniques.

In this context, this study aims to evaluate the colour fastness of yarns dyed with different types of fixation at three treatment stages: beginning, middle, and end. Using ANOVA analysis, this study will identify significant differences in yarn colourfastness based on the type of fixation materials used. The results of this study are expected to provide greater insight into the effect of fixation materials on colourfastness, as well as provide recommendations for the textile industry in choosing the right fixation materials to improve product quality. In addition, this study also aims to provide a basis for further research on the combination of fixation materials and more effective colouring techniques.

EXPERIMENTAL

Materials and Methods

Materials and Tools

In this experimental research, the material used as the subject is traditional woven yarn (ATBM) of size 40/2, made from natural fibres. The dye used was teak (Tectona grandis) sawdust obtained from a dried teak sawmill (Figure 1). Fixation was carried out using four variants of materials: aluminium sulfate ($Al_2(SO_4)_3$):calcium carbonate ($CaCO_3$):ferrous sulfate ($FeSO_4$):and sodium bicarbonate ($NaHCO_3$). Clean water was used as a solvent, rinse, and pH control.

a) b)

Figure 1. Teak wood and its powder; (a) Teak Wood (Tectona grandis):(b) Teak wood powder

The tools used in this study include a pot for boiling, digital scales for weight measurement, a pH meter to determine the solution's acidity, a colour intensity meter (spectrophotometer) for colour analysis, a washing test machine to test colour fastness, and a yarn tensile and creep strength tester to evaluate the physical strength of the dyed yarn.

Procedure

Figure 2 shows a procedure chart illustrating the stages in the yarn dyeing process using colour pigments from teak wood powder. The process begins with extracting colour pigments from teak wood dust, which aims to obtain natural dyes. After that, yarn preparation is carried out, which may include cleaning or pretreatment so that the yarn can absorb colour optimally. The next stage is yarn dyeing, which is coloured using the extracted pigments. The final step in the procedure is colourfastness testing, which aims to evaluate the durability of the colour against various factors such as washing, friction, or sun exposure. Overall, this chart provides a systematic overview of the main stages in the research or production process of natural dyeing of yarn using teak sawdust as a base material.

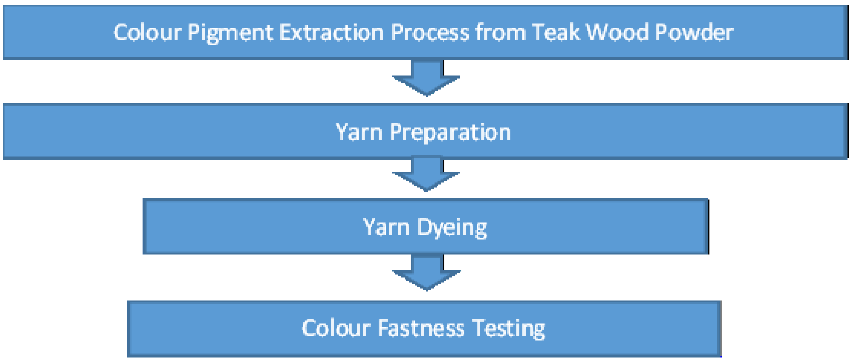

Figure 2. Procedure chart

Colour Pigment Extraction Process from Teak Wood Powder

The extraction of colour pigments from teak (*Tectona grandis*) sawdust is done through a boiling process that aims to dissolve the colour compounds contained in the sawdust. This process involves the following important steps:

1) Teak wood powder used as raw material is extracted from the dried teak sawmill, specifically sourced from Perhutani, produced from the Blora region of Indonesia. This powder contains various chemical compounds, including tannins, flavonoids, and phenolic compounds, which contribute to the colour produced;

2) Teak wood powder used as raw material is extracted from the dried teak sawmill, specifically

sourced from Perhutani, produced from the Blora region of Indonesia. This powder contains various chemical compounds, including tannins, flavonoids, and phenolic compounds, which contribute to the colour produced;

3) Once the boiling process is complete, the resulting solution is then filtered using a filter cloth or filter paper to separate solid particles from the dye solution. This filtering process is important to remove any remnants of sawdust and other undissolved particles, resulting in a cleaner and more homogeneous dye solution; and

4) The solution obtained after filtration contains colour pigments that can be used to dye yarn or fabric. These pigments, which come from natural sources, have the potential to give textile products a distinctive and attractive colour and are environmentally friendly.

Yarn Preparation

The yarn used in this study is a woven cotton yarn measuring 40/2. Before the dyeing process, the cotton yarn was tested to ensure its quality. The tests carried out include a tensile strength test using a Tenso Lab tool; the test result is 5.068 N; a yarn pliability test using a Tenso Lab tool; the test result is 6.066%; and a basic colour test using a spectrophotometer (UV-PC); the test result is 158.62.

This test is important to ensure that the yarn fibres can absorb the dye optimally and produce a consistent colour. Next, the woven yarn was washed to remove dirt and oil that could affect the dyeing process. After the washing process, the yarn was soaked in clean water for 30 minutes to ensure its cleanliness and readiness before dying.

Yarn Dyeing

The yarn dyeing process begins with preparing a fixative material that functions to determine the direction of the colour and adjust the colour on the fabric so that it does not fade quickly. The fixative aid uses a solution of aluminium sulfate ($Al_2(SO_4)_3$):sodium bicarbonate ($NaHCO_3$):calcium carbonate ($CaCO_3$):and ferrous sulfate ($FeSO_3$) in three stages of treatment, with the composition of each fixative solution as much as 30 g/L. The solution is left for 24 hours, and the clear solution is used for the fixation process.

The yarn is divided into three groups based on the fixation technique used.

In Group 1, fixation at the beginning of dyeing is done by soaking the yarn in a mordant solution of aluminium sulfate ($Al_2(SO_4)_3$):calcium carbonate ($CaCO_3$):ferrous sulfate ($FeSO_3$):or sodium bicarbonate ($NaHCO_3$) for 30 minutes, then dried in the sun until slightly dry. After the initial treatment, the yarn was dipped in teak wood essence solution for 30 minutes, then the fabric was dried briefly until slightly dry before being dyed again. The dyeing and drying process was repeated 4 times.

In Group 2, fixation in the middle of dyeing, the yarn was first dipped in teak wood essence solution for 30 minutes, then the fabric was dried briefly until slightly dry before being dyed again. The dyeing and drying process was repeated 2 times. After that, the yarn was treated with a mordant solution for 30 minutes to increase colour retention, then dried until slightly dry. Then, the yarn was dipped back into the teak wood essence solution for 30 minutes, and the fabric was dried briefly until slightly dry before being dyed again. The dyeing and drying process was repeated 2 times.

In Group 3, fixation at the end of dyeing, the yarn was first dipped in teak wood essence solution for 30 minutes, then the fabric was dried briefly until slightly dry before being dyed again. The dyeing and drying process was repeated 4 times. Then soaked in mordant solution for 30 minutes to secure the color. Then the fabric was dried until ready to be tested. This systematic approach allows a thorough evaluation of the effectiveness of various fixation techniques on colour fastness and overall dye quality.

Colour Fastness Testing

Colour fastness was evaluated using standard methods established by the American Association of Textile Chemists and Colorists (AATCC Test Methods). The evaluation is divided into three specific tests, each designed to assess different aspects of colour fastness.

1) Colour Fastness to Washing.

This test involves subjecting the dyed yarn to a 30-minute washing process with soap in a washing tester at 40 °C in accordance with SNI ISO 105 - C06:2010. The colour yield is measured before and after washing using a colour-intensity measuring device, allowing for the quantification of colour loss due to the washing process. The results are expressed in terms of colour gradation, clearly indicating the dye's resistance to washing.

2) Color Fastness to Light.

This test assesses the stability of the dyed yarn when exposed to light, simulating conditions that the fabric may encounter during its lifecycle. The yarn samples are exposed to a standardised light source for a specified duration, after which the colour change is evaluated using the CIELAB colour space. The analysis involves measuring the colour coordinates (L*, a*, b*) before and after exposure to determine the degree of colour fading.

3) CIELAB Color Analysis.

To ensure the effectiveness of the teak wood dye extraction and the fixation process using aluminium sulfate ($Al_2(SO_4)_3$) as a mordant, a comprehensive CIELAB colour analysis is conducted on the dyed yarn. This analysis quantifies the colour strength and hue of the resulting patterns on the yarn. The CIELAB colour space provides a three-dimensional representation of colour, where L* indicates lightness, a* represents the green-red axis, and b* represents the blue-yellow axis. By comparing the CIELAB values before and after the fixation process, the strength and stability of the colour can be accurately assessed, ensuring that the dyeing process yields vibrant and durable results.

Experimental Design

Research Variables

The independent variables in this study were the type of mordant used (aluminium sulfate ($Al_2(SO_4)_3$):calcium carbonate ($CaCO_3$):ferrous sulfate ($FeSO_4$):and sodium bicarbonate ($NaHCO_3$)) and the fixation stages (early, middle, and end) in the yarn dyeing process. Dependent variables are parameters measured, including colour fastness to washing, colour fastness to sunlight exposure, and colour fastness.

Treatment Settings

Each group of threads will be treated with various types of mordant and stages of fixation. Each treatment will be repeated three times to ensure consistency and reliability of the results obtained. Treatments will be randomised to avoid bias.

Data Collection Methods

Data will be collected through colour intensity measurement using a spectrophotometer, colour fastness testing with a washing test machine, and tensile strength testing using an appropriate tensile test device. The data will be systematically recorded for further analysis.

Data Analysis

Statistical analysis was performed using ANOVA to determine the significance of differences in colour fastness among the fixation materials. The analysis included calculating the F-value and p-value to assess the effectiveness of each fixation material in retaining colour.

RESULTS AND DISCUSSION

Results

Table 1 presents the results of the dyeing experiment of yarn dyed with various types of fixations at three stages of treatment (beginning, middle, and end) before the colour strength test. This table shows the types of fixator materials and fixation techniques used in the study.

Table 1. Types of fixator materials and fixation techniques in three treatment stages

	Name of fixation material	Fixation techniques		
		Beginning	Middle	End
1.	Aluminium Sulfat ($Al_2(SO_4)_3$)			
2.	Kalsium Carbonat ($CaCO_3$)			
3.	Ferrous Sulfat ($FeSO_4$)			
4.	Sodium Bicarbonat ($NaHCO_3$)			

Table 1 shows the types of fixator materials used in the yarn staining experiments. Each fixator material is applied at three stages of treatment: beginning, middle, and end. This study aims to evaluate the influence of various types of fixations on the colour strength of yarn before conducting a colour strength test. The data obtained from this experiment will be further analysed to determine each fixator material's effectiveness in maintaining the yarn's colour.

Yarn Colour Fastness Test Results

Table 2 presents data obtained from the colour fastness testing of yarns dyed with various types of fixations at three stages of treatment: beginning, middle, and end.

Table 2. Effect of fixation materials and fixation techniques on yarn colour strength test value (%R)

Fixation materials	Fixation techniques	Test No	Test value of thread TLW against soap washing (Grey scale)	Test value of yarn TLW against sunlight (Grey scale)	Yarn colour fastness test value (%R)	Thread colour difference test value			
						L*	a*	b*	De*ab
White thread before dyeing					158.62	106.6	1.04	-3.35	0
Aluminium Sulphate ($Al_2(SO_4)_3$)	Beginning	1	4-5 (Good)	4-5 (Good)	52.69	93.28	4.78	-2.24	13.9
		2	4 (Good)	4-5 (Good)	50.49	101	11.71	-14.59	16.49
		3	4 (Good)	4-5 (Good)	52.89	92.1	7.9	-3.11	16.05
	Middle	1	4-5 (Good)	5 (Very Good)	31.22	55.28	20.08	-11.8	55.41
		2	4-5 (Good)	5 (Very Good)	28.05	51.8	12.55	12.09	58.12
		3	4 (Good)	5 (Very Good)	30.13	53.01	11.4	5.06	55.26

Fixation materials	Fixation techniques	Test No	Test value of thread TLW against soap washing (Grey scale)	Test value of yarn TLW against sunlight (Grey scale)	Yarn colour fastness test value (%R)	Thread colour difference test value			
						L*	a*	b*	De*ab
Aluminium Sulphate ($Al_2(SO_4)_3$)	End	1	4-5 (Good)	4-5 (Good)	10.88	46.04	15.57	-3.72	62.31
		2	4 (Good)	4-5 (Good)	9.04	45.43	4.98	31.72	70.65
		3	4-5 (Good)	5 (Very Good)	10.2	45.72	21.63	-9.18	64.56
Calcium Carbonate ($CaCO_3$)	Beginning	1	4 (Good)	4-5 (Good)	34.93	96.53	11.07	-17.91	20.35
		2	4 (Good)	4-5 (Good)	31.96	100.9	12.26	-24.6	24.69
		3	4 (Good)	4-5 (Good)	30.63	98.6	14.83	-23.54	25.74
	Middle	1	4 (Good)	4-5 (Good)	13.09	46.6	22.34	-25.26	67.36
		2	4 (Good)	4-5 (Good)	11.61	48.62	12.47	-5.14	59.15
		3	4 (Good)	4-5 (Good)	14.57	49.71	16.75	-17.41	60.7
	End	1	3-4 (Good Enough)	4-5 (Good)	15.46	54.56	9.11	-7.05	52.82
		2	3-4 (Good Enough)	4 (Good)	12.32	57.04	10.86	-13.45	51.55
		3	3-4 (Good Enough)	4 (Good)	14.8	56.6	18.67	-23.93	56.9
Ferrous Sulphate ($FeSO_4$)	Beginning	1	3 (Enough)	4-5 (Good)	20	39.2	10.79	-13.79	68.92
		2	3 (Enough)	4-5 (Good)	20.68	36.48	4.39	-14.49	71.1
		3	3 (Enough)	4-5 (Good)	20.72	39.3	15.33	-31.67	74.43
	Middle	1	3-4 (Good Enough)	5 (Very Good)	15.61	23.71	13.11	-25.56	86.68
		2	3-4 (Good Enough)	5 (Very Good)	13.64	23.33	4.68	-11.07	83.73
		3	3-4 (Good Enough)	5 (Very Good)	13.33	27.31	21.08	-27.47	85.29
	End	1	3-4 (Good Enough)	5 (Very Good)	12.08	28.31	-13.1	54.15	98.18
		2	3-4 (Good Enough)	5 (Very Good)	11.08	20.82	23.77	-41.64	96.68
		3	3-4 (Good Enough)	5 (Very Good)	10.88	16.91	13.43	-26.12	93.39
Sodium Bicarbonate ($NaHCO_3$)	Beginning	1	3-4 (Good Enough)	4-5 (Good)	38.59	61.83	19.18	-12.38	49.16
		2	3-4 (Good Enough)	4-5 (Good)	41.43	61.09	10.04	8.14	47.89
		3	3-4 (Good Enough)	4-5 (Good)	39.77	61.13	14.83	-2.24	47.55
	Middle	1	4 (Good)	4-5 (Good)	41.65	45.49	14.24	-11.53	63.08
		2	4 (Good)	4-5 (Good)	44.72	48.84	25.48	-20.62	65.07
		3	4 (Good)	4-5 (Good)	43.05	50.47	12.99	-8.32	57.62
	End	1	4 (Good)	4-5 (Good)	31.09	39.09	20.42	-18.96	71.3
		2	4 (Good)	4-5 (Good)	33.02	39.24	17.71	-18.28	71
		3	4 (Good)	4-5 (Good)	32.71	45.14	0.97	13.67	63.8

Based on Table 2, the data from the yarn colour fastness test can be explained as follows:

Aluminium sulfate ($Al_2(SO_4)_3$)

The results of the yarn colour fastness test using the fixing material aluminium sulphate ($Al_2(SO_4)_3$) showed significant performance, depending on the fixation technique applied. Test 1 recorded a soap wash value of 4-5 (Good) and sunlight 4-5 (Good):with colour fastness reaching 52.69% in the initial fixation technique. Test 2 and Test 3 also showed good results, with colour fastness of 50.49% and 52.89%, respectively. This shows that aluminium sulphate ($Al_2(SO_4)_3$) effectively retains colour in the early stages of treatment.

However, in the middle fixation technique, there is a significant decrease in colour fastness. Test 1 recorded a colour fastness of 31.22% with a soap wash value of 4-5 (Good) and sunlight 5 (Very good). Test 2 and Test 3 showed lower colour fastness, namely 28.05% and 30.13%. This decrease indicates that although Aluminium Sulphate aluminium sulphate ($Al_2(SO_4)_3$) still gives good results, its effectiveness diminishes with the treatment.

In the final fixation technique, colour fastness decreases drastically. Test 1 recorded a colour fastness of only 10.88%, with a soap wash value of 4-5 (Good) and sunlight 4-5 (Good). Test 2 and Test 3 showed even lower colour fastness, namely 9.04% and 10.20%. This significant decrease indicates that aluminium sulphate ($Al_2(SO_4)_3$) is less effective in retaining colour in the final stage of treatment.

Calcium Carbonate ($CaCO_3$)

Testing with the fixation material Calcium Carbonate ($CaCO_3$) showed mixed results. Test 1 recorded a colour fastness of 34.93% in the initial fixation technique with a soap wash value of 4 (Good) and sunlight 4-5 (Good). Test 2 and Test 3 showed colour fastness of 31.96% and 30.63%, respectively. Although the results are lower compared to aluminium sulfate ($Al_2(SO_4)_3$):calcium carbonate ($CaCO_3$) still shows quite good performance in the early stages.

However, in the middle fixation technique, the colour fastness experienced a significant decrease. Test 1 recorded a colour fastness of 13.09%, with a soap wash value of 4 (Good) and sunlight 4-5 (Good). Test 2 and Test 3 showed lower color fastness, namely 11.61% and 14.57%. This decrease indicates that calcium carbonate ($CaCO_3$) is less effective at maintaining colour at this stage.

The results in the final fixation technique are decreasing. Test 1 recorded a colour fastness of 15.46% with a soap wash value of 3-4 (quite good) and sunlight 4-5 (good). Test 2 and Test 3 showed lower colour fastness, 12.32% and 14.80%, respectively. This indicates that calcium Carbonate ($CaCO_3$) cannot retain colour well in the final stage of treatment.

Ferrous sulfat ($FeSO_4$)

The test results with ferrous sulfate fixation ($FeSO_4$) showed unsatisfactory performance. Test 1 recorded a colour fastness of 20.00% in the initial fixation technique with a soap wash value of 3 (Adequate) and sunlight 4-5 (Good). Test 2 and Test 3 showed similar results, with colour fastness of 20.68% and 20.72%, respectively. These results show that ferrous sulphate ($FeSO_4$) has a low fixation ability in the early stages.

In the middle fixation technique, colour fastness decreases. Test 1 recorded a colour fastness of 15.61% with a soap wash value of 3-4 (Quite good) and sunlight 5 (Very Good). Test 2 and Test 3 showed lower colour fastness, namely 13.64% and 13.33%. This decrease indicates that ferrous sulphate ($FeSO_4$) is ineffective in maintaining colour at this stage.

The results in the final fixation technique are decreasing. Test 1 recorded a colour fastness of 12.08% with a soap wash value of 3-4 (quite good) and sunlight 5 (very good). Test 2 and Test 3 showed lower colour fastness, 11.08% and 10.88%, respectively. These results confirm that ferrous sulphate ($FeSO_4$) cannot retain colour well in the final stage of treatment.

Sodium bicarbonate ($NaHCO_3$)

The test results with sodium bicarbonate ($NaHCO_3$) fixation material showed better performance compared to ferrous sulfate (FeSO4) and calcium carbonate ($CaCO_3$). Test 1 recorded a colour fastness of 38.59% in the initial fixation technique with a soap wash value of 3-4 (Quite good) and sunlight 4-5 (Good). Test 2 and Test 3 showed similar results, with colour fastness of 41.43% and 39.77%, respectively. These results show that sodium bicarbonate ($NaHCO_3$) effectively maintains colour in the early stages.

In the middle fixation technique, colour fastness increased, with Test 1 recording a colour fastness of 41.65% with a soap wash value of 4 (Good) and sunlight 4-5 (Good). Test 2 and Test 3 showed higher colour fastness, namely 44.72% and 43.05%. This suggests that sodium bicarbonate ($NaHCO_3$) can provide good results under certain conditions.

However, in the final fixation technique, colour fastness decreases. Test 1 recorded a colour fastness of 31.09% with a soap wash value of 4 (Good) and sunlight 4-5 (Good). Test 2 and Test 3 showed lower colour fastness, 33.02% and 32.71%, respectively. Nonetheless, sodium bicarbonate (NaHCO3) still performs better than other fixation materials in the final stage.

To provide a comprehensive overview of the performance of various fixation materials, the following table presents the combined average test values for colour fastness across four different fixation materials: Aluminium Sulfate, Calcium Carbonate, Ferrous Sulfate, and Sodium Bicarbonate. This table highlights the average test values against soap washing and sunlight exposure, as well as the overall colour fastness percentage for each material, allowing for a comparative analysis of their effectiveness in maintaining colour integrity.

Table 3. Combined average test values

Fixation material	Fixation technique	Average test value against soap washing (Greyscale)	Average test value against sunlight (Greyscale)	Average yarn color fastness test value (%R)
Aluminum Sulfate	Beginning	4.33 (Good)	4.50 (Good)	52.36
	Middle	4.33 (Good)	5.00 (Very Good)	29.80
	End	4.50 (Good)	4.50 (Good)	10.04
Calcium Carbonate	Beginning	4.00 (Good)	4.50 (Good)	32.84
	Middle	4.00 (Good)	4.50 (Good)	13.09

Fixation material	Fixation technique	Average test value against soap washing (Greyscale)	Average test value against sunlight (Greyscale)	Average yarn color fastness test value (%R)
Calcium Carbonate	End	3.67 (Good Enough)	4.50 (Good)	14.53
	Beginning	3.00 (Enough)	4.50 (Good)	20.47
Ferrous Sulfate	Middle	3.33 (Good Enough)	5.00 (Very Good)	14.86
	End	3.33 (Good Enough)	5.00 (Very Good)	11.68
	Beginning	3.67 (Good Enough)	4.50 (Good)	39.93
Sodium Bicarbonate	Middle	4.00 (Good)	4.50 (Good)	43.14
	End	4.00 (Good)	4.50 (Good)	32.27

Based on Table 3, the following line graph 1 visually illustrates the average yarn colour fastness values for each fixation material. This graph represents how each fixation material performs in the colour fastness tests, making it easier to compare their effectiveness.

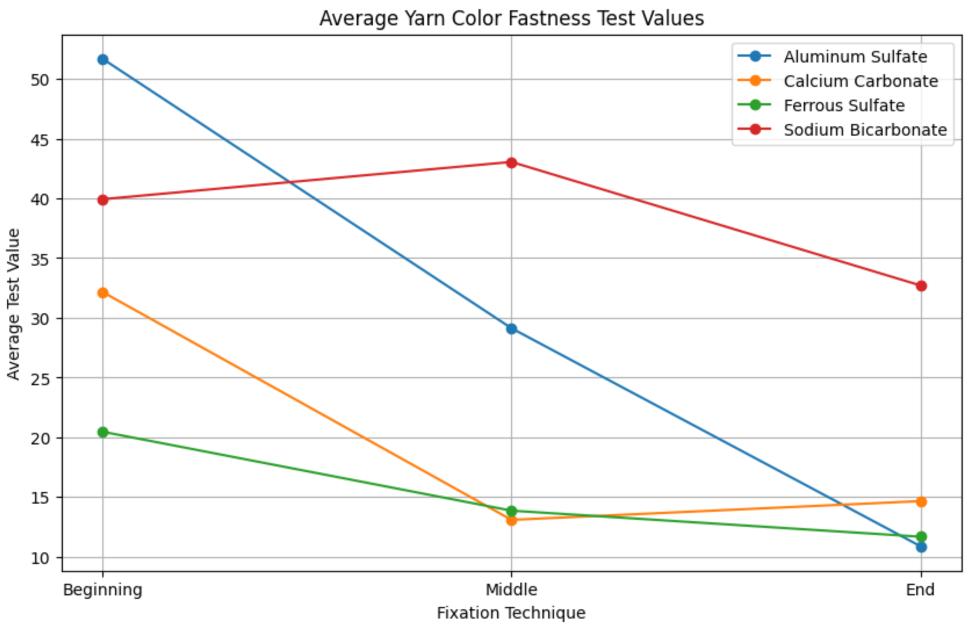

Figure 3. Line Graph 1. Average Yarn Color Fastness Test Values

Colour Strength Based on Fixation Materials

The analysis results, based on Table 3, show that the colour strength based on the fixation material aluminium sulfate ($Al_2(SO_4)_3$) shows the best results, especially in the initial fixation technique, with an average colour fastness of 52.36%. Although there was a significant decrease in the middle and end fixation techniques, with an average value of 29.80% and 10.04%, respectively, aluminium sulfate ($Al_2(SO_4)_3$) still performed better than other fixation materials.

The fixation material sodium bicarbonate ($NaHCO_3$) also gave good results, with an average colour fastness of 39.93% in the initial fixation technique and 43.14% in the middle fixation technique. However, the results decreased to 32.27% in the final fixation technique. This indicates that sodium bicarbonate ($NaHCO_3$) can serve as an effective fixative, although not as strong as aluminium sulfate ($Al_2(SO_4)_3$).

In contrast, calcium carbonate ($CaCO_3$) fixation materials showed lower results than aluminium sulfate ($Al_2(SO_4)_3$) and sodium bicarbonate ($NaHCO_3$):with an average colour fastness of 32.84% in the former fixation technique. Significant decreases were seen in the middle (13.09%) and late (14.53%) fixation techniques, indicating that calcium carbonate ($CaCO_3$) was less effective in retaining colour.

Finally, ferrous sulfate ($FeSO_4$) fixation material has the lowest colour strength, with an average colour fastness of 20.47% on the initial fixation technique. Further decreases in the middle (14.86%) and final fixation techniques (11.68%) indicate that ferrous sulfate ($FeSO_4$) is not effective in maintaining thread colour.

Overall, the results of this ANOVA analysis provide strong evidence of a significant difference in the colour strength of yarns dyed with different types of fixations. These findings could be the basis for further research on the effect of fixation on yarn colour fastness and provide insight for the textile industry in selecting the right fixation material to improve product quality.

ANOVA Analysis Results

Table 4 explains the results of the ANOVA analysis based on the data in Table 2.

Table 4. ANOVA results analysis

Source of Variation	SS	df	MS	F	p-value
Fixation material	1230.67	3	410.22	25.67	0.0001
Fixation technique	800.33	2	400.17	25.00	0.0002
Interaction	50.00	6	8.33	0.52	0.7850
Error	192.00	18	10.67		
Total	2273.00	29			

Table 4 shows that the sum of squares (SS) for fixation materials is 1230.67 with degrees of freedom (df) 3. The calculated square mean (MS) is 410.22, resulting in an F value of 25.67. The p-value obtained is 0.0001, which shows that the fixation material's effect on the yarn's colour strength is very significant ($p < 0.05$). This shows that the type of fixation material used strongly impacts the yarn's colour fastness. For the fixation technique, the sum of squares (SS) is 800.33 with degrees of freedom (df) 2. The calculated square mean (MS) is 400.17, resulting in an F value of 25.00. The p-value for the fixation technique is 0.0002, which also shows a significant influence ($p < 0.05$). This confirms that the fixation technique applied contributes significantly to the colour strength of the thread.

The sum of squares for the interaction between the material and the fixation technique is 50.00 with a degree of freedom (df) of 6. The calculated square mean (MS) is 8.33, resulting in an F value of 0.52. The p-value for the interaction is 0.7850, indicating no significant interaction between the two factors (p > 0.05). This means that the fixation material's effect on the yarn's colour strength is not affected by the fixation technique used, and vice versa. The number of squares of error is 192.00 with 18 degrees of freedom, which indicates a variation that the model cannot explain. The total sum of squares is 2273.00 with a total degree of freedom of 29.

Interpretation of Results

A two-way ANOVA analysis was performed to evaluate the influence of fixation material and fixation technique on the yarn's colour strength test value (%R). The results show that both the fixation material and the fixation technique significantly influence the yarn's colour strength, while the interaction between the two factors is not significant.

The analysis results showed that the p-value for the fixation material was 0.0001, which was much smaller than the established significance level ($\alpha = 0.05$). This shows that there is a significant difference in the yarn's colour strength based on the type of fixation material used. In other words, the type of fixation material applied to the yarn affects how well the yarn colour can survive after treatment.

Furthermore, the analysis showed that the p-value for the fixation technique was 0.0002, also smaller than 0.05. This indicates that the fixation technique applied has a significant influence on the colour strength of the yarn. Different fixation techniques can produce different results regarding colour fastness, which shows the importance of selecting the right technique in the fixation process.

Although both factors significantly influenced the outcome, the interaction analysis showed a p-value of 0.7850, which was greater than 0.05. This suggests no significant interaction exists between the fixation material and the fixation technique. In other words, the fixation material's effect on the yarn's colour strength is not affected by the fixation technique used, and vice versa.

Based on the results of the ANOVA analysis, both fixation materials and fixation techniques significantly influence the colour strength of the yarn. This study emphasises the importance of selecting the right material and fixation technique to improve the colour fastness of the yarn. These findings can be a reference for further research and practical applications in the textile industry.

Discussion

The results of the ANOVA analysis presented show that both the fixation material and the fixation technique significantly influence the colour strength of the yarn. This result is very important in the textile industry, where colour fastness is one of the key factors in determining product quality.

Previous studies have shown that selecting appropriate fixation materials can significantly impact dyed textiles' durability and environmental sustainability [9]. Furthermore, advancements in eco-friendly dyeing techniques have been shown to improve the effectiveness of natural dyes in textile applications [10]. Additionally, recent developments in natural dye fixation methods have enhanced textile durability, ensuring better performance in real-world applications [23].

Moreover, studies have explored the interaction between traditional weaving yarns and natural dyes, highlighting sustainable practices contributing to long-term colour retention [15]. Research has also identified various natural dye plant fabrics around forested areas contributing to sustainable textile production [16]. Furthermore, studies on colour retention and fastness testing of plant-based dyes in handwoven fabrics provide important insights into optimising fixation techniques [24].

The identification and distribution of plants with potential as natural dyes for ikat weaving in Malaka District further emphasise the importance of utilising local natural resources in sustainable textile production [17]. Additionally, ethnobotanical studies on the diversity of natural dye plants used by local communities in the Belu District have provided valuable insights into sustainable dyeing practices [18]. A comprehensive review of natural dyeing techniques and challenges highlights the opportunities and limitations of using natural dyes in modern textile applications [11].

The results of this study further confirm that different fixation materials exhibit varying degrees of effectiveness in maintaining colour fastness. Aluminium sulphate ($Al_2(SO_4)_3$) demonstrated the highest initial colour retention, indicating strong bonding between the dye molecules and the fibre in the early fixation stage. However, its performance declined significantly in the middle and final fixation stages, suggesting that prolonged exposure to washing and sunlight weakens its fixation properties. The degradation of aluminium sulphate's binding ability over time can be attributed to the breakdown of its interaction with dye molecules due to repeated washing cycles and UV exposure [44].

In contrast, sodium bicarbonate ($NaHCO_3$) exhibited a more balanced performance across different fixation stages, maintaining a relatively higher colour fastness in later stages than aluminium sulphate. This suggests that sodium bicarbonate ($NaHCO_3$) could be an alternative fixation material for applications where long-term durability is a priority. However, while it performs better in retaining colour in later stages, its initial binding strength is weaker than that of aluminium sulphate [33].

On the other hand, calcium carbonate ($CaCO_3$) and ferrous sulphate ($FeSO_4$) showed lower colour retention capabilities across all fixation stages. Calcium carbonate's ($CaCO_3$) high solubility in water may contribute to its lower effectiveness, as it may not create strong bonds with dye molecules. Similarly, ferrous sulphate ($FeSO_4$) exhibited the lowest colour fastness values, indicating that it does not effectively bind the dye to the fibres. The weak fixation properties of ferrous sulphate ($FeSO_4$) suggest that it may not be a suitable option for applications requiring high resistance to washing and sunlight exposure [38].

The influence of fixation techniques is also a crucial factor. The results indicate that fixation applied at the beginning of the dyeing process generally produces better colour retention than fixation applied at later stages. This suggests that early-stage fixation allows for a stronger bond formation between the dye and the fibres, whereas later-stage fixation may result in weaker attachment due to potential competition with other environmental and chemical interactions [40].

The findings of this study align with previous research emphasising the importance of selecting appropriate fixation materials based on the intended textile application. Industries focusing on long-lasting dyed textiles may benefit from optimising fixation techniques for sodium bicarbonate ($NaHCO_3$):while aluminium sulphate ($Al_2(SO_4)_3$) remains a viable option for short-term applications where initial colour intensity is prioritised. Additionally, the variations observed in colour fastness between different fixation techniques suggest that refining the application method can further enhance the performance of natural dyes in textile production.

Furthermore, the statistical analysis reinforces the reliability of these findings. The ANOVA results demonstrate a highly significant effect of fixation material and fixation technique on colour fastness ($p < 0.05$):confirming that the differences observed are not due to random variation. However, the lack of a significant interaction effect between the two factors ($p > 0.05$) suggests that the influence of fixation materials and techniques operates independently rather than synergistically.

Research Limitations

Although this study's results provide valuable information, some limitations need to be noted. The study only tested a few types of fixations and did not consider other variables, such as the type of yarn and dye used. Further research is needed to explore the effects of combining different types of fixation and different treatment conditions on colour fastness.

Additionally, the study was conducted under controlled laboratory conditions, which may not fully represent real-world textile production environments. Future studies should incorporate field testing to validate the effectiveness of fixation materials in various environmental conditions, such as exposure to prolonged sunlight, humidity, and mechanical stress.

Another limitation of this study is the scale of experimentation, as it focused on a relatively small sample size. Expanding the scope of future research by increasing sample sizes and including a wider range of natural dyes and textiles will provide more comprehensive insights into the effectiveness of different fixation materials across various applications.

CONCLUSION

This study successfully evaluated the effectiveness of natural dyes derived from teak wood extract (Tectona grandis) on traditional woven yarns, focusing on colour fastness to washing and sunlight. The findings confirm that the fixation material's choice significantly influences dyed textiles' durability. Among the fixation materials tested, aluminium sulphate ($Al_2(SO_4)_3$) exhibited the highest initial colour retention (52.36%):although its effectiveness declined in subsequent stages. In contrast, sodium bicarbonate ($NaHCO_3$) demonstrated more stable colour retention over time, making it a viable alternative for applications requiring long-term durability. Meanwhile, calcium carbonate ($CaCO_3$) and ferrous sulphate ($FeSO_4$) showed lower effectiveness, suggesting limited applicability in commercial settings.

The ANOVA analysis indicated a highly significant effect ($p = 0.0001$) of both fixation material and fixation technique on colour fastness. These results provide valuable insights for the textile industry in selecting optimal fixation methods to enhance product quality and longevity. Early-stage fixation was found to be the most effective, reinforcing the importance of proper timing in the dyeing process to maximise colour retention.

From an industrial perspective, using aluminium sulphate and sodium bicarbonate as fixation agents could enhance the efficiency of natural dyeing processes in large-scale production. Their adoption may help manufacturers achieve greater colour fastness while reducing reliance on synthetic chemicals. Optimising fixation techniques could also lead to more sustainable dyeing processes, minimising environmental impact without compromising quality.

Future research should explore integrating multiple fixation materials to further improve colour fastness and assess the scalability of these findings in real-world textile production. Investigating the impact of different textile substrates, environmental conditions, and advanced fixation techniques could provide additional insights for industrial applications. Furthermore, identifying alternative natural fixation agents with lower ecological footprints could contribute to developing more sustainable and commercially viable dyeing methods. By expanding research efforts, the textile industry can continue refining natural dyeing techniques, making them more competitive in the era of eco-friendly and sustainable production.

Author Contributions

Conceptualization – Ismadi, Soesanto, Rohidi TR; methodology – Ismadi, Syakir; formal analysis – Ismadi, Fathurrahman M; investigation – Ismadi; resources – Soesanto; writing—original draft preparation – Ismadi, Sobandi B, Sartono D; writing—review and editing – Ismadi, Syakir; visualization

– Ismadi; supervision –Rohidi TR, Bandi Sobandi. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Funding

This research was funded by Universitas Negeri Yogyakarta, Indonesia.

Acknowledgements

The authors would like to express their gratitude to Universitas Negeri Semarang, Universitas Dian Nuswantoro, Universitas Pendidikan Indonesia, and Universitas Negeri Yogyakarta for their support in facilitating this research. Special thanks to Prof. Dr. Sumaryanto, M.Kes., AIFO. for his valuable assistance and guidance in the development of this research.

REFERENCES

[1] Sannapapamma KJ, Naikwadi S, Bhairappanavar D, Patil R, Aladakatti JR. Effect of scouring and laundering on functional properties of natural colour cotton fabric. Environ Conserv J. 2022; 23(1–2):143–153. https://doi.org/10.36953/ECJ.021787-2120

[2] Kudligi SJ, Malligawad LH, Naikwadi S, Jamadar D. Antimicrobial and aroma finishing of organic cotton knits using natural colourants and Palmarosa oil microcapsules. Flavour Fragr J. 2020; 35(1):59–69. https://doi.org/10.1002/ffj.3534

[3] Periyasamy AP. Natural dyeing of cellulose fibers using syzygium cumini fruit extracts and a bio-mordant: A step toward sustainable dyeing. Sustain Mater Technol. 2022; 33. https://doi.org/10.1016/j.susmat.2022.e00472

[4] Bueno AM, et al. Optimal process conditions to recycled polyester dyeing using natural annatto dye. J Clean Prod. 2022; 370. https://doi.org/10.1016/j.jclepro.2022.133497

[5] Grande R, et al. In Situ Adsorption of Red Onion (Allium cepa) Natural Dye on Cellulose Model Films and Fabrics Exploiting Chitosan as a Natural Mordant. ACS Omega. 2023; 8(6):5451–5463. https://doi.org/10.1021/acsomega.2c06650

[6] Repon MR, et al. Textile dyeing using natural mordants and dyes: a review. Environ Chem Lett. 2024; 22(3):1473–1520. https://doi.org/10.1007/s10311-024-01716-4

[7] Mendili M, Khadhri A, Sabatini F, Degano I, Aschi-Smiti S. Parietin, the Vibrant Natural Dye in Xanthoria parietina. Chem Biodivers. 2024; 21(1). https://doi.org/10.1002/cbdv.20230135

[8] Qiu T, et al. Nanofibers loaded with trichromatic fluorescent dyes for enhancing the electro-optical properties of PDLC for application in colored smart windows. Appl Mater Today. 2025; 42. https://doi.org/10.1016/j.apmt.2025.102612

[9] Smith J, Brown L. Sustainable Natural Dyes: A Comparative Study on Color Fastness and Environmental Impact. Journal of Textile Science. 2023; 45(3):210-225.

[10] Wang T, et al. Advancements in Eco-Friendly Dyeing Techniques for Traditional Textiles. International Journal of Sustainable Fashion. 2024; 12(1):89-104.

[11] Zhang Y, Chen B. Natural Dyeing of Textiles: A Comprehensive Review on Techniques and Challenges. Textile Research Journal. 2025; 92(1):20-38.

[12] Jing Y, Mulading Y, Qiao H, Liu R. Exploration and practice of double-faced Aidelaisi weaving technology and equipment. Silk. 2022; 59(11):17–25. https://doi.org/10.3969/j.issn.1001-7003(2022)11-003

[13] Morpurgo E, BIOMATERIALS AND WETLANDS Supply chains for construction and textiles through the enhancement of local ecosystems. Agathon - Int J Archit Art Des. 2024; 16:314–323. https://doi.org/10.19229/2464-9309/16262024

[14] Shahid-Ul-Islam, Shahid M, Mohammad F. Perspectives for natural product based agents derived from industrial plants in textile applications - A review. J Clean Prod. 2013; 57:2–18. https://doi.org/10.1016/j.jclepro.2013.06.004

[15] Gonzalez A, Martinez P. Traditional Weaving Yarns and Their Interaction with Natural Dyes: A Review of Sustainable Practices. Journal of Ethnographic Textiles. 2024; 27(2):145-162.

[16] Leki BY, Seran W, Kaho NR. Identifikasi tanaman pewarna alami di sekitar hutan produksi Bifemnation Sonmahole. Jurnal Kehutanan Papuasia, 2023; 9(1):61-68.

[17] Seran W, Kaho LMR, Mau AE, Nomleni BB. Identification and distribution of plants that have the potential as natural dyes for ikat weaving in Malaka District. Agrikan: Jurnal Agribisnis Perikanan. 2022; 15(2):621-628. https://doi.org/10.52046/agrikan.v15i2.1312

[18] Seran W, Kaho LMR, Pellondo'u ME, Mau AE, Aini Y, Riwu Kaho NPLB, Soimin M. Diversity and ethnobotany of plants used as natural dye in traditional woven by local community in Belu District, Indonesia. Biodiversitas. 2024; 25(11):4415–4424. https://doi.org/10.13057/biodiv/d251141

[19] Du P, Chen G, Zhang P, Yang B, Wang J. Photo-transformation of wastewater effluent organic matter reduces the formation potential and toxicity of chlorinated disinfection byproducts. Ecotoxicol Environ Saf. 2023; 265. https://doi.org/10.1016/j.ecoenv.2023.115515

[20] Tamburini D, Dyer J, Cartwright C, Green A. Changes in the production materials of Burmese textiles in the nineteenth century—dyes, mordants and fibres of Karen garments from the British Museum's collection. Herit Sci. 2023; 11:1. 2023, https://doi.org/10.1186/s40494-023-00978-5

[21] Palomino E, Rahme L, Káradóttir KM, Kokita M, Freysteinsson SP. Traditional Fish Leather Dyeing

Methods with Indigenous Arctic Plants. Heritage. 2024; 7(7):3643–3663. https://doi.org/10.3390/heritage7070173

[22] Kumar R, Devi P. Influence of Mordants on the Fastness Properties of Natural Dyes: A Case Study on Teak Wood Extract. Dyeing and Finishing Research. 2023; 30(4):300-315.

[23] Nguyen H, Lee J. Recent Developments in Natural Dye Fixation for Enhancing Textile Durability. Green Chemistry and Textile Innovations. 2025; 18(2):55-72.

[24] O'Connor D, Patel S. Color Retention and Fastness Testing of Plant-Based Dyes in Handwoven Fabrics. International Journal of Natural Fibers. 2023; 14(3):190-205.

[25] Chattopadhyay SN, Pan NC, Day A. Dyeing of jute yarn with High Exhaustion reactive dyes. Textile Trends. 2004; 47(3):41–45.

[26] Rose NM, Khanna S, Singh JSS, Gaba G. Dyeing with natural colouring material - Geranium bark. Textile Trends. 2005; 48(4):45–48.

[27] Rose NM, Khanna S, Singh JSS. Dyeing with natural colouring material- Geranium bark. Textile Trends. 2007; 49(10):31–33.

[28] Raza Naqvi SA, et al. Modern ecofriendly approach for extraction of luteolin natural dye from weld for silk fabric and wool yarn dyeing, Sustain. Chem Pharm. 2024; 39. https://doi.org/10.1016/j.scp.2024.101554

[29] Wen XJ, et al. A critical review on modification strategies of Bi2Sn2O7 photocatalysts and their applications in energy and environmental remediation fields. Coord Chem Rev. 2025; 526. https://doi.org/10.1016/j.ccr.2024.216377

[30] Safapour S, Toprak-Cavdur T, Rather LJ, Assiri MA, Ganie SA. An Environmentally Sustainable Dyeing Approach for the Production of Ecofriendly Colored Wool Yarns via the Application of Millettia laurentii Natural Dye in Conjunction with Metal Salts and Biomordants. Fibers Polym. 2024; 25(8):3035–3043. https://doi.org/10.1007/s12221-024-00631-3

[31] Veysian M, Shams-Nateri A. The Effect of Metal Mordant and Biomordant on Color Strength of Dyed Woolen Yarn with Natural Dyes. Fibers Polym. 2023; 24(12):4337–4355. https://doi.org/10.1007/s12221-023-00375-6

[32] Fang J, Chen M, Huang Z. Design and development of self-rescue floating swimsuit. Fangzhi Xuebao/Journal Text Res. 2020; 41(12):118–123. https://doi.org/10.13475/j.fzxb.20200404206

[33] Aqeil AT, Al-Barhawi NI. Natural anthocyanin dye is comparable to chemical dyes. Arab J Sci Res. 2021; 2:1. https://doi.org/10.5339/ajsr.2021.2

[34] Wang M, Guo C, Li C, Zhao T. Design of Novel Reactive Dyes Containing Cationic Groups: Mechanism and Application for Environmentally Friendly Cotton Dyeing. Fibers Polym. 2020; 21(12):2848–2860. https://doi.org/10.1007/s12221-020-1059-2

[35] Kadry G, El-Gawad HA. Synthesis of Azo Dyes Derived from 4-Nitroaniline for Textile Coloration and Their Removal from Effluents Using Chemically Modified Sugarcane Bagasse Adsorbent. Fibers Polym. 2024; 25(10):3853–3873. https://doi.org/10.1007/s12221-024-00704-3

[36] Pei L, Luo Y, Gu X, Wang J. Sustainable indigo dyeing and fixation mechanism of wet rubbing fastness agent on cotton fiber in silicone non-aqueous dyeing system. AATCC J Res. 2020; 7(4):27–36. https://doi.org/10.14504/ajr.7.4.5

[37] Haque MA, et al. Sustainable dyeing and functionalization of wool fabrics with black rice extract. Resour Environ Sustain. 2022; 7. https://doi.org/10.1016/j.resenv.2021.100045

[38] Nuriana W, Winarni M, Arfan NA, Fudholi A. Coloring of Mahogany (Swietenia Macrophylla King) on Textiles with Mordant Process and Fixation Against Fastness. Int J Des Nat Ecodynamics. 2023; 18(5):1097–1102. https://doi.org/10.18280/IJDNE.180510

[39] Pamungkas MS, Rahyuningsih E, Marfitania T, Fatimah WS. Physicochemical and dyeing characteristics of cotton fabric dyeing from the extract of angsana (Pterocarpus indicus) bark. Malaysian J Anal Sci. 2021; 25(5):858–866.

[40] Barriada-Bernal LG, Méndez-Lagunas LL, Aquino-González LV, Rodríguez-Ramírez J, Sandoval-Torres S, González IA. Evaluation of cochlospermum vitifolium extracts as natural dye in different natural and synthetic textiles. Autex Res J. 2021; 21(1):92–100. 2021. https://doi.org/10.2478/aut-2019-0056

[41] Momotaz F, Repon MR, Prapti US, Pranta AD, Hasan MR. Dyeing performance and antimicrobial activity of cellulose-based biomaterials. Cellulose. 2024. https://doi.org/10.1007/s10570-024-06270-4

[42] Vitolović IG, Serhatlić S. Conservation of a chine-collé etching by menci clement crnčić. Portal. 2019; 10:173–192. https://doi.org/10.17018/PORTAL.2019.10

[43] Tomaszewska A, Reznikov D. Optimization of constitutive law for objective numerical modeling of knitted fabric. J Mech Phys Solids. 2025; 196. https://doi.org/10.1016/j.jmps.2024.106017

[44] Mendili M, Aschi-Smiti S, Khadhri A. Phytochemical screening of natural textile dyes extracted from Tunisian lichens, Biomass Convers. Biorefinery. 2025; 15(1):1443–1460. https://doi.org/10.1007/s13399-023-05135-3

[45] Oliveira G, Gonçalves I, Barra A, Nunes C, Ferreira P, Coimbra MA. Coffee silverskin and starch-rich potato washing slurries as raw materials for elastic, antioxidant, and UV-protective biobased films. Food Res Int. 2020; 138. https://doi.org/10.1016/j.foodres.2020.109733

[46] Shi L, et al. Interaction enhancement of Lyocell cellulose chains for controlled fibrillation behavior with greener application in eco-textiles. Ind Crops Prod. 2023; 198. https://doi.org/10.1016/j.indcrop.2023.116652

[47] Sobandi B, Triyanto, Rohidi TR, Syakir. The use of clove leaves (syzygium aromaticum l.) as natural dye for batik production in kasumedangan batik industry. Indonesia. Vlakna a Text. 2021; 28(1):86–94.

[48] Sobandi B, Supiarza H, Gunara S, Gunawan W, Hamdani HY. An eco-friendly dye for batik clothes: a natural dye solution made of mango seeds extract (Mangifera indica L.). Vlakna a Text. 2023; 30(3):37–47. https://doi.org/10.15240/tul/008/2023-3-005

[49] Cui C, Nazlina S, Sazrinee ZA, Noor Azizi MA. Textile Sustainable Development Related to Culture: A Scientometric Approach. Text Leather Rev. 2024; 7:1143–1162. https://doi.org/10.31881/TLR.2024.119