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Effect of Mordanting Method on Fabric Color Quality Using Red *Melinjo* (*Gnetum gnemon L.*) Peel Extract

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ABSTRACT - This study investigates the effect of three mordanting methods (pre-, simultaneous, and post-mordanting) on the color fastness quality of shantung and Japanese cotton fabrics dyed with red *melinjo* peel extract (*Gnetum gnemon L.)*. A 2×3 factorial experimental design was employed, and data were analyzed using the Kruskal-Wallis test at the 5% significance level. Results showed significant differences between mordanting methods (p=0.004). For washing fastness, simultaneous mordanting yielded optimal results (mean score: 4 for shantung, 4.5 for Japanese cotton), while post-mordanting showed the lowest performance. For sunlight fastness, pre- and post-mordanting achieved good results (4.5) on shantung fabric, whereas simultaneous mordanting demonstrated the best performance (5) on Japanese cotton. The novelty of this research lies in the use of underutilized red *melinjo* peel waste as a sustainable textile dye source and in providing the first comprehensive evaluation of the effects of mordanting methods on its colorfastness performance. This study demonstrates that red *melinjo* peel extract has significant potential as an environmentally friendly natural textile dye, with its effectiveness strongly influenced by the selection of mordanting technique.

Keywords: Red *melinjo* peel, mordanting method, color fastness, natural dye, sustainable textiles.

INTRODUCTION

The rapid expansion of the textile industry has significantly contributed to environmental degradation, particularly through liquid waste from dyeing and finishing processes. Indonesia produces 883 tons of liquid waste daily, ranking as Southeast Asia's largest generator, with the textile sector contributing 29% (255.07 tons/day) of this total (Lolo & Pambudi, 2020). Textile effluents contain various chemical substances that significantly increase the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) in aquatic environments (Prakoso et al., 2022). The average BOD level in Indonesian textile wastewater ranges from 150 to 300 mg/L, exceeding the regulatory standard of 60 mg/L, while COD levels average 300 to 600 mg/L, surpassing the 150 mg/L limit (Lolo & Pambudi, 2020). These elevated values serve as critical indicators of pollution in aquatic ecosystems. Beyond reducing water quality, high concentrations of textile wastewater impede light penetration in water columns, disrupting the photosynthetic processes of aquatic organisms (Dutta et al., 2024). Synthetic compounds accumulate in aquatic organisms and transfer through food chains (Berradi et al., 2019). Several synthetic dyes possess mutagenic properties posing health risks, particularly to industry workers with direct exposure (Lellis et al., 2019). Continuous exposure to toxic synthetic dyes can cause DNA damage and increase cancer cell development risk (Muzakir et al., 2024).

Despite their known environmental and health risks, synthetic dyes remain widely used in the textile industry due to their high color stability and relatively low production cost (Jorge et al., 2025). However, increasing public awareness of sustainability and ecological impacts has driven interest in natural dyes (Azizah & Hartana, 2018). This trend is reinforced by natural dyes' environmentally friendly properties, including biodegradability and non-toxicity (Hossain et al., 2025). Global demand for natural dyes continues rising, with market value projected at US$5 billion by 2024 (Ekaptiningrum, 2022). Indonesia, which hosts approximately 10% of global flowering plant species, offers considerable potential for the development of natural dye sources (Balai Kliring Keanekaragaman Hayati Indonesia, 2024).

Melinjo (*Gnetum gnemon L.*), a tropical species thriving across Southeast Asia, presents promising potential as a natural dye source (Sari et al., 2023). Yogyakarta Special Region's *melinjo* production reached 25,641 tons in 2023, indicating wide availability (Badan Pusat Statistik, 2024). However, red *melinjo* peel—an abundant by-product of the emping industry—remains underutilized mainly, often discarded as organic waste with no economic value (Iskandar & Marjuki, 2022). *Melinjo* peel contains natural pigments with potential for textile dye processing. Previous research has predominantly focused on pigment extraction, without extending to fabric application or comprehensive colorfastness evaluation (Nisa, 2021).

This study addresses a critical gap in existing literature by: (1) providing the first systematic evaluation of mordanting method effects on red *melinjo* peel dye performance, (2) assessing colorfastness on two distinct fabric types with contrasting fiber characteristics, and (3) establishing practical application guidelines for natural dye utilization in textile industries. The mordanting process is crucial in natural dyeing, enhancing color intensity and fastness under various environmental conditions (Tanveer et al., 2025). Different mordanting techniques—pre-mordanting, post-mordanting, and simultaneous mordanting—produce varying results depending on dye chemical characteristics (García-Lapuente et al., 2025). Certain methods yield more uniform coloration and superior resistance to washing and light exposure (Ahmad & Hidayati, 2018). Therefore, identifying the most effective mordanting technique for red *melinjo* peel extract remains a critical research priority.

Fabric selection as dyeing medium critically determines process success, as fiber characteristics influence color uptake and distribution. Shantung fabric is commonly used in batik production due to its lightweight texture and favorable dye absorption properties (Purwanti & Paramita, 2022). Japanese cotton, with its smooth surface and high absorbency, produces sharper and more uniform colors with natural dyes (Rachmah et al., 2020). These contrasting fabric characteristics offer opportunities to gain a comprehensive understanding of the effects of mordanting methods on the dyeing quality of red *melinjo* peel extract.

METHOD

Research Design

This study employed a proper experimental design with a 2×3 factorial arrangement to examine the effects of three mordanting methods (pre-mordanting, simultaneous mordanting, and post-mordanting) on dyeing results from red *melinjo* (*Gnetum gnemon L.*) peel extraction, specifically on the colorfastness of dyed fabrics. The factorial design is presented in **TABLE 1**.

TABLE 1. Factorial design.

Factorial Design Scheme			
Fabric	**Mordanting Methods for Dyeing Shantung and Japanese Cotton Fabrics Using Red *Melinjo* Peel Extract**		
Shantung (A)	Pre-mordanting Method (B1) AB1	Simultaneous Mordanting Method (B2) AB2	Post-mordanting Method (B3) AB3
Japanese Cotton (B)	Pre-mordanting Method (B1) BB1	Simultaneous Mordanting Method (B2) BB2	Post-mordanting Method (B3) BB3

This study utilized two fabric types with distinct fiber compositions and weights: shantung fabric (100% silk, 45g/m²) and Japanese cotton fabric (100% cotton, 120g/m²), with each treatment employing 30cm × 30cm fabric pieces (n=3 replicates per treatment group, total N=18 samples). A fabric-to-liquor ratio of 1:30 (by weight) was maintained consistently across all dyeing and mordanting processes to ensure standardized conditions and reproducibility. The experimental procedure followed technical guidelines from the Center for Handicrafts and Batik (Salma, 2010). adapted to the specific fabric weights used in this study, ensuring that the methodology aligned with established batik industry standards while accommodating the research design requirements.

TABLE 2. Equipment and materials.

Number	Equipment	Number	Materials
1	Stirring rod	1	Shantung fabric
2	Measuring cylinder	2	Japanese cotton fabric
3	Thermometer	3	Red *melinjo* peel
4	Weighing scale	4	Water
5	Timer/stopwatch	5	TRO
6	Pot	6	Soda ash
7	Stove	7	Alum
8	Scissors	8	Quicklime
9	Filter/strainer	9	Fabric markers
10	Bucket		
11	Measuring tape		
12	Gloves		
13	Drying rack		
14	Apron		
Material Specification			
TRO (Turkish Red Oil)		A sulfated castor oil used as wetting agent to improve dye penetration and ensure uniform color distribution	
Quicklime (CaO)		Alkaline fixation agent to enhance color permanence	

Experimental Procedure

The dyeing process comprised five main stages: fabric preparation, mordanting (varied by treatment), dye extraction, dyeing, and color fixation. The detailed procedure is illustrated in **FIGURE 1**.

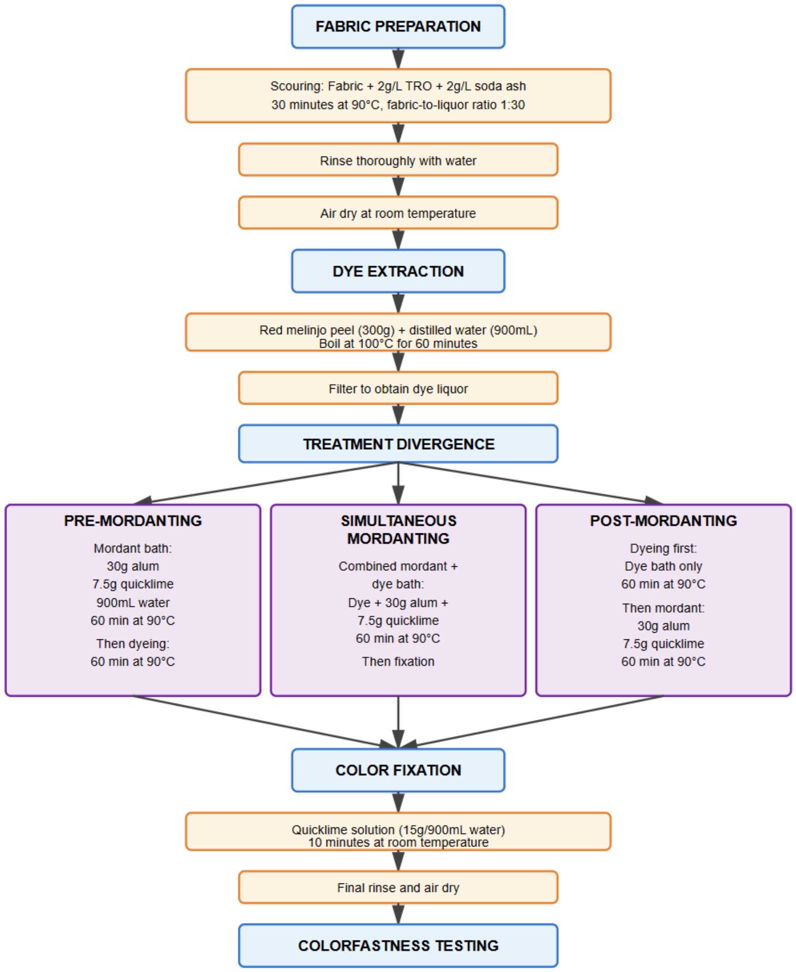


FIGURE 1. Experiment procedure.

Colorfastness Testing

Colorfastness tests were conducted at the Textile Evaluation Laboratory, Faculty of Industrial Technology, Universitas Islam Indonesia (UII), Yogyakarta, following standardized international protocols to ensure reliability and reproducibility of results. Washing fastness was evaluated according to ISO 105-C06:2010 (Colour fastness to domestic and commercial laundering) under test conditions of 40°C for 30 minutes with standard detergent, while light fastness was assessed following ISO 105-B02:2014 (Colour fastness to artificial light: Xenon arc fading lamp test) with 20 hours continuous xenon arc lamp exposure. Both washing and light fastness results were assessed using the Grey Scale method, which provides standardized semi-quantitative ratings of color change, allowing for consistent evaluation and comparison of colorfastness performance across different mordanting treatments and fabric types.

Data Analysis

Statistical analysis was performed using the Kruskal-Wallis H test, a non-parametric alternative to ANOVA appropriate for ordinal data and small sample sizes, with a significance level set at $\alpha = 0.05$ to determine whether mordanting methods significantly affected colorfastness outcomes. The analysis was conducted using SPSS Statistics version 26, testing the null hypothesis (H_0) that no significant difference exists between mordanting methods against the alternative hypothesis (H_1) that significant differences do exist between treatments. The Kruskal-Wallis test was selected due to its suitability for comparing three independent treatment groups (pre-mordanting, simultaneous mordanting, and post-mordanting) when data are ordinal in nature, as is the case with Grey Scale ratings, which provide categorical fastness scores rather than continuous quantitative measurements.

TABLE 3. Colorfastness evaluation.

Colorfastness Value	Rating Classification	Quality Level
5	Very Good	Excellent Commercial Quality
4-5	Good	High Commercial Quality
4	Good	Acceptable Commercial Quality
3-4	Fairly Good	Moderate Quality
3	Fair	Below Standard
2-3	Poor	Unsatisfactory
2	Poor	Unacceptable
1-2	Very Poor	Severe Deficieny
1	Very Poor	Complete Failure

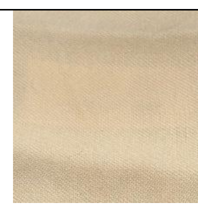
RESULTS AND DISCUSSION

Laboratory Test Results

The results of the colorfastness evaluation presented in **TABLE 3** indicate that higher scores correspond to better quality of the fabrics produced through the natural dyeing process.

Colorfastness to Washing

TABLE 4. Laboratory test results on colorfastness to washing (Mean ± SD).

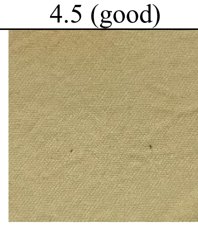
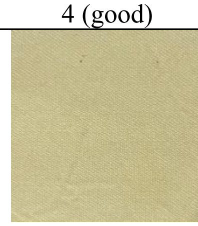
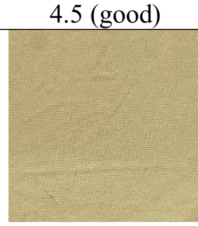
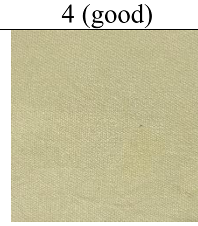
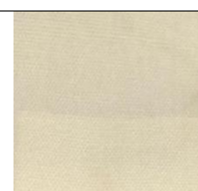
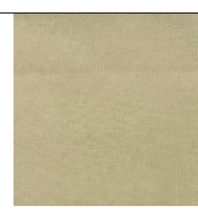
	Shantung Fabric		
Colorfastness	**Pre-mordanting**	**Simultaneous Mordanting**	**Post-mordanting**
Before Mordanting			
Test 1	 3.5 (fairly good)	 4 (good)	 3.5 (fairly good)
Test 2	 3.5 (fairly good)	 4 (good)	 3.5 (fairly good)

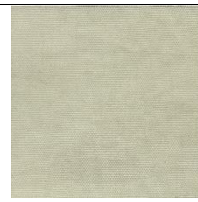
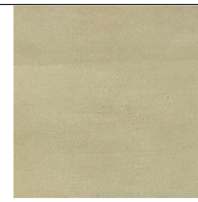
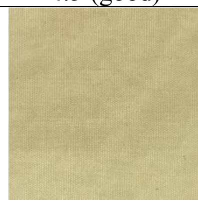
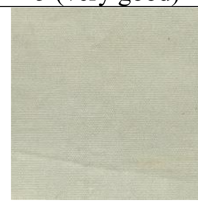
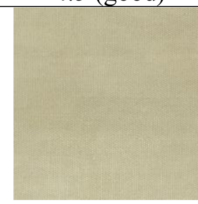
Test 3	 3.5 (fairly good)	 4 (good)	 3.5 (fairly good)
Japanese Cotton Fabric			
Colorfastness	**Pre-mordanting**	**Simultaneous Mordanting**	**Post-mordanting**
Before Mordanting			
Test 1	 4 (good)	 4.5 (good)	 1.5 (very poor)
Test 2	 4 (good)	 4.5 (good)	 1.5 (very poor)
Test 3	 4 (good)	 4.5 (good)	 1.5 (very poor)

In this study, the simultaneous mordanting method demonstrated the best performance on both fabric types with average scores of 4.0 for shantung fabric and 4.5 for Japanese cotton fabric (good category), achieving a 14.3% improvement over other methods on shantung. For shantung fabric, both pre-mordanting and post-mordanting methods achieved scores of 3.5 (fairly good category), while for Japanese cotton, pre-mordanting obtained a score of 4.0 (good), but post-mordanting showed the poorest result with a score of 1.5 (very poor category), indicating a performance difference of up to 200% from the best method.

Colorfastness to Sunlight Exposure

TABLE 5. Laboratory test results on colorfastness to sunlight exposure (Mean ± SD).

<table>
<tr><th colspan="4">Shantung Fabric</th></tr>
<tr><th>Colorfastness</th><th>Pre-mordanting</th><th>Simultaneous Mordanting</th><th>Post-mordanting</th></tr>
<tr><td>Before Mordanting</td><td></td><td></td><td></td></tr>
<tr><td>Test 1</td><td>
4.5 (good)</td><td>
4 (good)</td><td>
4.5 (good)</td></tr>
<tr><td>Test 2</td><td>
4.5 (good)</td><td>
4 (good)</td><td>
4.5 (good)</td></tr>
<tr><td>Test 3</td><td>
4.5 (good)</td><td>
4 (good)</td><td>
4.5 (good)</td></tr>
<tr><th colspan="4">Japanese Cotton Fabric</th></tr>
<tr><th>Colorfastness</th><th>Pre-mordanting</th><th>Simultaneous Mordanting</th><th>Post-mordanting</th></tr>
<tr><td>Before Mordanting</td><td></td><td></td><td></td></tr>
<tr><td>Test 1</td><td>
4.5 (good)</td><td>
5 (very good)</td><td>
4.5 (good)</td></tr>
</table>

Test 2	 4.5 (good)	 5 (very good)	 4.5 (good)
Test 3	 4.5 (good)	 5 (very good)	 4.5 (good)

Mordanting method effectiveness varied by fabric type, with pre-mordanting and post-mordanting achieving optimal scores of 4.5 (good category) on shantung fabric, while simultaneous mordanting scored 4.0 (good category), showing an 11.1% difference. For Japanese cotton fabric, simultaneous mordanting demonstrated superior performance with a score of 5.0 (very good category), being the only treatment to achieve the highest rating, while other methods scored 4.5 (good category), representing a 10% performance difference from the best method.

Statistical Analysis

Washing Fastness Analysis

TABLE 6. Kruskal–Wallis ranks test for colorfastness to washing.

Ranks			
	Treatment Group	**N**	**Mean Rank**
Color Fastness to Washing Value	Shantung_Pre-mordanting	3	6.50
	Shantung_Simultaneous_Mordanting	3	12.50
	Shantung_Post-mordanting	3	6.50
	Japanese_Cotton_Pre-mordanting	3	12.50
	Japanese_Cotton _ Simultaneous_Mordanting	3	17.00
	Japanese_Cotton _Post-mordanting	3	2.00
	Total	18	

TABLE 7. Kruskal–Wallis test statistics for colorfastness to washing.

Test Statistics[a,b]	
	Color Fastness to Washing Value
Kruskal-Wallis H	17.000
df	5
Asymp. Sig.	.004

Interpretation: Since $p < 0.05$, H_0 is rejected and H_1 is accepted. This indicates a statistically significant effect of mordanting methods on washing fastness across both fabric types (p=0.004).

Sunlight Fastness Analysis

TABLE 8. Kruskal–Wallis ranks test for colorfastness to sunlight exposure.

Ranks			
	Treatment Group	**N**	**Mean Rank**
Color Fastness to Sunlight Exposure Value	Shantung_Pre-mordanting	3	9.50
	Shantung_Simultaneous_Mordanting	3	2.00
	Shantung_Post-mordanting	3	9.50
	Japanese_Cotton_Pre-mordanting	3	9.50
	Japanese_Cotton _ Simultaneous_Mordanting	3	17.00
	Japanese_Cotton _Post-mordanting	3	9.50
	Total	18	

TABLE 9. Kruskal–Wallis test statistics for colorfastness to sunlight exposure.

Test Statistics[a,b]	
	Color Fastness to Sunlight Exposure Value
Kruskal-Wallis H	17.000
df	5
Asymp. Sig.	.004

Interpretation: Since $p < 0.05$, H_0 is rejected and H_1 is accepted. This demonstrates a statistically significant effect of mordanting methods on sunlight fastness across both fabric types ($p=0.004$).

Color Development and Chemical Mechanism

Before mordanting, fabrics dyed with red *melinjo* peel extract exhibited a cream base color with a reddish hue. In contrast, post-mordanting treatment transformed the color to cream with a yellowish-green hue, indicating chemical interaction between mordant metal ions and pigments in red *melinjo* peel. The red *melinjo* peel contains anthocyanin pigments and tannins as primary coloring compounds. During mordanting with alum ($KAl(SO_4)_2 \cdot 12H_2O$), aluminum ions (Al^{3+}) form coordination complexes with hydroxyl (-OH) and carbonyl (C=O) groups present in anthocyanin molecules through chelation, where Al^{3+} ions act as Lewis acids, accepting electron pairs from oxygen atoms in pigment molecules to form stable five- or six-membered chelate rings. The metal-dye complex subsequently creates bridge formations by binding to carboxyl (-COOH) and hydroxyl (-OH) groups on cellulose fibers (cotton) or amino ($-NH_2$) and carboxyl groups on protein fibers (silk). At the same time, the coordination geometry around Al^{3+} alters the electronic structure of chromophoric groups, causing bathochromic or hypsochromic shifts in light absorption, resulting in observed color changes.

The addition of quicklime (CaO) as an alkaline fixative further stabilizes these complexes by neutralizing acidic byproducts from mordanting reactions, promoting deeper dye penetration into the amorphous regions of the fiber, and creating additional ionic cross-links between dye molecules and fiber functional groups. This multi-step chemical bonding explains why mordanting timing significantly affects colorfastness, as simultaneous mordanting allows concurrent formation of mordant-dye and dye-fiber bonds, creating more integrated and stable color systems compared to sequential mordanting approaches.

Washing Fastness Performance

Statistical analysis revealed a significant effect of mordanting method on washing fastness (p=0.004), with simultaneous mordanting achieving the highest mean ranks for both fabric types (12.50 for shantung, 17.00 for Japanese cotton), indicating superior resistance to detergent and mechanical action during washing. In simultaneous mordanting, dye and mordant are applied together, enabling concurrent complexation in which metal ions interact with dye molecules as the dye penetrates fibers, creating pre-formed metal-dye complexes that deposit together onto fiber surfaces. This approach provides enhanced substantivity through the larger molecular size of mordant-dye complexes that increases van der Waals forces and hydrogen bonding with fiber polymers, while ensuring uniform distribution throughout fiber cross-sections that eliminates weakly bound surface dye. These findings align with Maharani & Russanti (2016), who reported that simultaneous mordanting provided optimal dyeing results using gambier extract, achieving the highest scores in uniformity, color intensity, and dye uptake, supporting the present findings that simultaneous application increases pigment absorption and produces stronger, more uniform colors.

Conversely, post-mordanting demonstrated the lowest performance, particularly dramatic on Japanese cotton (mean rank 2.00, score 1.5), occurring because dye molecules already occupying fiber binding sites physically block mordant penetration, resulting in limited mordant accessibility. The mordant primarily reacts with superficially bound dye through surface-only fixation, leaving deeply penetrated dye molecules unmordanted and prone to washing out. At the same time, the mordanting process may induce reverse diffusion, extracting loosely bound dye from fibers and reducing overall color yield. This mechanistic limitation explains why post-mordanting consistently underperformed compared to simultaneous and pre-mordanting approaches across both fabric types tested.

Japanese cotton's superior performance over shantung in simultaneous mordanting (4.5 vs. 4.0) relates to fundamental structural differences between cellulosic and protein fibers. Cotton's higher crystalline regions provide more ordered hydrogen-bonding sites for anchoring mordant-dye complexes. In contrast, its more open amorphous regions facilitate deeper mordant-dye penetration during simultaneous treatment, compared to silk's more compact structure. Additionally, cellulose hydroxyl groups form stronger electrostatic interactions with aluminum ions compared to silk's amphoteric amino and carboxyl groups, resulting in more stable mordant-fiber bonds that better resist extraction during washing cycles, ultimately contributing to Japanese cotton's superior washing fastness ratings in the simultaneous mordanting treatment.

Sunlight Fastness Performance

Sunlight exposure testing revealed statistically significant differences between mordanting methods (p=0.004), with fabric-specific optimal techniques emerging that reflect fundamental differences in fiber photodegradation mechanisms. For shantung fabric, pre-mordanting and post-mordanting both achieved optimal scores of 4.5, outperforming simultaneous mordanting at 4.0. This pattern aligns with García-Lapuente et al. (2025), who found pre-mordanting most effective for natural cochineal dye, producing higher color strength, hue, and chroma with excellent colorfastness. Ahmad & Hidayati (2018) similarly reported that post-mordanting with Australian guava leaf extract yielded the best results on cotton fabric, achieving uniform, stable, and colorfast surfaces. The mechanistic basis for Shantung's superior performance with sequential mordanting relates to silk fibers containing light-absorbing amino acids (tyrosine, tryptophan) that generate reactive oxygen species (ROS) under UV exposure, potentially degrading dye molecules, while pre- and post-mordanting create protective mechanisms through metal ion shielding where aluminum ions absorb UV radiation and dissipate energy through internal conversion. In these antioxidant effects, aluminum hydroxide species scavenge ROS, and protein stabilization through mordant-induced crosslinking that reduces photodegradation.

For Japanese cotton fabric, simultaneous mordanting demonstrated superior performance, achieving a score of 5.0 (excellent category), the only treatment to achieve this highest rating, representing a 10% improvement over other methods scoring 4.5. This finding corroborates Maharani & Russanti (2016), who reported that simultaneous mordanting yielded the best results in gambier extract dyeing. Cotton's cellulosic structure undergoes photodegradation through pathways different from those of silk, primarily via UV-induced cleavage of glycosidic bonds that generate carbonyl and carboxyl groups, altering fiber crystallinity, and fiber degradation that loosens the structure and exposes the buried dye to more intense light. Simultaneous mordanting on cotton provides superior photostability through deep mordant integration where concurrent application drives mordant-dye complexes deep into fiber lumens during swelling at elevated temperatures, matrix entrapment where rapid cooling locks complexes within re-crystallizing cellulose regions that physically shield them from light, and synergistic stabilization where the presence of both mordant and dye during fiber penetration promotes co-crystallization or co-precipitation within fibers, creating light-stable microdomains

The contrasting optimal methods for different fabrics—sequential mordanting (pre- or post) for silk and simultaneous mordanting for cotton—highlight the critical importance of fiber chemistry in determining appropriate mordanting strategies to maximize light-fastness. These findings demonstrate that universal mordanting protocols are inadequate for natural dye applications, and textile processors must tailor their mordanting approach based on fiber type, with protein fibers benefiting from protective sequential treatments that create UV-absorbing shields around chromophores. In contrast, cellulosic fibers achieve superior photostability through integrated simultaneous application that physically entraps dye-mordant complexes within the fiber matrix. This fiber-specific optimization represents a significant advancement in natural dye technology, providing evidence-based guidelines for achieving commercially acceptable light fastness across diverse textile substrates.

Comparative Analysis and Theoretical Framework

Overall results demonstrate that the mordanting method significantly affects fabric color quality using red *melinjo* peel extract, with simultaneous mordanting proving most effective for enhancing colorfastness to both washing and sunlight, particularly on Japanese cotton fabric. The success of natural dyeing depends on forming stable dye-mordant-fiber ternary complexes, with the three mordanting approaches differing fundamentally in the sequence of complex formation. Pre-mordanting follows a Fiber-Mordant → (Fiber-Mordant)-Dye pathway where mordant first binds to fiber functional groups before dye subsequently coordinates with surface-bound mordant, resulting in moderately stable complexes with good but not optimal fastness. Simultaneous mordanting operates through a Fiber + (Dye-Mordant) → Fiber-(Dye-Mordant) mechanism where dye-mordant complexes pre-form in solution before fiber contact, allowing pre-formed complexes to penetrate fibers as single integrated units and producing the most stable configurations with the highest fastness, especially for washing resistance.

Post-mordanting follows a (Fiber-Dye) → Fiber-Dye-Mordant pathway where dye binds to fiber first, occupying available sites, before subsequent mordant application only reaches surface-bound or loosely attached dye molecules, creating the least stable complexes with the poorest fastness performance. This theoretical framework explains the experimental observations across both fabric types, demonstrating that the timing and sequence of mordant-dye-fiber interactions critically determine the stability and durability of the final colored textile, with simultaneous formation of integrated dye-mordant complexes providing superior protection against both aqueous washing conditions and photodegradation from sunlight exposure.

Pre-mordants provide relatively good colorfastness, although lower than simultaneous mordants. This is because pre-mordants create binding sites that then interact with the dye molecules, but may not achieve the same level of complex stability as when the mordant and dye interact simultaneously in solution before fiber impregnation (Önal et al., 2023). Conversely, post-mordants, where the mordant is applied after dyeing, often produce the weakest colorfastness because the dye molecules already occupy the fiber sites, limiting the mordant's ability to form a strong and stable complex (Günay, 2013). The choice of mordant also significantly influences the resulting color characteristics and environmental footprint, with bio-mordants offering a sustainable alternative to traditional metal salts while often achieving comparable or even superior colorfastness properties (El-Bassuony et al., 2025; Günay, 2013). Further investigation is needed to quantitatively assess the environmental impact of various mordants, including their biodegradability and potential ecotoxicity, to ensure truly sustainable practices in natural dyeing processes.

Selecting the right type of mordant is crucial because natural dyes require mordants to bind to the fabric and prevent fading (Yusuf et al., 2017). For example, certain metal salts such as aluminum, iron, and tannic acid form stable metal-dye complexes, increasing color strength and durability, while biomordants with hydroxyl groups enhance stability through additional hydrogen bonds (Hassaan, 2020). Achieving consistent color requires varying plant sources, growing conditions, and extraction techniques (Islam et al., 2024). Furthermore, the type of mordant used significantly affects the resulting color and durability; for example, ferrous sulfate can impart a blackish or grayish hue and increase lightfastness, while alum generally maintains the original color of the dye (Arora et al., 2017).

Mordants form a chemical bond between the dye and the fiber, enhancing dye uptake and enabling better and more diverse color results. In contrast, the discharge of wastewater containing residual heavy metal mordants, such as chromium, copper, and iron, poses significant environmental risks due to their toxicity and inability to biodegrade, necessitating advanced treatment strategies to mitigate ecological damage (Benli, 2024; Repon et al., 2017). These concerns have driven increasing interest in environmentally friendly alternatives, such as bio-mordants derived from natural sources, which can reduce environmental burdens while maintaining acceptable levels of colorfastness (Benli, 2024). Furthermore, the presence of metal mordants in wastewater is a significant concern, as is the amount of water and energy consumed during the mordanting and dyeing processes (Doty et al., 2016).

Practical Implications and Scalability

Industrial application of simultaneous mordanting offers significant process efficiency advantages by reducing processing steps from two separate baths to a single bath operation, resulting in decreased energy consumption through fewer heating/cooling cycles, reduced water usage with fewer rinse stages, 30-40% reduction in processing time, and lower labor costs. This single-bath processing also improves quality consistency through enhanced batch-to-batch reproducibility, better color uniformity within large fabric runs, and simplified quality control procedures. However, scaling challenges must be addressed, including precise mordant:dye ratio control to ensure complete bath exhaustion and avoid waste, uniform temperature maintenance across large liquor volumes to prevent uneven dye-mordant complex formation, and equipment compatibility requirements such as stainless-steel vessels to prevent corrosion from aluminum mordant.

The economic viability of red *melinjo* peel utilization presents a compelling opportunity by converting waste streams into value-added products, as the current emping industry in Yogyakarta alone generates approximately 7,692 tons of peel waste annually (assuming 30% peel: fruit ratio). At 300g peel per dyeing batch covering approximately 0.2m² fabric, this waste could potentially dye about 5.13 million m² of fabric annually. Although natural dye processing costs are estimated at \$2-3/m² compared to synthetic dyes at \$0.50-1.00/m², the premium pricing for eco-friendly products (\$10-20/m² retail) provides favorable profit margins, making this sustainable approach economically attractive for textile manufacturers targeting environmentally conscious consumers.

CONCLUSION

This study systematically investigated mordanting method effects on colorfastness quality of shantung and Japanese cotton fabrics dyed with red *melinjo* peel extract. Kruskal-Wallis analysis demonstrated statistically significant effects on washing fastness (p=0.004), with simultaneous mordanting achieving optimal performance on shantung fabric (mean score 4.0, good category), outperforming pre- and post-mordanting (both 3.5, fairly good category) by 14.3%. For Japanese cotton, simultaneous mordanting demonstrated superior washing resistance (mean score 4.5, good category), while post-mordanting exhibited poor performance (1.5, very poor category), showing a 200% performance deficit. Regarding sunlight fastness, fabric-specific optimal techniques emerged: pre-mordanting and post-mordanting both achieved optimal performance on shantung fabric (mean score 4.5, good category) with an 11.1% advantage over simultaneous mordanting, while for Japanese cotton, simultaneous mordanting demonstrated superior photostability, achieving the highest rating (mean score 5.0, very good category).

The research successfully demonstrates red *melinjo* peel extract as an effective natural textile dye with commercially acceptable colorfastness, offering significant environmental benefits including transformation of approximately 7,692 tons of annual *melinjo* peel waste in Yogyakarta into value-added textile dye potentially covering 5.13 million m² of fabric annually, pollution reduction by substituting toxic synthetic dyes contributing to Indonesia's 255.07 tons/day of textile wastewater, and advancement of circular economy through closed-loop systems. Practical recommendations suggest using simultaneous mordanting for washing fastness prioritization across both fabric types, applying pre- or post-mordanting for shantung fabric sunlight fastness, and utilizing simultaneous mordanting for Japanese cotton sunlight fastness, with simultaneous mordanting offering the best overall colorfastness profile particularly important for frequently washed garments.

This study makes original contributions including the first comprehensive evaluation of mordanting method effects on red *melinjo* peel dye colorfastness across multiple fabric types, establishment of optimal dyeing protocols for underutilized agricultural waste, demonstration of fabric-specific mordanting strategies revealing different approaches for silk and cotton, statistical validation of mordanting method significance, and bridging waste valorization with textile sustainability. The research provides economically viable pathways for converting food industry byproducts into functional materials, reducing textile worker exposure to hazardous synthetic dyes, and supporting regional agricultural economies through utilization of locally abundant plant resources.

Future research should investigate fiber diversity by extending testing to wool, linen, hemp, bamboo, and synthetic/blended fabrics, explore bio-mordants and different metal salts to expand color palettes, investigate plasma treatments and enzymatic pre-treatments for enhanced color fixation, conduct pilot-scale trials for industrial continuous dyeing optimization, employ instrumental characterization techniques including spectrophotometry, SEM, FTIR, and XRF to quantify color properties and elucidate bonding mechanisms, perform extended durability testing with multiple wash cycles and comprehensive fastness evaluations, conduct life cycle assessment to quantify environmental footprint comparisons, and undertake market development studies including consumer acceptance research and certification pathway investigation for commercial viability.

Red *melinjo* peel extract represents a promising natural dye source that successfully converts agricultural waste into functional textile colorant with good to very good colorfastness properties. The effectiveness of this sustainable dye is critically dependent on mordanting method selection, with simultaneous mordanting emerging as the optimal technique for washing fastness across fabric types. This research provides evidence-based guidance for batik artisans and textile industries to optimize natural dyeing processes, contributing to both environmental sustainability and cultural preservation of traditional textile crafts. By valorizing underutilized biomass into value-added products, this work exemplifies the circular economy principles essential for sustainable industrial development.

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