

Taguchi-Based Optimization of Cotton Fabric Dyeing Using Monascus Pigments

Margono Margono^{*,1}

Ajeng Kamilah¹

Raihan Naufal Widian¹

Ainur Rosyida²

¹ Chemical Engineering Department, Faculty of Engineering, Universitas Sebelas Maret, Jl. Ir. Sutami 36A, Jebres, Surakarta, Indonesia 57126

² Department of Mechanical Engineering, Faculty of Engineering, Sekolah Tinggi Teknik Warga, Surakarta, Jl. Raya Solo-Baki, Km. 2, Sukoharjo, Indonesia 57552

*e-mail: margono@ft.uns.ac.id

Submitted 12 April 2025

Revised 21 April 2026

Accepted 16 July 2026

Abstract. The application of monascus pigments as natural dyes in textile dyeing is limited by low color intensity, poor washing fastness, and the need for repeated immersion. In addition, systematic optimization of dyeing parameters and the reusability of dye solutions have received limited attention. This study aims to systematically optimize the dyeing process of cotton fabric with anka extract (monascus pigments) using a single-immersion method, employing a Taguchi experimental design and multi-response signal-to-noise (MRSN) analysis. The effects of immersion time, mordant type, mordant concentration, sodium chloride concentration, and solution pH on color strength and fastness properties were evaluated. The results showed that immersion time, mordant type, mordant concentration, and pH significantly affected color strength, while sodium chloride concentration had a negligible effect. The optimal dyeing condition yielded a maximum color strength (K/S) of 2.43 at 120 minutes of immersion time, 25 g/L poly aluminum chloride (PAC), 20 g/L NaCl, and pH 10. The fastness results indicated good rubbing resistance but relatively low washing fastness. Furthermore, the dye solution demonstrated reusability with only a slight reduction in color intensity, indicating its potential to improve process efficiency and sustainability. This study provides a systematic, efficient optimization framework for monascus pigment-based dyeing and contributes to the development of a more practical, sustainable natural dyeing process.

Keywords: Anka Extract, Cotton Fabric, Dyeing Process, Monascus Pigments, Optimization, Taguchi Method

INTRODUCTION

Synthetic dyes, predominantly derived from petrochemical sources, contribute significantly to environmental pollution through toxic and non-biodegradable wastewater and may pose risks to human

health (Holkar *et al.*, 2016; Kant, 2012; Negi, 2025). In contrast, natural dyes derived from renewable biological resources, such as plants, animals, or microorganisms, are generally biodegradable, less toxic, and environmentally friendly, making them attractive for sustainable textile applications

(Dey *et al.*, 2025; Shahid *et al.*, 2013). These concerns have driven increasing interest in natural colorants as sustainable alternatives (Kant, 2012; Shahid *et al.*, 2013). Furthermore, natural dye-based batik has attracted increasing attention due to its distinctive aesthetic qualities, including natural, ethnic, and exclusive visual impressions that enhance its cultural and commercial value (Pujilestari, 2017).

Various sources of natural dyes have been used in dyeing cotton fabric in the process of making batik cloth, including jackfruit wood extract (Rosyida *et al.*, 2022), *Acalypha wilkesiana* (Rehman *et al.*, 2021), waste from eucalyptus steaming (Rossi *et al.*, 2017), nettle leaf extract (Ketema and Worku, 2023), and turmeric powder (Alam *et al.*, 2022). Among them, microbial pigments have emerged as a promising alternative due to their rapid, scalable, and consistent production under controlled conditions (Daud *et al.*, 2021; Venil *et al.*, 2020). One of the most widely studied microbial pigments is monascus pigments extracted from anka (red yeast rice), produced by *Monascus* sp. through fermentation. Monascus pigments have been widely used as food colorants, especially in traditional fermentation systems, and have been reported to possess diverse bioactive properties, including antioxidant and anticancer activities (Chen *et al.*, 2015; Kim and Ku, 2018).

The monascus pigments compositions contain yellow pigment consisting of monascin ($C_{21}H_{26}O_5$) and ankaflavin ($C_{23}H_{30}O_5$), orange pigment consisting of monascorubrin ($C_{23}H_{26}O_5$) and rubropunctatin ($C_{21}H_{22}O_5$), and red pigment consisting of monascorubramine ($C_{23}H_{27}NO_4$) and rubropuntamine ($C_{21}H_{23}NO_4$), which contribute to its potential application as a textile dye (Dong *et al.*, 2024; Zhang *et al.*,

2024). The structural formulas of each chemical are shown in Fig. 1.

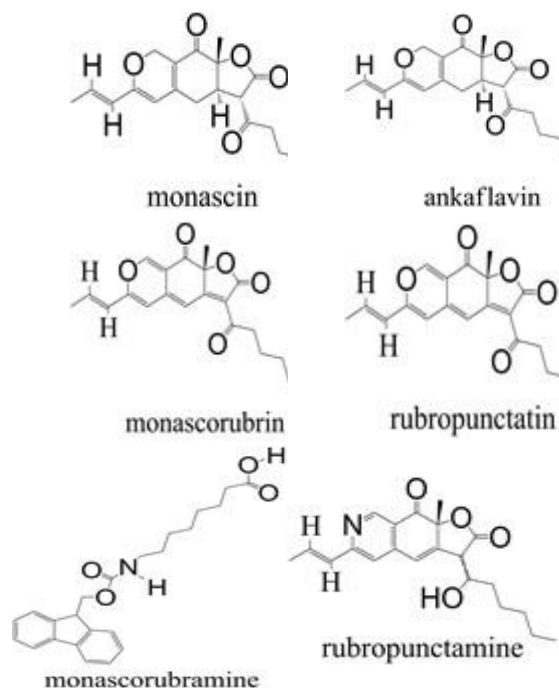


Fig. 1: The structural formulas of some metabolites contained in monascus pigments

Several studies have investigated the application of monascus pigments in textile dyeing, particularly on cotton fabrics, while broader reviews have also highlighted their potential in textile applications (Velmurugan *et al.*, 2013; Venil *et al.*, 2020; Xie *et al.*, 2024). However, several studies have reported limitations, including relatively low color intensity and challenges in achieving consistent color performance, particularly under different dyeing conditions and mordant systems (De Santis *et al.*, 2005; He *et al.*, 2022). Furthermore, most previous studies have primarily evaluated individual dyeing parameters, with limited attention to the systematic optimization of multiple interacting factors. These parameters, including immersion time, mordant type and concentration, and pH, are known to influence dye uptake and fixation in textile

dyeing systems significantly (Adeel *et al.*, 2019; Failisnur *et al.*, 2018; Ketema and Worku, 2023). From a chemical engineering perspective, these parameters influence dye uptake through mass transfer and diffusion, as well as through fiber interactions during mordant-assisted dyeing (Swami *et al.*, 2014).

Process optimization plays a crucial role in improving dyeing performance while reducing resource consumption and processing time. Optimization approaches such as Response Surface Methodology (RSM) have been widely applied in textile dyeing studies to evaluate the effects and interactions among multiple variables (Evitasari *et al.*, 2019; Ketema and Worku, 2023). Recent studies have demonstrated that RSM enables systematic optimization of dyeing parameters, leading to improved color intensity and, in some cases, enhanced fastness properties in natural dyeing systems (Adham *et al.*, 2025; Eren *et al.*, 2025). However, these methods often require a relatively large number of experimental runs, particularly when multiple factors and levels are involved.

In contrast, the Taguchi method provides a more efficient experimental design by employing orthogonal arrays to evaluate multiple parameters with fewer experiments while maintaining statistical robustness. This method has been widely applied in textile process optimization to reduce experimental cost and time, while enabling the identification of significant factors affecting process performance (Oguz and Akarslan, 2022; Pervez *et al.*, 2023; Wahyudin *et al.*, 2018). Its application in textile dyeing has also been reported to optimize dyeing parameters and improve dye uptake and color strength (Vidhya *et al.*, 2024). Nevertheless, most of these studies have focused on plant-based natural dyes, and their application to

microbial pigments, particularly monascus pigments, remains limited.

Although monascus pigments have been used in textile dyeing, previous studies have primarily investigated conventional batch dyeing processes with limited focus on systematic optimization strategies (Mauliza *et al.*, 2016; Velmurugan *et al.*, 2013). While several process parameters, such as temperature, time, and pH, have been examined, the application of structured multi-factor optimization methods remains limited in monascus pigment-based dyeing systems. Furthermore, although both color strength and fastness properties have been evaluated, their simultaneous optimization under a single-immersion framework has not been systematically explored. In addition, the reusability of monascus pigment solution, which is crucial for improving process efficiency and reducing operational costs in natural dyeing systems, has received limited attention. These gaps highlight the need for a more systematic and efficient optimization approach to enhance dyeing performance while reducing process complexity.

This study aims to systematically optimize the dyeing process of cotton fabric with monascus pigments via a single-immersion method, employing Taguchi experimental design and multi-response signal-to-noise (MRSN) analysis. The effects of key process parameters, including immersion time, mordant type, mordant concentration, sodium chloride concentration, and solution pH, were analyzed in relation to color strength and fastness properties. Furthermore, the reusability of the dyeing solution was assessed to evaluate its potential to improve process efficiency and sustainability. This work provides a process-oriented framework for monascus pigment-based dyeing and

contributes to the development of a more efficient and practical natural dyeing system.

MATERIALS AND METHOD

Materials

Monascus Pigments

The monascus pigments were a solution of extracted red yeast rice (anka) in water. The local anka powder, a brand of Herbadream, was used and obtained from Surakarta, Indonesia.

Cotton Fabric

The cotton fabric used in these experiments was a Primiissima brand, produced by PT Primatexco, a local textile industry in Jawa Tengah, Indonesia. Its specification was 105 g/m² (warp: 155, weft: 73).

Mordant Chemicals

The chemicals used as the mordant were technical grade and consisted of aluminum sulfate (Al₂(SO₄)₃) containing 3.5% Al₂O₃, poly aluminum chloride (PAC) containing 30% Al₂O₃, calcium oxide (CaO), and a natural mordant of simplokos leaf.

Supporting Chemicals

The supporting chemicals included acetic acid (CH₃COOH, analytical grade), sodium hydroxide (NaOH, analytical grade), sodium chloride (NaCl, ≥99%, analytical grade), surfactant (technical grade), and soap (technical grade). All chemicals were used without further purification.

Method

Preparation of Dyeing Solution of Anka

Ninety grams of anka powder were dissolved in 600 mL of deionized water at room temperature, with continuous agitation

for 15 minutes. The solution was filtered, and the filtrate was used as the dyeing solution after adjustment to the desired pH with CH₃COOH or NaOH. Sodium chloride (NaCl) was added to the solution at concentrations specified in the dyeing recipe, i.e., 10, 15, 20, or 25 g/L.

Preparation of Mordant Solution

The mordant solution was prepared by weighing the mordant chemical at 15, 20, 25, or 30 g/L, as specified in the dyeing recipe, and mixing it with demineralized water at room temperature while agitating to obtain a homogeneous solution.

Dyeing Process Experiment

The cotton fabric (40x50 cm) was soaked for 15 minutes at room temperature in a wetting solution containing 1 g turkey red oil (TRO) in 100 mL demineralized water. The wetted fabric was drained and immersed in the dyeing solution for the duration specified by the dyeing recipe, which could be 100, 120, 140, or 160 minutes. The dyed cotton fabric was drained and soaked in a mordant solution for 60 minutes. Finally, the fabric was drained and dried in the sun.

Design of Experimental Set-Up

The experimental design employed an orthogonal L16 (4⁵) matrix with five factors at four levels. Five independent variables were investigated as controlling factors: immersion time, mordant type, mordant concentration, salt (sodium chloride) concentration, and pH of the dyeing solution. The controlling factor levels and the orthogonal array of L16 (4⁵) are presented in Tables 1 and 2, respectively. Table 2 lists the combination of factors in each experiment, called the experimental recipe. Each experiment was conducted in triplicate.

Table 1. Factors and levels in the experiments

Level	Immersion Time (minutes)	Mordant Type	Mordant concentration (g/L)	Sodium chloride Concentration (g/L)	Dyeing Solution pH
	A	B	C	D	E
1	100	Al ₂ (SO ₄) ₃	15	10	4
2	120	PAC	20	15	Original
3	140	CaO	25	20	8
4	160	Simplokos	30	25	10

Table 2. Recipes of the dyeing experiments

Exp.	A	B	C	D	E
1	100	Al ₂ (SO ₄) ₃	15	10	4
2	100	PAC	20	15	Original
3	100	CaO	25	20	8
4	100	Simplokos	30	25	10
5	120	Al ₂ (SO ₄) ₃	20	20	10
6	120	PAC	15	25	8
7	120	CaO	30	10	Original
8	120	Simplokos	25	15	4
9	140	Al ₂ (SO ₄) ₃	25	25	Original
10	140	PAC	30	20	4
11	140	CaO	15	15	10
12	140	Simplokos	20	10	8
13	160	Al ₂ (SO ₄) ₃	30	15	8
14	160	PAC	25	10	10
15	160	CaO	20	25	4
16	160	Simplokos	15	20	Original

Parameter Tests

The parameter tests of the dyed fabrics were color strength (color values) and fastness tests. Color strength (K/S) and fastness properties were selected as response variables because they are widely recognized indicators of dyeing performance based on standardized textile quality assessments (SNI ISO 105-C06:2010 and SNI 0288:2008). A spectrophotometer (Datacolor 600 Spectrophotometer, USA) and a D65 illuminant with a 10° standard observer were used to assess the color values of the dyed fabrics. The absorbances of the dyed fabric were measured over the wavelength range, $\lambda = 360\text{--}740$ nm. The L, a*, and b* represent lightness, redness-greenness of color, and

yellowness-blueness of color. The relative color strength of the dyed fabrics, expressed as K/S, was measured using the light reflectance technique and the Kubelka–Munk Equation, $K/S = (1-R^2)/2R$ (Kubelka, 1954). At the same time, the fastness tests for washing and rubbing were determined according to Indonesian standard test methods SNI ISO 105-C06:2010 and SNI 0288:2008, respectively.

Data Analysis of Taguchi Experiment

The Taguchi optimization in this study employed the signal-to-noise (S/N) ratio to evaluate the robustness of the dyeing process against variations in process parameters. For color strength (K/S), the

"larger-is-better" criterion was applied, as higher K/S values indicate improved dye uptake. The S/N ratio was calculated using a Taguchi method, as shown in Eq. (1) (Taguchi *et al.*, 1989).

$$\frac{S}{N} (dB) = -10 \log_{10} \left(\frac{1}{n} \sum \frac{1}{y_i^2} \right) \quad (1)$$

For the fastness tests, including washing and rubbing, the "smaller-is-better" criterion was applied, as lower color difference values indicate better color stability and resistance to fading or staining. The S/N ratio for the smaller-is-better criterion was calculated based on the Taguchi method, as shown in Eq. (2) (Taguchi *et al.*, 1989)

$$\frac{S}{N} (dB) = -10 \log_{10} \left(\frac{1}{n} \sum y_i^2 \right) \quad (2)$$

where y_i represents the observed response value, and n is the number of experimental repetitions. The main effects of each factor were determined by averaging the S/N ratios at each level of the corresponding factor.

To obtain a single optimum condition that simultaneously accounts for all responses, a multi-response signal-to-noise (MRSN) analysis was performed. Each S/N ratio was normalized to a common range of 0–1 using Eq. (3).

$$X_{ij}^* = \frac{SN_{ij} - SN_{j,min}}{SN_{j,max} - SN_{j,min}} \quad (3)$$

where SN_{ij} is the S/N ratio of response j in experiment i , and $SN_{j,min}$ and $SN_{j,max}$ are the minimum and maximum S/N ratio values of response j across the 16 trials. The normalized S/N ratios were then combined into a single composite index, the MRSN index, using a weighted-sum approach (Eq. (4)).

$$MRSN_i = \sum_j W_j X_{ij}^* \quad (4)$$

where W_j is the weight assigned to response

j ($\sum W_j = 1$), a weight of 0.6 was assigned to K/S, reflecting its role as the primary indicator of dyeing performance, while the remaining four fastness responses were each assigned a weight of 0.1 to ensure that fabric durability characteristics remained represented in the optimization. The average MRSN value was calculated for each factor level, and the delta (difference between the highest and lowest level average) was used to rank the relative influence of each factor. The factor-level combination that yielded the highest average MRSN value was selected as the single optimal dyeing condition.

Each experiment was conducted in triplicate to ensure reproducibility, and the average values were used for further analysis. Statistical analysis was performed using analysis of variance (ANOVA) to evaluate the significance of each process parameter on the response variables, including color strength (K/S) and fastness properties. The ANOVA was conducted at a 95% confidence level ($\alpha = 0.05$), and a factor was considered statistically significant when the p -value was less than 0.05.

RESULTS AND DISCUSSION

The single-immersion dyeing process resulted in variations in color strength influenced by several process parameters, including immersion time, mordant type and concentration, and solution pH. In contrast, sodium chloride concentration showed a negligible effect on color strength. The fastness tests also yielded varying results, with good rubbing fastness (SS: 4–5) and poor washing fastness (GS: 1–2).

Color Strength

The dyeing process produced a range of hues from light red to yellow, with variations

in color strength. These variations were confirmed by spectrophotometric analysis using the Datacolor 600, as presented in Table 3.

Table 3 shows that the color strength due to dyeing varies from experiment to experiment. It is indicated by the K/S value, which quantifies the amount of pigment absorbed by the fabric. The statistical significance of these variations was evaluated using ANOVA ($\alpha = 0.05$), and the results are presented in Table 4.

Table 3. Color directions and the color strength of the dyed cotton fabric

Exp.	L	a*	b*	K/S	Colour Obtained
1	82.06	8.03	19.21	1.423	
2	79.37	9.00	22.89	2.156	
3	88.29	3.80	9.55	1.881	
4	86.06	1.28	34.92	1.817	
5	82.49	6.82	35.86	2.031	
6	79.30	10.36	27.82	1.957	
7	86.26	3.53	19.76	1.716	
8	87.74	-0.99	36.68	1.613	
9	82.31	6.99	34.30	1.843	
10	87.55	-0.63	31.81	1.617	
11	89.73	-1.06	21.58	1.624	
12	81.05	8.74	42.51	1.807	
13	79.37	8.67	31.61	1.637	
14	78.94	10.75	43.16	2.384	
15	88.73	2.06	13.40	1.269	
16	83.53	2.43	41.33	1.963	

The test results (Table 4) show that immersion time (A), mordant type (B), mordant concentration (C), and pH of the dyeing solution (E) all have significant effects

($p < 0.05$) on the color strength of the fabric. In contrast, the sodium chloride concentration (D) has no significant effect ($p > 0.05$). The fourteenth dyeing recipe, with a K/S of 2.384, yields the most robust color. The next test, the SN-Ratio test using "larger is better" criteria, determines the optimal factors for maximum color strength. The outcomes are shown in Table 5.

Table 5 shows that the optimum experiment recipe for dyeing is A2B2C3D3E4, with a K/S value of 2.43. The highest color strength was obtained with a 120-minute immersion time, 25 g/L PAC, 20 g/L sodium chloride, and a solution pH of 10.

Table 4. P-value of ANOVA Analysis

Table 1. Value of ANOVA Analysis					
Factor	K/S	Washing Fastness		Rubbing Fastness	
		GS	SS	Dry (SS)	Wet (SS)
	P - value				
A	0.044	0.000	0.918	0.045	0.000
B	0.049	0.000	0.906	0.002	0.000
C	0.025	0.000	0.396	0.001	0.000
D	0.080	0.313	0.320	0.001	0.000
E	0.011	0.112	0.761	0.000	0.000

Note: GS: grayscale; SS: staining scale

Table 5. Results of the SN-ratio test on the color strength

Level	Factor				
	A	B	C	D	E
1	5.102	4.702	4.742	5.109	3.096
2	5.208	6.057	5.010	4.830	5.341
3	4.709	4.115	5.624	5.420	5.186
4	4.94	5.085	4.582	4.60	5.774
Delta:	0.499	1.942	1.042	0.820	2.678
Rank:	5	2	3	4	1
Optimum Factors: A2B2C3D3E4					

Immersion time (factor A) affects color strength: longer immersion increases color intensity to an optimal point, after which further immersion decreases it. Extended

immersion allows the pigment to be adsorbed and bonded to the fabric, resulting in a more intense color. However, when the optimum is reached, pigment adsorption ceases, and pigment desorption occurs, resulting in lower color intensity. This behavior can be explained by mass transfer and adsorption equilibrium, where prolonged contact time enhances pigment diffusion into the fiber matrix until equilibrium is reached, after which desorption may occur. Velmurugan *et al.* (2013) reported that immersion time significantly affects color strength under different mordant conditions. Nagia and EL-Mohamedy (2007) also observed that color strength increased with dyeing time up to an optimum value, followed by a decrease as dyeing time was further prolonged.

In addition to immersion time, the type of mordant (factor B) also significantly affects color strength, as shown in Table 5. PAC mordant increases the color strength of monascus pigments. PAC is thought to contain more Al than other mordants, resulting in higher Al^{3+} levels in the fabric. The higher the Al^{3+} bonded in the fabric, the more complex the aluminum-pigment compound, resulting in higher color strength. According to Failisnur *et al.* (2018), the amount of adsorbed mordant on the fabric affects the strength of the fabric color by forming a metal-pigment complex. Aluminum sulfate and PAC contain 3.5% and 30% aluminum, respectively, while simplokos contains 49.775 ppm (Hadi and Siswadi, 2011). It indicates that the mordant's role is not only to enhance pigment fixation but also to modify the adsorption sites on the fiber surface via coordination bonding.

In addition to the type, the mordant concentration (factor C) also influences color strength. The increased mordant

concentration enabled the formation of a more complex mordant-pigment compound that bonded to the fabric, thereby increasing color strength (Ali *et al.*, 2009; Samanta and Agarwal, 2009). The highest color strength value is obtained at a PAC concentration of 25 g/L. The effect of PAC concentration on color strength exhibits a typical optimum behavior: before and after the optimal concentration. Before reaching the optimum concentration, increasing the mordant concentration enhances the color strength. However, beyond the optimum point, further increases in concentration lead to a decrease in color strength.

Another important parameter affecting dye uptake is the solution pH (factor E). The pH influences the interaction between the fiber and the pigment by altering the ionization states of both the dye molecules and the fiber's functional groups. Extremely acidic conditions may limit effective dye-fiber interactions by altering the chemical environment, whereas alkaline conditions can enhance dye uptake, depending on the dyeing system. In this study, the highest color strength was obtained at pH 10. It may be attributed to improved fiber swelling under alkaline conditions, which increases the accessibility of dye molecules to the fiber structure. Adeel *et al.* (2019) also reported that pH plays a significant role in determining dye uptake by influencing dye-fiber interactions.

In this recent study, the concentration of sodium chloride (factor D) does not affect color strength. This finding differs from previous research. A high salt concentration might cause the pigment solution to coagulate or aggregate, reducing pigment adsorption to the fabric (Umbreen *et al.*, 2008). When sodium chloride is added to the dyeing solution before coloring, the pigment

molecule becomes bound to the Na⁺ cation. It reduces the negative charge on the surface of the cotton fabric and interferes with its pigment sorption. This deviation from previous studies may be attributed to differences in pigment chemistry and dyeing mechanisms between monascus pigments and conventional natural dyes. Although these mechanisms may occur, their overall influence on color strength was not statistically significant in the present study. This suggests that the role of electrolyte addition in monascus pigment-based dyeing systems may differ from that in conventional natural dyeing systems.

Washing Fastness

The test results for the color fastness of the fabric to washing and rubbing are presented in Table 6. They are subjected to the SN-Ratio test using the "smaller is better" criterion to determine the optimal factor, as shown in Tables 7-10.

The washing test results (Table 6) show that the dyed fabric exhibits relatively low resistance to washing, with an average grayscale (GS) value of 1–2, indicating poor color fastness. In contrast, the rubbing test demonstrates excellent performance, with a staining scale (SS) value of 5. Based on the data in Table 6, the S/N ratio analysis (Table 7) indicates that the optimal conditions for washing fastness correspond to the dyeing parameters A4B3C2D4E1, with an immersion time of 160 minutes, CaO as the mordant at 20 g/L, a sodium chloride concentration of 25 g/L, and a pH of 4. Under these conditions, the best color change performance is achieved with a GS value of 2, corresponding to a color difference (CD) of 5.85. The relatively low washing fastness can be attributed to the nature of the interaction between the pigment–mordant complex and

the cotton fiber, which is likely dominated by physical adsorption and weak coordination bonding rather than strong covalent interactions.

Table 6. The color responses of the washing and rubbing fastness test

No.	Washing Fastness				Rubbing Fastness			
	Color Change		Color Staining		Dry Rubbing		Wet Rubbing	
	GS	CD	SS	CD	SS	CD	SS	CD
1	1-2	10.28	5	0.53	5	0.73	5	1.03
2	2	6.41	5	0.81	4-5	2.10	4	3.66
3	1-2	8.27	5	0.06	5	0.70	4-5	1.55
4	1-2	8.64	5	0.55	5	0.22	4-5	1.30
5	1-2	9.10	5	0.07	5	0.70	3-4	5.31
6	1-2	9.82	5	0.45	4-5	1.71	4-5	2.59
7	1-2	8.79	5	0.81	5	0.37	4-5	1.75
8	1-2	10.35	5	0.33	5	0.19	5	0.50
9	1-2	10.57	5	0.21	5	0.84	4	3.54
10	1-2	10.31	5	0.33	5	0.04	5	0.50
11	1-2	10.08	5	0.15	5	0.51	5	0.50
12	1-2	10.20	5	0.75	4-5	1.15	4	3.41
13	1-2	9.87	5	0.53	5	1.00	4-5	2.72
14	2	7.14	5	0.42	5	1.01	4	4.35
15	2	5.85	5	0.82	5	0.26	5	0.93
16	1-2	9.51	5	0.27	5	0.06	4-5	2.16
x	1-2	9.07	5	0.44	5	0.72	4-5	2.00

These findings highlight the need to improve the fixation mechanism, for example, by using more effective mordants or process modifications, to enhance the durability of *Monascus*-based dyeing systems.

On the other hand, the staining scale of the washing test ranged from 5, with varied color differences (0.06 to 0.82). Its SN-Ratio test for color differences yields optimal values for the dyeing factors in the recipe A4B2C4D1E1 (Table 8). It is the dyeing process with an immersion time of 160 minutes, 30 g/L PAC, 10 g/L sodium chloride,

and a solution pH of 4.

Table 7. S/N-Ratio analysis on the grayscale (GS) of the washing test

Level	Factor				
	A	B	C	D	E
1	-18.42	-19.96	-19.95	-19.11	-18.70
2	-19.58	-18.35	-17.79	-19.12	-19.10
3	-20.26	-18.25	-19.08	-19.38	-19.59
4	-18.03	-19.72	-19.48	-18.67	-18.81
Delta	2.23	1.71	2.16	0.710	0.89
Rank	1	3	2	5	4
Optimum Factors:		A4B3C2D4E1			

Table 8. S/N-Ratio analysis on the staining scale (SS) of the washing test

Level	Factor				
	A	B	C	D	E
1	7.785	8.640	7.126	1.509	3.698
2	8.013	3.898	5.275	5.532	4.058
3	7.514	8.926	11.023	14.662	7.537
4	2.765	4.612	2.652	4.373	10.694
Delta	5.248	5.028	8.371	13.153	6.996
Rank	4	5	2	1	3
Optimum Factors:		A4B2C4D1E1			

Rubbing Fastness

In contrast to the washing fastness test results, the ANOVA test (Table 4) shows that all factors affect the staining scale of the fabric's color in response to the rubbing test, with results ranging from good fastness. All factors result in a staining scale range of 4-5. These results indicate that all factor levels can produce relatively stable color under mechanical stress. Mordants, in particular, could stabilize the pigment adsorbed into the fabric. The fabric's stable pigment remained intact during the rubbing test, resulting in no staining on the white fabric tester.

All mordants used in these experiments contain one of two metal elements:

aluminum or calcium. Aluminum (Al) and calcium (Ca) can promote the binding of monascus pigments to cotton fabric. However, the color produced by the Ca mordant is lighter than that of Al because the pigment binding to the fabric promoted by Ca is weaker than that of Al. All mordants form a pigment-fabric binding that remains stable during the rubbing test, as indicated by no staining of the white fabric testee; i.e., a staining scale of 4-5.

Various concentrations of sodium chloride yield different results in the rubbing fastness test, both dry and wet. According to the ANOVA analysis (Table 4), the differences are statistically significant ($p < 0.05$). Using 15-20 g/L sodium chloride increases pigment adsorption into fabrics. However, the pigment settles as concentration increases, impeding the dyeing process. Wet rubbing tests yield a lower value than dry rubbing tests. When the fabrics were wet, the pores may have opened, allowing the pigment to dissolve and be released. This result shows that although salt content does not affect color strength, it must be optimized for good color fastness.

On the other hand, the pH of the dyeing solution also influences the fabric's wet- and dry-rubbing fastness. Acidity levels influence the interaction between cotton fabrics and the pigment's negative charge. For monascus pigments on cotton fabric, a pH 8 solution yields the best fabric fastness, as shown in Tables 9 and 10 (factor E level 3).

A staining scale (SS) of 5 dominates the dry rubbing fastness responses, while a scale of 4-5 dominates the wet rubbing responses, as outlined in Table 6. The SN-Ratio test (Table 9) on the dry rubbing data indicates that the trial's recipe A1B1C2D1E3 yielded the best dry rubbing response. The condition represents a dyeing process with 20 g/L

$\text{Al}_2(\text{SO}_4)_3$, 10 g/L sodium chloride, a pH of 8, and a 100-minute immersion time. It achieves a staining scale (SS) of 5, corresponding to a color difference (CD) of 0.2.

Table 9. S/N-Ratio analysis on the dry rubbing responses

Level	Factor				
	A	B	C	D	E
1	1.704	1.109	5.220	1.641	7.222
2	4.130	3.023	0.753	2.457	9.517
3	6.957	5.068	3.664	12.478	-1.380
4	7.445	11.035	10.598	3.661	4.303
Delta	5.741	9.926	9.845	10.837	10.897
Rank	5	3	4	2	1
Optimum Factors:		A1B1C2D1E3			

Table 10. S/N-Ratio analysis on the wet rubbing responses

Level	Factor				
	A	B	C	D	E
1	-14.132	-16.686	-10.215	-16.819	-1.796
2	-9.599	-14.520	-17.458	-5.269	-13.883
3	-8.626	-8.603	-10.780	-11.507	-17.163
4	-16.180	-8.728	-10.084	-14.942	-12.673
Delta	7.554	8.083	7.374	11.549	15.367
Rank	4	3	5	2	1
Optimum Factors:		A4B1C2D1E3			

Table 10 shows the results of the SN-Ratio test for the wet rubbing data. Its optimal result is the combination of factors A4B1C2D1E3. The optimum condition of the dyeing process has a staining scale (SS) of 4-5, corresponding to a color difference (CD) of 0.55. The dyeing treatment is the experiment using 20 g/L $\text{Al}_2(\text{SO}_4)_3$ mordant, 10 g/L sodium chloride, a dyeing solution pH of 8, and a 160-minute immersion time.

The fastness tests informed us that the colored fabrics were weak when exposed to water. They have poor washing fastness and

perform worse in the wet rubbing test than in the dry rubbing test. This fact can be explained by previous experiments showing that natural dyes bind to cotton fabric through coordination interactions among dye molecules, metal mordants, and the fiber (Amutha K *et al.*, 2020; Darmawan *et al.*, 2024). The poor results of the washing fastness test indicate that the binding of the fabric-mordant-pigment (monascus pigments-metal-fiber complex) is unstable when exposed to water. This limitation highlights the need for further research to enhance the stability of the pigment-mordant-fiber interaction under aqueous conditions.

The individual S/N Ratio analyses for all responses each pointed to a different optimal factor combination. To obtain a single overall optimal dyeing condition, the S/N ratios of the five responses were normalized and combined into a composite MRSN index using Equations (3) and (4), with 60% weight assigned to K/S and 10% to each fastness response. The average MRSN value at each factor level, is presented in Table 11.

Table 11. The average MRSN at each factor level

Level	Factors				
	A	B	C	D	E
1	0.461	0.380	0.410	0.415	0.314
2	0.470	0.555	0.441	0.435	0.496
3	0.412	0.387	0.533	0.545	0.427
4	0.444	0.465	0.402	0.391	0.551
Delta	0.058	0.175	0.131	0.154	0.237
Rank	5	2	4	3	1
Optimum Factors		A2B2C3D3E4			

Table 11 shows that the optimum combination was identified as A2B2C3D3E4, corresponding to an immersion time of 120 minutes, PAC mordant, a mordant concentration of 25 g/L, a sodium chloride

concentration of 20 g/L, and a solution pH of 10. This combination coincides with the optimum condition previously obtained from the single-response analysis of K/S (Table 5). It should be noted that this combination does not correspond to any of the 16 trials, which achieved the highest individual MRSN value of 0.711, while the predicted MRSN value of the optimum combination is 0.867.

Reusability of The Anka Solution

These experiments also demonstrated the anka solution's ability to be reused in the dyeing process. This was evidenced by a decrease in the dye solution's absorbance during dyeing, reflecting the difference in absorbance before and after immersion of the cotton fabric. However, the change in absorbance at each immersion step was too small to be measured individually; therefore, observations were conducted over three immersion cycles. Before immersion, the average absorbance of all dyeing solutions was 1.298 ± 0.313 and decreased to 1.258 ± 0.321 after immersion. The color density reduction was reflected by a decrease in absorbance of 0.04 per triple-dyeing process, or approximately 0.013 per single dyeing cycle. This gradual decrease in absorbance indicates partial adsorption of pigment onto the fabric during each dyeing cycle, resulting in a progressive reduction in dye concentration.

This finding shows that color density decreased slowly in each dyeing process, accounting for only about 1% per immersion, indicating that the dye solution retains most of its coloring capacity after repeated use. Similar trends have been reported in natural dyeing systems, where repeated use of dyeing solutions leads to gradual depletion of active dye molecules due to adsorption and possible degradation processes.

These results suggest that reusing the dyeing solution can improve the effectiveness and efficiency of natural dyes in batik production. This finding highlights the potential of process integration strategies, such as dye bath reuse and concentration adjustment, to improve resource efficiency in textile dyeing. Furthermore, it may be necessary to concentrate the used dye solution, for example, by evaporation, to restore pigment concentration and maintain adequate color strength during reuse.

CONCLUSION

Optimizing cotton fabric dyeing with monascus pigments using a Taguchi-based approach showed that immersion time, mordant type, mordant concentration, and solution pH significantly influenced color strength, whereas sodium chloride concentration did not. The optimal dyeing condition for maximum color strength ($K/S = 2.43$) was achieved at 120 minutes of immersion time, 25 g/L PAC, 20 g/L sodium chloride, and pH 10. The fastness results indicated that although good rubbing fastness was achieved, the washing fastness remained low, suggesting limited stability of the pigment–mordant–fiber complex under aqueous conditions. The reusability analysis revealed that the anka extract solution could be reused with only a minor decrease in color intensity, indicating its potential for improving process efficiency and sustainability. However, this study is limited by the relatively low washing fastness, which indicates weak bonding between the pigment and the fiber. Future research should focus on improving the stability of the dye–fiber interaction, for example, by using alternative mordants, crosslinking agents, or process modifications to enhance durability.

and practical applicability in textile production.

ACKNOWLEDGMENTS

The authors acknowledge financial support from Universitas Sebelas Maret through a research grant (Contract No. 260/UN27.22/HK.07.00/2021).

REFERENCES

- Adeel, S., Hussaan, M., Rehman, F. ur, Habib, N., Salman, M., Naz, S., Amin, N., and Akhtar, N., 2019. "Microwave-assisted sustainable dyeing of wool fabric using cochineal-based carminic acid as natural colorant." *J. Nat. Fibers*, 16(7), 1026-1034. <https://doi.org/10.1080/15440478.2018.1448317>
- Adham, N.M., Shukri, N.N.M., Khodir, W.K.W.A., Jalal, A.F.A., and Hamid, S.A., 2025. "Central composite design for the optimisation of silk yarn dyeing with natural extract from *Melastoma malabathricum* L. fruit." *Malay. J. Anal. Sci.*, 29(2), 1411.
- Alam, S.S., Ghosh, J., and Das, D.J., 2022. "The coloration of cotton fabric with natural dye extracted from turmeric powder." *J. Text Eng. Fashion Technol.*, 8(4), 134-138. <https://doi.org/10.15406/jteft.2022.08.0311>
- Ali, S., Hussain, T., and Nawaz, R., 2009. "Optimization of alkaline extraction of natural dye from Henna leaves and its dyeing on cotton by exhaust method." *J. Clean. Prod.*, 17, 61-66. <https://doi.org/10.1016/j.jclepro.2008.03.002>
- Amutha K, Grace Annapoorani S, and Sudhapriya N, 2020. "Dyeing of textiles with natural dyes extracted from *Terminalia arjuna* and *Thespesia populnea* fruits." *Ind. Crops Prod.*, 148, 112303. <https://doi.org/10.1016/j.indcrop.2020.112303>
- Chen, G., Shi, K., Song, D., Quan, L., and Wu, Z., 2015. "The pigment characteristics and productivity shifting in high cell density culture of *Monascus anka mycelia*." *BMC Biotechnol.*, 15, 72. <https://doi.org/10.1186/s12896-015-0183-3>
- Darmawan, A., Widowati, Riyadi, A., Muhtar, H., Kartono, and Adhy, S., 2024. "Enhancing cotton fabric dyeing: optimizing mordanting with natural dyes and citric acid." *Int. J. Biol. Macromol.*, 276, 1-12.
- Daud, N.F.S., Said, F.M., Chisti, Y., and Yasin, N.H.M., 2021. "Recovery of red pigments from *Monascus purpureus* FTC 5357 by Extraction of fermented solids: operational conditions and kinetics." *Braz. Arch. Biol. Technol.*, 64, e21200182. <https://doi.org/10.1590/1678-4324-2021200182>
- De Santis, D., Moresi, M., Gallo, A.M., and Petruccioli, M., 2005. "Assessment of the dyeing properties of pigments from *Monascus purpureus*." *J. Chem. Technol. Biotechnol.*, 80, 1072-1079. <https://doi.org/10.1002/jctb.1285>
- Dey, Pallab, Dey, Priyata, Hoque, M.B., Baria, B., Rahman, M.M., Shovon, S., and Das, D., 2025. "Sustainable and eco-friendly natural dyes: a holistic review on sources, extraction, and application prospects." *Text. Res. J.*, 95, 19-20. <https://doi.org/10.1177/00405175251321139>
- Dong, C., Cheng, Y., Zhang, M., Chen, M., Yan, Z., Zhou, S., Yang, B., Guo, Q., Wang, C., and Wu, S., 2024. "Monascus pigments

-
- suppress fructose-mediated BSA glycation by trapping methylglyoxal and covalent binding to proteins." *Int. J. Biol. Macromol.*, 280, 1–10.
- Eren, S., Öztürk, M., Akarsu Özenç, A., and Aksel Eren, H., 2025. "Optimization of hemp fabric natural dyeing in supercritical carbon dioxide medium by response surface methodology." *Cellulose Chem. Technol.*, 59, 929–938.
- Evitasari, R.T., Rahayuningsih, E., and Mindaryani, A., 2019. "Dyeing of cotton fabric with natural dye from peristrophe bivalvis extract," *AIP Conf. Proc.*, 2085, 020055.
<https://doi.org/10.1063/1.5095033>
- Failisnur, F., Sofyan, S., Kasim, A., and Angraini, T., 2018. "Study of cotton fabric dyeing process with some mordant methods by using gambier (*Uncaria gambir* Roxb) extract." *Int. J. Adv. Sci. Eng. Inf. Technol.*, 8 (4), 1098–1104.
<https://doi.org/10.18517/ijaseit.8.4.4861>
- Hadi, D.S., and Siswadi, S., 2011. "Aluminum levels on leaves, bark, and root of two loba species: loba wawi (*Symplocos fasciculata* Zoll.) and loba manu (*Symplocos cochinchinensis*)," in: Parthama, P., Mas'ud, A.F. (Eds.), *Proceeding Inafor: 2011. Ministry of Forestry, Forestry Research and Development Agency, Bogor*, pp. 672–674.
- He, J.T., Jia, M.X., Li, W., Deng, J., Ren, J.L., Luo, F.J., Bai, J., and Liu, J., 2022. "Toward improvements for enhancement the productivity and color value of *Monascus* pigments: a critical review with recent updates." *Crit. Rev. Food Sci. Nutr.*, 62(26) 7139–7153.
<https://doi.org/10.1080/10408398.2021.1935443>
- Holkar, C.R., Jadhav, A.J., Pinjari, D. V., Mahamuni, N.M., and Pandit, A.B., 2016. "A critical review on textile wastewater treatments: Possible approaches." *J. Environ. Manage.*, 182, 351–366.
<https://doi.org/10.1016/j.jenvman.2016.07.090>
- Kant, R., 2012. "Textile dyeing industry an environmental hazard." *Nat. Sci. (Irvine)*, 04, 22–26.
<https://doi.org/10.4236/ns.2012.41004>
- Ketema, A., and Worku, A., 2023. "Optimization of process conditions of cotton fabric dyeing with nettle leaf extract for antibacterial application using central composite design." *J. Nat. Fibers*, 20, 2228485.
<https://doi.org/10.1080/15440478.2023.2228485>
- Kim, D., and Ku, S., 2018. "Beneficial effects of *Monascus* sp. KCCM 10093 pigments and derivatives: A mini review." *Molecules*, 23 (1), 98.
<https://doi.org/10.3390/molecules23010098>
- Kubelka, P., 1954. "New contributions to the optics of intensely light-scattering materials part II: Nonhomogeneous layers*." *J. Opt. Soc. Am.*, 44, 330–335.
<https://doi.org/10.1364/josa.44.000330>
- Nagia, F.A., and EL-Mohamedy, R.S.R., 2007. "Dyeing of wool with natural anthraquinone dyes from *Fusarium oxysporum*." *Dyes Pigment.*, 75, 550–555.
<https://doi.org/10.1016/j.dyepig.2006.07.002>
- Negi, A., 2025. "Natural dyes and pigments: sustainable applications and future scope." *Sustain. Chem.*, 6(3), 23.
<https://doi.org/10.3390/suschem6030023>
- Oguz, N.S., and Akarslan, F., 2022. "Applications of taguchi experimental design method in the field of textile." *Int.*
-

-
- J. Eng. Innov. Res.*, 4, 134–142.
<https://doi.org/10.47933/ijeir.1039263>
- Pervez, M.N., Yeo, W.S., Lin, L., Xiong, X., Naddeo, V., and Cai, Y., 2023. "Optimization and prediction of the cotton fabric dyeing process using Taguchi design-integrated machine learning approach." *Sci. Rep.*, 13, 12363.
<https://doi.org/10.1038/s41598-023-39528-1>
- Pujilestari, 2017. "Batik fabric dyeing process optimization using natural dyes tingi (*Cerriops tagal*) and *Indigofera Sp.*" *Dinamika Kerajinan Batik*, 34, 53–62.
- Rehman, A., Ahmad, A., Hameed, A., Kiran, S., and Farooq, T., 2021. "Green dyeing of modified cotton fabric with *Acalypha wilkesiana* leave extracts." *Sustain. Chem. Pharm.*, 21, 100432.
<https://doi.org/10.1016/j.scp.2021.100432>
- Rossi, T., Silva, P.M.S., De Moura, L.F., Araújo, M.C., Brito, J.O., and Freeman, H.S., 2017. "Waste from eucalyptus wood steaming as a natural dye source for textile fibers." *J. Clean. Prod.*, 143, 303–310.
<https://doi.org/10.1016/j.jclepro.2016.12.109>
- Rosyida, A., Suranto, S., Masykuri, M., and Margono, M., 2022. "Optimisation of the process of dyeing cotton fabric with natural dyes from jackfruit wood by immersion without heating." *Pigm. Resin Technol.*, 51(6), 663–673.
<https://doi.org/10.1108/PRT-03-2021-0034>
- Samanta, A.K., and Agarwal, P., 2009. "Application of natural dyes on textiles." *Indian J. Fibre Text. Res*, 34(4), 384–399.
- Shahid, M., Shahid-Ul-Islam, and Mohammad, F., 2013. "Recent advancements in natural dye applications: A review." *J. Clean. Prod.*, 53, 310–331.
<https://doi.org/10.1016/j.jclepro.2013.03.031>
- Swami, C., Saini, S., and Gupta, V.B., 2014. "Kinetic and diffusion studies of a dye extracted from *Sesbania aculeata* plant." *Pigm. Resin Technol.*, 43 (3), 118–126.
<https://doi.org/10.1108/PRT-06-2012-0041>
- Taguchi, G., Elsayed, E.A. and Hsiang, T.C., 1989. *Quality Engineering in Production Systems*. McGraw. Inc., New York.
- Umbreen, S., Ali, S., Hussain, T., and Nawaz, R., 2008. "Dyeing properties of natural dyes extracted from turmeric and their comparison with reactive dyeing." *Res. J. Text. Appar.*, 12, 1–11.
<https://doi.org/10.1108/RJTA-12-04-2008-B001>
- Velmurugan, P., Tamilselvi, A., Lakshmanaperumalsamy, P., Park, J., and Oh, B.T., 2013. "The use of cochineal and *Monascus purpureus* as dyes for cotton fabric." *Color, Technol.*, 129, 246–251.
<https://doi.org/10.1111/cote.12032>
- Venil, C.K., Velmurugan, P., Dufossé, L., Devi, P.R., and Ravi, A.V., 2020. "Fungal pigments: Potential coloring compounds for wide ranging applications in textile dyeing." *J. Fungi*, 6(2), 68.
<https://doi.org/10.3390/jof6020068>
- Vidhya, A.S., Sumitha, V.R., and Gangaprasad, A., 2024. "Adventitious root culture dyeing and optimisation of dyeing parameters using roots of *Gynochthodes umbellata* (L.) Razafim and *B. Bremer*." *Plant Science Today*, 11 (2), 660–670.
<https://doi.org/10.14719/pst.2637>
- Wahyudin, Kharisma, A., Murphiyanto, R.D.J., Perdana, M.K., and Kasih, T.P., 2018. "Application of Taguchi method and ANOVA in the optimization of dyeing process on cotton knit fabric to reduce
-

-
- re-dyeing process," *IOP Conf. Ser.: Earth Environ. Sci.*, *109*, 012023. <https://doi.org/10.1088/1755-1315/109/1/012023>
- Xie, H., Huang, Z., Shi, K., Zheng, K., Qiu, L., and Wu, Z., 2024. "Color vibrancy enhancement of water-soluble Monascus yellow pigments through a two-step derivation with double sulfonic groups." *Food Biosci.*, *58*, 103653. <https://doi.org/10.1016/j.fbio.2024.103653>
- Zhang, X., Zhao, Y., Yan, W., Wang, P., Li, J., and Lu, Y., 2024. "Light stability and mechanism of monascus pigment under different lights." *LWT*, *191*, 115666. <https://doi.org/10.1016/j.lwt.2023.115666>
-