CELLULOSE CHEMISTRY AND TECHNOLOGY

A STUDY ON ECO-FRIENDLY DYEING WITH BANANA LEAVES AND MORDANTS: PROCESS INVESTIGATION AND OPTIMISATION

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Received October 9, 2025

The widespread use of synthetic dyes in textile dyeing and printing has intensified environmental concerns due to pollutant discharge, prompting interest in sustainable natural alternatives. This study explores banana leaves as a renewable natural dye source for cotton fabric and evaluates the influence of mordants on colour performance. A mixed-level factorial design was applied using three variables: dyeing method, mordant type, and mordant concentration. Results showed that both exhaust and cold pad-batch methods achieved comparable dye uptake with banana leaf extract. Ferrous sulphate at 8% concentration, applied through the cold pad-batch method, produced the highest K/S values, indicating superior shade depth. Fabrics dyed with onion skin and pomegranate rind mordants exhibited poor wash fastness, whereas the exhaust method provided better wash fastness than cold pad-batch dyeing. Neither dyeing method nor mordant concentration significantly affected dry rubbing fastness in warp or weft directions. The findings demonstrate the potential of banana leaves as an eco-friendly substitute for synthetic dyes in textile applications.

Keywords: banana leaves, natural dye, mordants, eco-friendly, dyeing

INTRODUCTION

With growing global awareness of environmental pollution, the need to replace harmful synthetic dyes with natural alternatives has become more pressing. In recent years, the textile industry has witnessed a rising global demand for natural dyes, largely due to their non-toxic nature and the environmental issues associated with the manufacturing and use of synthetic dyes.[1,2] Worldwide, experts are working to develop eco-friendly cotton dyeing techniques that comply with environmental regulations while conserving water, energy, and time.[3] Incorporating green ingredients or achieving zero wastewater discharge is essential for sustainable textile colouration.[4]

Natural dyes have gained increasing interest in textile dyeing due to their renewable nature and biodegradability. They can be broadly classified into three categories based on their source: plant-based, animal-based, and mineral-based dyes.[1] Animal dyes are primarily obtained from insect secretions and dried insect bodies, while some shellfish also yield colouring substances. Certain minerals and natural materials, such as seru, cow urine, cow dung, and egg albumin, are also used as colouring agents.[5]

In recent years, researchers have successfully extracted natural dyes from a variety of plants, including henna leaves, *Acalypha wilkesiana* leaves, rhubarb, and *Helichrysum bracteatum*, which have been effectively applied in textile dyeing.[6-8] Some plants also possess antimicrobial properties, adding functional value to dyed fabrics.[9-10]

Among the notable plant sources for textiles, the banana plant stands out for its diverse applications. It has been observed that cellulose can be extracted from kepok banana peel and used for the adsorption of Procion dye.[11] Pigment extraction from banana leaves has also been reported.[12] Other studies investigated dyeing with onion skin and marigold flower dyes using banana peel as a biomordant.[13,14] Natural dyes have been extracted from banana floral stems, and the stability of dye–fibre bonding was evaluated through colour fastness tests against washing, water, perspiration, rubbing, and light.[15] The dried aqueous extract of banana flower petaloids has also been utilised as a mordant in wool dyeing.[16]

Banana pseudostem sap has been used as a biomordant for silk dyeing with Celosia flowers.[17] It is also employed in dyeing cotton and silk fabrics with naturally extracted dye from *Tagetes erecta.*[18] A study examined the treatment of cotton fabric with banana pseudostem sap and evaluated its physical characteristics, emphasising its unique staining properties and potential applications.[19] Another study developed an industrially adaptable method for converting pseudostem waste into a textile binder.[20]

The banana hump has been used to dye a batik cloth, followed by the evaluation of colour fastness to washing and rubbing. The results of the colour fastness test against washing showed that quicklime had good criteria when compared to the use of Tunjung mordant and lime mordant.[21]

A recent study explored banana leaf–derived natural dyes for sustainable dyeing of Pima cotton using different mordants. The study evaluated colour properties, fastness, and fabric performance. UV–Vis and FTIR analyses were used to characterise dye–fiber interactions. Results showed improved colour strength and good fastness with effective mordanting. The findings support banana leaf extract as a sustainable alternative to synthetic dyes.[22]

In an investigation made by Mohtashim *et al.*, a green chemistry-based dyeing method was developed for the colouration of cotton fabric using banana bioresource waste. Dyeing trials with different parts of the banana plant demonstrated significant colour strength along with good wash and rub fastness. Through experimental design analysis, a standardised and resource-efficient dyeing recipe was formulated, achieving reasonably good wash and rub fastness.[23]

A study investigated salt-free dyeing of cotton fabric using mango and banana leaf colourants. The findings revealed that the results of salt-free dyeing were essentially comparable to those obtained with conventional salt-assisted dyeing.[24]

An investigation by Balakrishnan highlighted sustainable natural dyeing of banana fibre as an eco-friendly alternative to conventional colouration by reducing environmental impact and utilizing renewable, plant-based resources. The research investigated locally available natural dyes, including banana pseudostem sap, jamun fruit, coconut shell powder, Ceylon green spinach, and tree turmeric, which produced a diverse range of pastel shades. Particular emphasis was placed on mordant-free dyeing, demonstrating satisfactory dye absorption, colour retention, and fastness properties without the use of chemical mordants. The findings emphasise the potential of natural dyes to enhance the commercial value of banana fibre products, while promoting sustainable textile practices and supporting local economic development.[25]

A recently published work evaluated banana peel (*Musa*) and guava leaves (*Psidium guajava*) extracts as bio-mordants for jute–cotton fabrics dyed with onion skin extract. The results demonstrated significant improvements in both colour strength and wash fastness compared with untreated samples. Fabrics post-mordanted with banana peel extract showed the best wash fastness performance, whereas guava leaf extract produced higher colour strength values. These findings suggest that banana peel and guava leaves offer sustainable and effective alternatives to conventional metallic salt mordants in natural dyeing applications.[26]

Although previous studies have reported the use of different banana plant components as natural dyes or biomordants for textile applications, most of these investigations were limited to preliminary performance evaluation and did not provide a systematic optimisation framework for cotton dyeing. The combined effects of key processing variables, such as dyeing method, mordant type (natural versus synthetic), and mordant concentration on colour strength and fastness properties remain insufficiently explored, particularly through statistically robust experimental designs. In addition, limited research has focused on simultaneously optimising multiple response variables for practical and sustainable industrial implementation. Therefore, the present study fills this knowledge gap by applying a mixed-level full factorial design, ANOVA, interaction analysis, and composite desirability optimisation to identify the optimum conditions for sustainable cotton colouration using banana leaf pigments.

In this study, pigments were extracted from banana plant leaves, and cotton fabric was dyed using both natural and synthetic mordants. The effects of various process parameters, including dyeing method (exhaust and cold pad-batch), mordant type (natural or synthetic), and mordant concentration, were examined through a $2^1.3^1.4^1$ mixed-level full factorial design. Analysis of

Variance (ANOVA) was applied to identify the significant factors influencing colour strength and fastness properties. Main effect and interaction plots of the significant factors were analysed to evaluate their influence on the response variables. The study further aimed to determine the optimum processing parameters for achieving sustainable colouration of cotton fabric. Multi-response optimisation using composite desirability was employed to identify the optimal parameters that maximise both colour strength and fastness properties in the green colouration process utilising banana bio-resource waste.

EXPERIMENTAL

Materials

A plain woven, bleached, 100% cotton fabric having GSM 120 and EPIxPPI-76x68 was used throughout the study. Fabric samples were dyed with commercial-grade alkalis, including sodium hydroxide and sodium carbonate. In addition, natural and synthetic mordants were also used, including pomegranate rind, onion skin, ferrous sulphate and aluminium acetate.

Dye extraction

Banana by-products are often collected from agricultural fields, sun-dried, and subsequently burned, contributing to environmental pollution. The chemical treatment of banana leaves offers a promising approach for natural dye extraction and their subsequent application in textile dyeing.

Banana leaves were procured from a local market and dried for 10–13 days before extraction. For dye preparation, 100 g of the dried leaves were cut into small pieces and boiled in 1 L of a 0.1% sodium hydroxide (NaOH) solution for approximately 6–7 minutes. The mixture was then allowed to react and subsequently filtered to remove solid residues. The collected filtrate was used as the base dye liquor for textile dyeing.

Dyeing methods

Exhaust dyeing

Exhaust dyeing experiments were conducted in sealed stainless-steel containers using an infrared dyeing machine. Cotton fabric was placed in a bath containing extracted dye (10%), sodium hydroxide (1%), sodium carbonate (3%), and a wetting agent (3%) with a liquor ratio (L:R) of 15:1. The temperature of the dye bath was gradually increased to 45 °C, 75 °C, or 98 °C at a rate of 4 °C per minute, then held steady for 80 minutes. After dyeing, the samples were rinsed with cold water, then squeezed and dried.

Cold pad batch dyeing

The cotton fabric samples were also dyed using the cold pad batch (CPB) method. The bath contained extracted dye (10 g/L), sodium hydroxide (10 g/L), sodium carbonate (30 g/L) and a wetting agent (30 mL/L). In this dyeing method, fabric was passed through the dye trough, then through nip rollers, achieving a 70% wet pickup. The bath temperature was kept at 25 °C, and the two-dip–two-nip technique was applied throughout the process. Immediately after padding, the fabric was sealed in a polyethene bag to prevent air exposure, then stored at 25–30 °C for up to 12 hours. Finally, the fabric was rinsed with cold water, then squeezed and dried.

Preparation and application of mordant solution

For the fixation of dye to the fabric and to improve the colourfastness of a naturally dyed fabric, natural and synthetic mordants were applied through pre- and post-mordanting techniques.

Synthetic mordant

Mordanting was performed using ferrous sulphate or aluminium acetate at concentrations of 3%, 5%, and 8%. The mordant solution was prepared in distilled water and stirred for 8–10 minutes with a magnetic stirrer. It was then filtered through filter paper to obtain a clear solution. The fabric was boiled in this solution for one hour, then allowed to cool at room temperature.

Natural mordants

A 3%, 5%, and 8% solution of pomegranate rind or onion skin was prepared by adding the plant material to boiling water and simmering for one hour. The mixture was then filtered through filter paper to remove residues. The fabric was boiled in the extracted solution for one hour, then allowed to cool at room temperature.

Determination of fastness properties

The colour fastnesses of the dyeing samples were tested according to ISO standard methods, including fastness to washing (ISO 105 C06/C2S) and rubbing (ISO 105 X12).

Colour measurement

The colourimetric data of the dyed cotton fabrics were measured using a Datacolour Spectroflash 600 spectrophotometer, with a 10 ° standard observer and D65 illuminant, and were the average of four measurements. The colour strength (K/S) was evaluated using the Kubelka–Munk equation (represented in Eq. 1):

$$\left(\frac{K}{S}\right)_\lambda = \frac{(1-R_\lambda)^2}{2R_\lambda} \quad (1)$$

where K is the absorption coefficient, S is the scatter coefficient, and R is the reflectance expressed as a fractional value at a wavelength of maximum absorption λ.

Experimental setup

To systematically investigate the green colouration of cotton fabric using natural dyes extracted from banana leaves, a Design of Experiments (DOE) approach was employed. This method provides a structured and efficient strategy for exploring the influence of multiple process variables and their interactions on key performance indicators. The DOE methodology also facilitates statistical validation and reproducibility of experimental outcomes, which is essential for process optimisation and scientific rigour. The variable factors, including their respective levels, are outlined comprehensively in Table 1. A mixed-level full factorial design of type $2^1.3^1.4^1$, encompassing a total of 24 experimental runs, was constructed based on this matrix, as detailed in Table 2. This factorial design enables the study of both main effects and interactions between process variables under controlled conditions. All dyeing experiments were conducted in a completely randomised order to mitigate the impact of potential systematic bias.

The evaluation of dyed samples included measurement of colour strength (K/S values) and CIELAB coordinates (L, a, b), as well as assessment of colour fastness to wet and dry rubbing in both the warp and weft directions, in addition to a change in shade and staining on adjacent fabrics. These measurements were carried out by standard textile testing protocols, as outlined above.

To enhance data reliability and account for experimental variability, each trial was conducted in duplicate, and the average values of the two replicates were computed and presented in Table 3. The experimental data were statistically analysed using Minitab 18 software. Analysis of Variance (ANOVA) was performed to identify statistically significant main effects and interaction effects among the selected process variables.

Table 1
$2^{1}\cdot3^{1}\cdot4^{1}$ mixed-level full factorial design

Factors	Levels			
X_1: Dyeing method	Exhaust	Cold pad batch		
X_2: Mordant type	Onion skin	Pomegranate rind	Aluminium acetate	Ferrous sulphate
X_3: Mordant concentration	3	5	8	

Table 2
Experiment run order for green colouration process using banana leaf-based natural dyes

Run No.	Variable factors		
	X_1 Dyeing method	X_2 Mordant type	X_3 Mordant concentration
1	Cold pad batch	Pomegranate rind	3
2	Cold pad batch	Ferrous sulphate	8
3	Cold pad batch	Pomegranate rind	5
4	Cold pad batch	Onion skin	8
5	Exhaust	Pomegranate rind	8
6	Cold pad batch	Aluminium acetate	8
7	Exhaust	Ferrous sulphate	8
8	Exhaust	Pomegranate rind	3
9	Cold pad batch	Ferrous sulphate	3
10	Cold pad batch	Pomegranate rind	8
11	Exhaust	Onion skin	5
12	Exhaust	Ferrous sulphate	5
13	Exhaust	Aluminium acetate	8
14	Exhaust	Aluminium acetate	3
15	Exhaust	Onion skin	8
16	Exhaust	Pomegranate rind	5
17	Cold pad batch	Aluminium acetate	3
18	Cold pad batch	Onion skin	3
19	Exhaust	Aluminium acetate	5
20	Cold pad batch	Aluminium acetate	5
21	Cold pad batch	Ferrous sulphate	5
22	Cold pad batch	Onion skin	5
23	Exhaust	Ferrous sulphate	3
24	Exhaust	Onion skin	3

Table 3
Response results for green colouration process using banana leaf-based natural dyes

Run No.	Measured responses									
	K/S	L*	a*	b*	Colour change	Staining	Dry rubbing (warp)	Dry rubbing (weft)	Wet rubbing (warp)	Wet rubbing (weft)
1	0.66	84.24	1.95	18.15	1.5	5	5	5	4.5	4.5
2	6.01	55.91	22.57	45.6	5	5	4.5	4	3	2.5
3	0.36	86.78	1.42	14.38	4	5	5	5	5	5
4	2.54	67.17	10.37	23.9	1	5	5	5	4.5	4.5
5	0.42	84.29	1.57	13.17	2.5	5	5	5	5	5
6	0.15	90.44	0.38	8.6	4.5	5	5	5	5	5
7	3.25	71.23	11.62	31.65	4.5	5	4.5	4	4	3.5
8	0.29	86.19	1.57	11.02	4	5	5	5	5	5
9	4.68	67.17	14.39	36.77	5	5	5	4.5	4.5	4.5
10	1.12	80.68	2.93	22.39	1	5	5	5	4.5	4.5
11	0.38	83.25	2.86	11.14	3.5	5	5	5	5	5
12	3.63	71.76	11.81	33.7	4.5	5	4	3.5	4	3.5
13	0.07	92.79	-0.14	5.38	5	5	5	5	5	5
14	0.06	92.51	-0.18	4.35	5	5	5	5	5	5
15	0.51	80.76	4.22	12.73	1.5	5	5	5	5	5
16	0.23	86.53	1.71	9.3	4.5	5	5	5	5	5
17	0.15	89.47	0.34	8.05	4.5	5	5	5	5	5
18	1.55	73.71	7.53	22.11	1	5	5	5	4.5	4.5
19	0.07	92.13	-0.11	5.06	5	5	5	5	5	5
20	0.13	91.24	-0.08	8.08	4.5	5	5	5	5	5
21	3.45	75.26	8.99	33.76	3.5	5	3	3	3.5	3.5
22	1.45	72.48	7.95	20.25	1	5	5	5	4.5	4.5
23	4.41	71.48	13.07	36.61	4.5	5	4	4	4.5	4
24	0.48	81.6	5.43	12.03	1.5	5	5	5	5	5

Furthermore, main effects plots and interaction plots were generated for all response variables, enabling visual interpretation of how changes in individual and combined factors influence the dyeing outcomes. This analytical approach provided valuable insights into the optimal conditions for achieving improved dye uptake, shade uniformity, and fastness performance using banana leaf-based natural dyes, thereby contributing to the advancement of sustainable textile processing.

RESULTS AND DISCUSSION

Investigation of colour strength (K/S)

Colour strength (K/S value) serves as a crucial parameter in assessing the depth and visual intensity of dyed fabrics, reflecting the effectiveness of the dye-fibre interaction. In the context of sustainable dyeing using natural extracts, understanding the factors influencing K/S values is essential for optimising dyeing protocols.

The results of the analysis of variance (ANOVA) presented in Table 4 reveal that the type of mordant used has a statistically significant effect on the colour strength of fabrics dyed with banana leaf extract ($p = 0.010$). This highlights the pivotal role of mordants in enhancing dye uptake and fixation during the natural dyeing process.

The main effects plot (Fig. 1) clearly shows that ferrous sulphate led to the highest K/S values among the mordants tested, indicating its superior ability to form stable dye-mordant complexes with the polyphenolic compounds present in banana leaf extract. This enhanced complexation likely contributes to more intense shades on the fabric. Conversely, the other tested variables, dyeing method (exhaust versus cold pad-batch) and mordant concentration, did not show a statistically significant influence on colour strength within the studied range, suggesting that the mordant type is the dominant factor in determining colour depth for this system.

HPTLC analysis of banana peel extracts identified luteolin as a major pigment compound, which may contribute to the yellow to brown shades developed on the fabric due to the presence of polyphenolic colourants. Similarly, alkaline extraction of banana leaves revealed the presence of luteolin and apigenin. These compounds are capable of forming glucosidic linkages with the textile substrate.[27] Furthermore, when interacting with iron metal ions, the polyphenolic constituents form strong coordination complexes that enhance the wash fastness of the dyed fabric.

The interaction plot (Fig. 2) further supports these findings, as it shows minimal variation in K/S values between the two dyeing methods, indicating that both the exhaust and cold pad-batch methods are comparable in terms of dye uptake when using banana leaf extract. However, it is noteworthy that a mordant concentration of 8% emerged as a potentially optimal condition, yielding relatively higher colour strength values. This suggests that while concentration alone may not have a statistically significant standalone effect, its interaction with other parameters, particularly mordant type, could contribute to improved dyeing performance.

Overall, these findings underscore the importance of mordant selection in achieving desirable colour strength when employing eco-friendly dye sources such as banana leaves.

Investigation of colour fastness to washing

Colour fastness to washing refers to a material's resistance to alterations in its colour properties due to laundering. According to the analysis of variance (ANOVA) results presented in Table 5, two primary factors, mordant type and dyeing method, exhibited statistically significant effects on the wash fastness of green-coloured samples ($p = 0.001$ and $p = 0.027$, respectively). The corresponding main effects and interaction plots are illustrated in Figures 3 and 4.

Table 4
ANOVA of colour strength for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	193.71	11.395	2.69	0.113
Linear	6	148.36	24.726	5.83	0.025
Dyeing method	1	13.08	13.083	3.09	0.129
Mordant type	3	124.71	41.569	9.81	0.010
Mordant concentration	2	10.57	5.283	1.25	0.353
2-Way interactions	11	45.36	4.123	0.97	0.543
Dyeing method*mordant type	3	14.55	4.849	1.14	0.405
Dyeing method*mordant concentration	2	11.93	5.965	1.41	0.315
Mordant type*mordant concentration	6	18.88	3.147	0.74	0.637
Error	6	25.43	4.239		
Total	23	219.15			
[f]R^2 = 88.39%					

Notes: [a]degree of freedom; [b]Adjusted sum of squares; [c]Adjusted mean squares; [d]The test statistic used in the analysis of variance; [e]A measure of the probability that an observed difference could have occurred just by random chance; [f]Coefficient of determination/goodness of fit

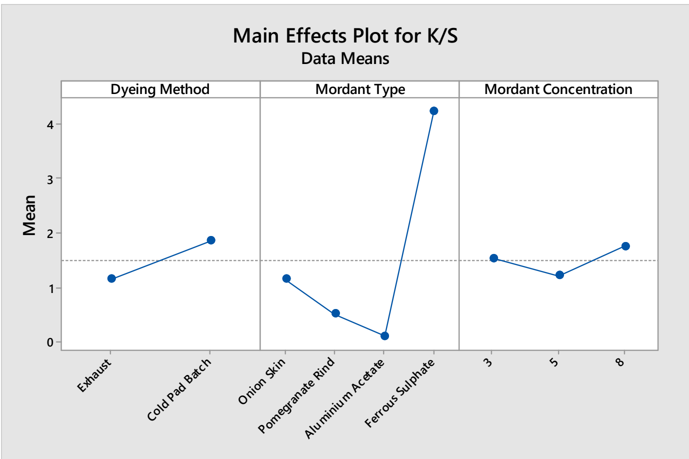

Figure 1: Main effects plot of variables on K/S of green dyeing process using banana leaf-based natural dyes

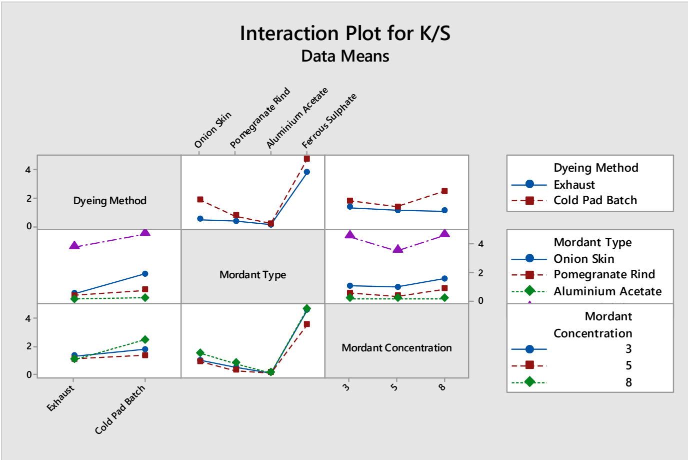

Figure 2: Interaction plot of variables on K/S of the green dyeing process using banana leaf-based natural dyes

Dyeings utilising onion skin and pomegranate rind extracts as mordants demonstrated poor wash fastness, with grey scale (GS) ratings ranging from 1 to 2, indicating substantial colour loss upon washing. In contrast, samples mordanted with aluminium acetate and ferrous sulphate showed good to excellent wash fastness, with GS ratings between 4 and 5.

Table 5
ANOVA of colour change for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	53.9688	3.1746	7.09	0.012
Linear	6	45.0625	7.5104	16.77	0.002
Dyeing method	1	3.7604	3.7604	8.40	0.027
Mordant type	3	39.3646	13.1215	29.29	0.001
Mordant concentration	2	1.9375	0.9688	2.16	0.196
2-Way interactions	11	8.9062	0.8097	1.81	0.241
Dyeing method*mordant type	3	2.0313	0.6771	1.51	0.305
Dyeing method*mordant concentration	2	0.3958	0.1979	0.44	0.662
Mordant type*mordant concentration	6	6.4792	1.0799	2.41	0.154
Error	6	2.6875	0.4479		
Total	23	56.6563			
[f]R^2 = 95.26%					

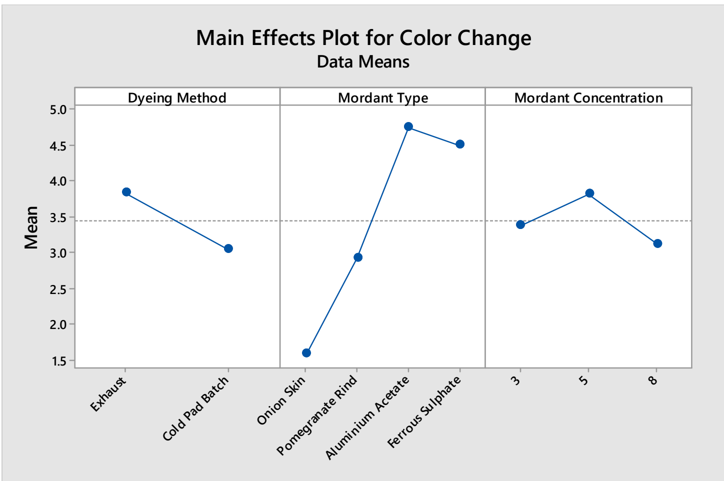

Figure 3: Main effects plot of variables on colour fastness to wash of green dyeing process using banana leaf-based natural dyes

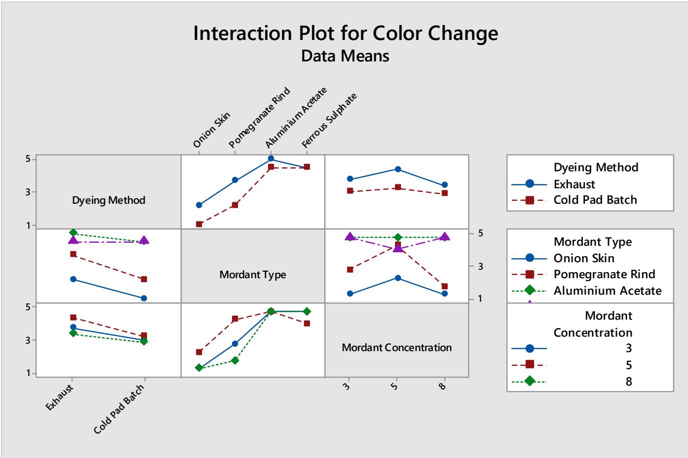

Figure 4: Interaction plot of variables on colour fastness to wash of green dyeing process using banana leaf-based natural dyes

Furthermore, the main effects plot revealed that the exhaust dyeing method yielded superior wash fastness results compared to the cold pad batch technique. Notably, variations in mordant concentration had no significant influence on the shade stability of the eco dyeing process when banana leaf extract was employed as the dye source.

Investigation of colour fastness to dry rubbing

Rubbing fastness refers to the resistance of dyed fabrics to colour fading due to friction, and it is typically assessed under both dry and wet conditions. Tables 6 and 7 present the ANOVA results for colour fastness to dry rubbing in the warp and weft directions, respectively.

Table 6 indicates that dry rubbing fastness in the warp direction is significantly influenced by the type of mordant used ($p = 0.015$). In contrast, Table 7 shows that dry rubbing fastness in the weft direction is affected not only by the mordant type, but also by the interaction between mordant type

The interaction plot (Fig. 4) confirmed that samples dyed with aluminium acetate using the exhaust method consistently achieved excellent wash fastness (GS = 5), regardless of the mordant concentration. Additionally, as indicated in Table 3, all experimental runs involving banana leaf-based eco-dyeing exhibited no staining on the multi-fibre fabric, with a uniform GS rating of 5.

and concentration ($p = 0.000$ and $p = 0.049$, respectively). The main effects plots in Figures 5 and 6 demonstrate that the dyeing method, whether cold pad-batch or exhaust, has no significant impact on dry rubbing fastness in either direction. Similarly, the mordant concentration alone does not exert a statistically significant effect on rubbing fastness in either the warp or weft direction.

However, samples mordanted with onion skin, pomegranate rind, or aluminium sulfate exhibited excellent dry rubbing fastness in both warp and weft directions, with a grey scale (GS) rating of 5 for colour change.

Table 6
ANOVA of dry rubbing (warp) for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	4.70833	0.27696	2.22	0.166
Linear	6	3.45833	0.57639	4.61	0.043
Dyeing method	1	0.00000	0.00000	0.00	1.000
Mordant type	3	3.12500	1.04167	8.33	0.015
Mordant concentration	2	0.33333	0.16667	1.33	0.332
2-Way interactions	11	1.25000	0.11364	0.91	0.580
Dyeing method*mordant type	3	0.00000	0.00000	0.00	1.000
Dyeing method*mordant concentration	2	0.25000	0.12500	1.00	0.422
Mordant type*mordant concentration	6	1.00000	0.16667	1.33	0.368
Error	6	0.75000	0.12500		
Total	23	5.45833			
[f]R^2 = 86.26%					

Table 7
ANOVA of dry rubbing (weft) for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	7.27083	0.42770	13.69	0.002
Linear	6	6.39583	1.06597	34.11	0.000
Dyeing method	1	0.00000	0.00000	0.00	1.000
Mordant type	3	6.12500	2.04167	65.33	0.000
Mordant concentration	2	0.27083	0.13542	4.33	0.068
2-Way interactions	11	0.87500	0.07955	2.55	0.131
Dyeing method*mordant type	3	0.00000	0.00000	0.00	1.000
Dyeing method*mordant concentration	2	0.06250	0.03125	1.00	0.422
Mordant type*mordant concentration	6	0.81250	0.13542	4.33	0.049
Error	6	0.18750	0.03125		
Total	23	7.45833			
[f]R^2 = 97.49%					

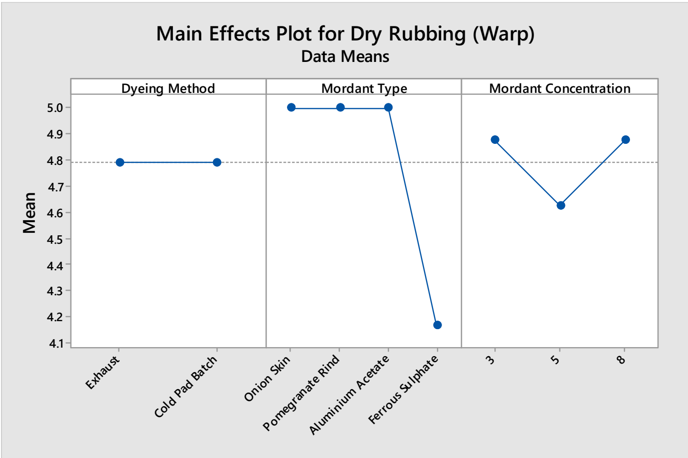

Figure 5: Main effects plot of variables on dry rubbing warp of green dyeing process using banana leaf-based natural dyes

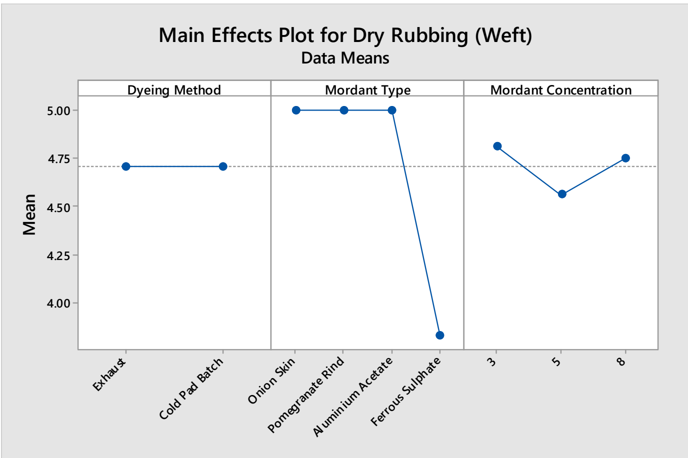

Figure 6: Main effects plot of variables on dry rubbing weft of green dyeing process using banana leaf-based natural dyes

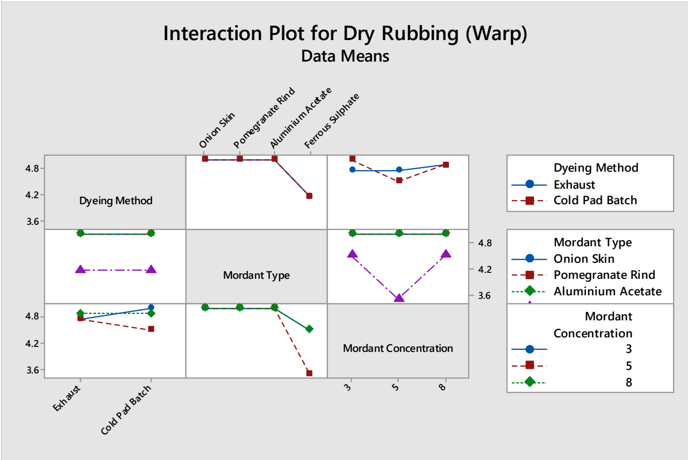

Figure 7: Interaction plot of variables on dry rubbing warp of green dyeing process using banana leaf-based natural dyes

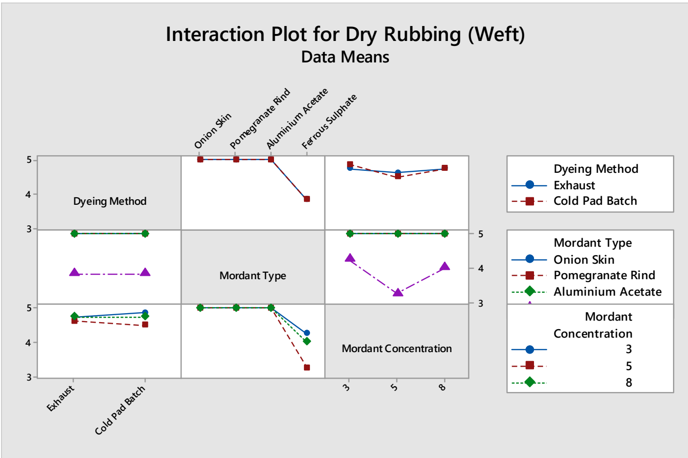

Figure 8: Interaction plot of variables on dry rubbing weft of green dyeing process using banana leaf-based natural dyes

Dyeings mordanted with ferrous sulphate, while slightly less effective, still demonstrated good rubbing fastness, achieving a GS rating of 4.

Given the significant interaction between mordant type and concentration in the case of dry rubbing in the weft direction, further analysis through the interaction plot in Figures 7 and 8 is warranted. This plot confirms that samples mordanted with aluminium acetate consistently achieved a GS rating of 5 across all tested concentrations. In contrast, the other mordants exhibited variable performance, with rubbing fastness fluctuating as mordant concentration increased from 3% to 5% or 8%.

Investigation of colour fastness to wet rubbing

Wet rubbing fastness is a critical parameter in evaluating the post-dyeing performance of textiles, particularly their behaviour during laundering. The ANOVA results for wet rubbing fastness in the warp and weft directions are presented in Tables 8 and 9, respectively.

As indicated by Table 8, wet rubbing fastness in the warp direction is significantly influenced by both the mordant type ($p = 0.007$) and the dyeing method ($p = 0.000$). In contrast, Table 9 reveals that wet rubbing fastness in the weft direction is solely dependent on the mordant type ($p = 0.000$).

The main effects plots in Figures 9 and 10 demonstrate that, except for ferrous sulphate, all mordants produced good to excellent wet rubbing fastness in both directions, with grey scale (GS) ratings for colour change ranging between 4.5 and 5. Notably, in the warp direction, dyeings carried out using the exhaust method yielded comparatively higher wet rubbing fastness values than those obtained through the cold pad-batch method.

Although no statistically significant interactions were observed in the ANOVA for wet rubbing fastness in either direction, further insights are provided by the interaction plots in Figures 11 and 12. These plots suggest that aluminium acetate at a 3% concentration, when applied using either the exhaust or cold pad-batch dyeing method, consistently results in good to excellent wet rubbing fastness.

Table 8
ANOVA of wet rubbing (warp) for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	6.37500	0.37500	9.00	0.006
Linear	6	5.12500	0.85417	20.50	0.001
Dyeing method	1	0.66667	0.66667	16.00	0.007
Mordant type	3	4.20833	1.40278	33.67	0.000
Mordant concentration	2	0.25000	0.12500	3.00	0.125
2-Way interactions	11	1.25000	0.11364	2.73	0.115
Dyeing method*mordant type	3	0.25000	0.08333	2.00	0.216
Dyeing method*mordant concentration	2	0.08333	0.04167	1.00	0.422
Mordant type*mordant concentration	6	0.91667	0.15278	3.67	0.069
Error	6	0.25000	0.04167		
Total	23	6.62500			
[f]R^2 = 96.23%					

Table 9
ANOVA of wet rubbing (weft) for green dyeing process using banana leaf-based natural dyes

Source	DF[a]	Adj SS[b]	Adj MS[c]	$F_{Statistics}$[d]	p-value[e]
Model	17	9.9792	0.58701	7.35	0.010
Linear	6	8.3125	1.38542	17.35	0.001
Dyeing method	1	0.3750	0.37500	4.70	0.073
Mordant type	3	7.5417	2.51389	31.48	0.000
Mordant concentration	2	0.3958	0.19792	2.48	0.164
2-Way interactions	11	1.6667	0.15152	1.90	0.223
Dyeing method*mordant type	3	0.2083	0.06944	0.87	0.507
Dyeing method*mordant concentration	2	0.1875	0.09375	1.17	0.371
Mordant type*mordant concentration	6	1.2708	0.21181	2.65	0.130
Error	6	0.4792	0.07986		
Total	23	10.4583			
[f]R^2 = 95.42%					

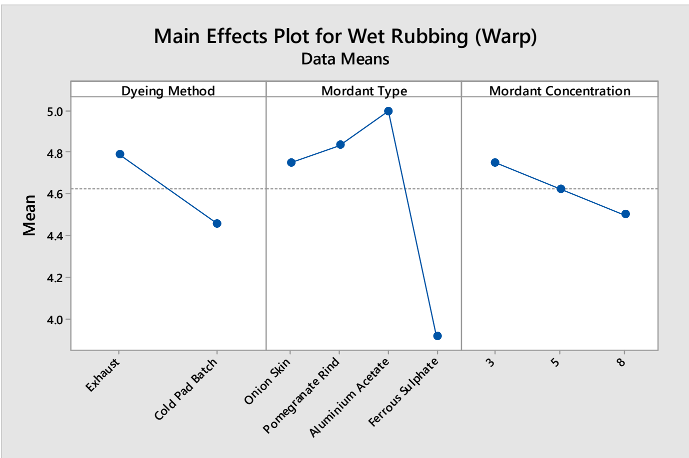

Figure 9: Main effects plot of variables on wet rubbing warp of green dyeing process using banana leaf-based natural dyes

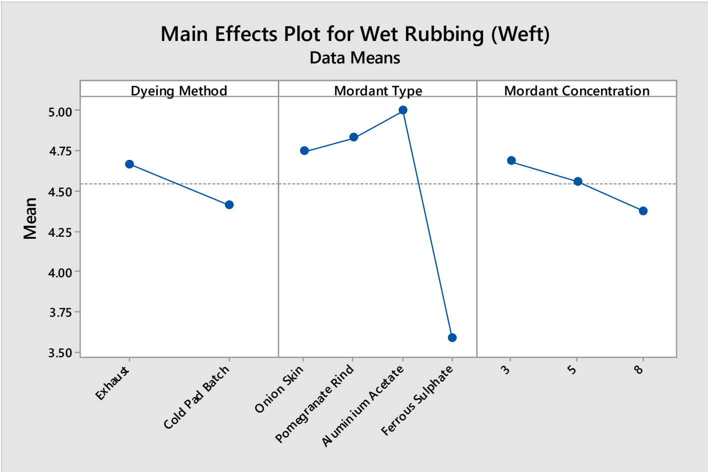

Figure 10: Main effects plot of variables on wet rubbing weft of green dyeing process using banana leaf-based natural dyes

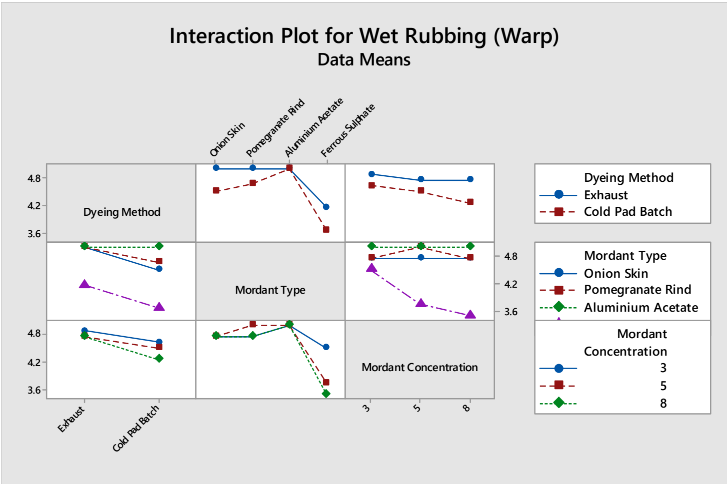

Figure 11: Interaction plot of variables on wet rubbing warp of green dyeing process using banana leaf-based natural dyes

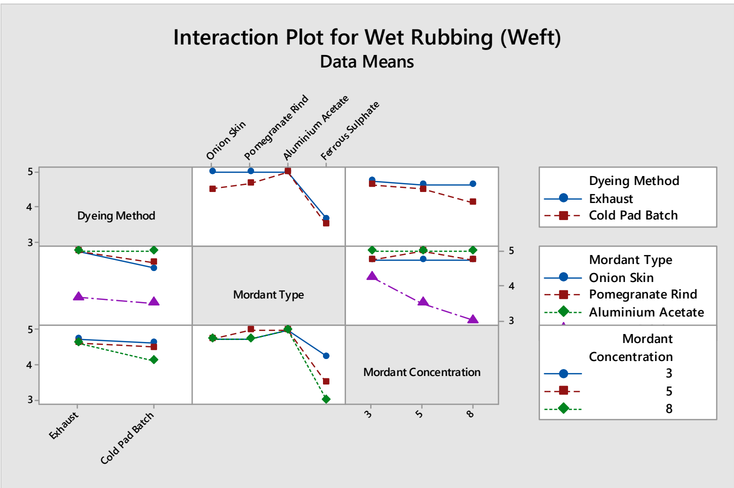

Figure 12: Interaction plot of variables on wet rubbing weft of green dyeing process using banana leaf-based natural dyes

Table 10
Optimum values of process parameters for green dyeing process using banana leaf-based natural dyes through Multiple Response Prediction (all responses maximized)

Variable factors	Levels	Composite desirability (D)
X_1: Dyeing method	Cold pad batch	
X_2: Mordant type	Ferrous sulphate	
X_3: Mordant concentration	3	
Responses (y)		0.7531
K/S	4.89	
Colour change	5	
Dry rubbing (warp)	5	
Dry rubbing (weft)	4.5	
Wet rubbing (warp)	4.5	
Wet rubbing (weft)	4.5	

This finding supports the potential application of aluminium acetate as an effective mordant for enhancing colour durability under wet frictional conditions.

Optimisation of process parameters using composite desirability approach

To enhance the colour strength and fastness properties of textiles dyed through a sustainable green colouration process utilising banana leaves, a comprehensive optimisation of the process parameters was conducted. This optimisation was performed using a multiple response prediction methodology based on the composite desirability function (D), a robust statistical tool that enables the simultaneous optimisation of multiple dependent variables.

The statistical analysis and optimisation were executed using Minitab 18 software, which facilitated the estimation of the composite desirability by integrating individual desirability values of multiple responses into a single metric. In this study, six key responses, including colour strength (K/S value) and various fastness properties, were considered critical indicators of dyeing performance. Each response was assigned equal weightage, ensuring a balanced consideration of all quality attributes in the optimisation process. The detailed summary of results derived from this desirability-based approach is presented in Table 10.

The analysis revealed that the optimal dyeing conditions for maximising both colour strength and fastness characteristics involved the use of the cold pad batch (CPB) dyeing method, in conjunction with ferrous sulphate as a mordant at a concentration of 3% (on weight of fabric). Under these optimised conditions, the process achieved a composite desirability (D) value of 0.7531, indicating a high level of overall process desirability. This configuration not only enhanced the depth of shade, but also yielded good to excellent ratings across all evaluated fastness parameters, confirming its efficacy and potential for sustainable textile colouration using agro-based natural resources.

CONCLUSION

The findings of this study demonstrate that the choice of mordant and dyeing method plays a pivotal role in determining the fastness properties of eco-dyed cotton fabrics. Natural mordants, such as onion skin and pomegranate rind extracts, resulted in lower colour strength and poor wash fastness, whereas aluminium acetate and ferrous sulphate imparted good to excellent fastness properties. Among the mordants tested, ferrous sulphate at an 8% concentration applied through the cold pad batch method resulted in the highest K/S values (6.01), demonstrating its superior ability to form stable dye–mordant complexes with the polyphenolic compounds present in banana leaf extract and its potential for enhancing shade depth. It also exhibited the best wash fastness performance, showing negligible colour change and staining after laundering.

Nevertheless, the exhaust dyeing method consistently provided superior wash fastness, particularly when aluminium acetate was employed as the mordant, as indicated by colour change ratings ranging from 4.5 to 5.

The interaction between mordant type and concentration was evident in rubbing fastness, especially in the weft direction. Aluminium acetate demonstrated superior consistency, maintaining the highest rating across concentrations, whereas other mordants showed variability with increasing concentration.

Overall, these findings establish aluminium acetate, in combination with the exhaust dyeing method, as the most effective and reliable strategy for achieving durable and sustainable colouration using banana leaf-based natural dyes. The results highlight the potential of eco-friendly dyeing processes to balance environmental responsibility with high textile performance, while also providing a foundation for future work on optimising mordant–dye interactions for improved fastness properties.

Future work may focus on the development and evaluation of fully bio-based mordants as sustainable alternatives to metallic salts, as well as the application of banana leaf pigments on other textile substrates, such as silk, wool, viscose, and blended fabrics.

ACKNOWLEDGEMENTS: The authors would like to thank the Department of Textile Engineering, NED University of Engineering and Technology and Archroma Pakistan Limited for providing technical facilities to fulfil the requirements of the experimental work.

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