EXPLORING ECO-FRIENDLY APPLICATION OF JASHIR (*PRANGOS FERULACEA*) AND POMEGRANATE (*PUNICA GRANATUM*) BASED BINARY MIXTURE AS NATURAL DYE FOR COTTON DYEING

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The reuse of agro-waste materials as a source of sustainable dyes is a global demand for the textile and allied industries. This study appraises the dyeing performance of a binary extract from Jashir leaves (*Prangos ferulacea*) and pomegranate peel (*Punica granatum*) onto cotton fabric. A central composite design consisting of 31 experiments was developed using Design-Expert software, and the experimental results were analyzed using a two-way ANOVA. Eco-friendly chemical mordants and bio-mordants were applied before, after, and during the dyeing of the cotton. It was found that the binary extract at pH 11, obtained from 8 g of powder after microwave (MW) treatment for up to 4 min at 80 °C for 35 min, with 2 g/100 mL of salt, gave excellent colour strength. The evaluation of fastness properties revealed that using the optimum values of the variables, the binary mixture has the potential to furnish colorfast shades.

Keywords: cellulosic dyeing, color fastness, CCD, eco-friendly coloration, natural dyeing, sustainable textiles

INTRODUCTION

The toxic effluents discharged by the textile and other industries are destroying the beauty and the health of ecosystems.[1-2] For a healthy environment, it is imperative to promote non-toxic and biodegradable substitutes for carcinogenic synthetic products. The use of eco-friendly products, such as natural dyes in the textile, leather, food and other industries, has gained popularity due to their promising role in protecting aquatic eco-systems and human health.[3] In the textile industry, by utilizing green alternatives derived from plant sources, bio-dyes have the potential to enhance the environmental sustainability of this sector, while providing visual appeal to textiles.[4–5] Natural dyes are obtained from various origins, but plant sources offer a wide range of colorants that furnish a variety of shades onto fabrics.[6] These natural colorants not only impart soothing hues to textiles, but also possess distinct biological and ayurvedic characteristics.[7]

Although natural dyes have many advantages over synthetic dyes, they also have some limitations that need to be overcome.[8] One of the limitations is the low yield, which can be enhanced by using modern isolation methods, *e.g.*, microwave assisted extraction (MAE) techniques.[9] Among the conventional methods for the extraction of natural colorants, microwave assisted extraction (MAE) has manifold benefits.[10-11] It is an easy-to-use and a low-cost technique that has potential to provide maximum color strength.[12-13] Moreover, under the influence of heat and microwave power, colorants penetrate more deeply into the fabric, which helps in the formation of high strength shades.[14] Microwaves transfer their energy to water molecules; when these molecules hit the plant cell wall, they break the bonds, which accelerates mass transfer kinetics.[15-16] Thus, through this rapid water-colorant interaction, notably less solvent, energy, and time are consumed, and an efficient yield is obtained. Another limitation of natural dyeing is a low colorfastness rating, which can be improved by using eco-friendly chemicals and bio-mordants. Bio-mordanting are very promising, as the use of biomolecules is sustainable, eco-friendly, and has the potential to replace toxic heavy metal electrolytes.[17-19] The use of bio-mordants not only increases colorfastness, but also yields a variety of shades with enhanced color strength.[20]

The use of binary mixtures from different plant sources is a relatively new approach in the sustainable dyeing industry. Although numerous efforts to standardize the natural dyeing process are currently undergoing laboratory trials, product development aimed at saving time, energy, and labor costs has already greatly influenced the industry. Among these methods, central composite design (CCD) has been successfully used to not only improve dye uptake, but also enhance color depth, while reducing the number of experiments.[21-22] This useful tool adds value to process optimization by optimizing selected variables, which ultimately helps save energy, time, and costs.

In this study, Jashir leaves (*Prangos ferulacea* = JL) and pomegranate peel (*Punica granatum* = PP) were selected as sources of a binary colorant system for cotton dyeing. The extract of pomegranate peel possesses both coloring and medicinal potential.[23] This extract exhibits antioxidant, antibacterial, antiseptic, antifungal, and wound-healing properties, which are attributed to the presence of tannins (Fig. 1a) and other biomolecules. Jashir is also a source of flavonoid-based colorants (Fig. 1b), exhibiting antimicrobial, antioxidant, and various other medicinal properties.[24] Cotton is a versatile fiber composed of cellulosic units (Fig. 1c), whose terminal hydroxyl groups (-OH) form bonds with dye molecules.

To the authors' knowledge, no studies have yet explored the binary mixture of natural dyes from Jashir leaves (*Prangos ferulacea*) and pomegranate peels (*Punica granatum*) for cotton dyeing. Specifically, the integration of a statistical approach for process optimization, microwave (MW) irradiation to improve dye uptake, and eco-friendly bio-mordants to enhance color strength and colorfastness has not been reported so far. Therefore, the current study was undertaken to investigate the dyeing performance of this binary colorant system on cotton fabric using central composite design (CCD). Additionally, this research aims to determine the optimum concentrations of eco-friendly additives required to develop new, colorfast shades.

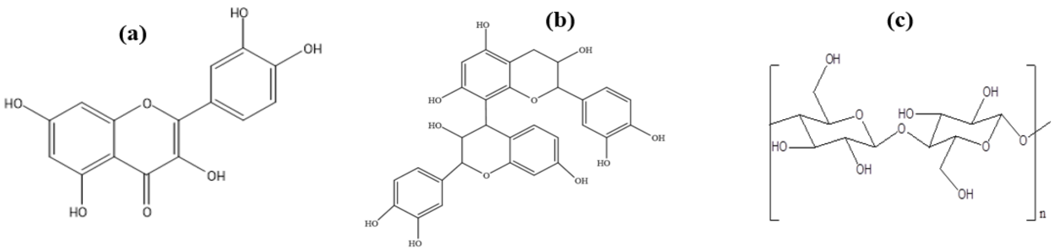

Figure 1: Chemical structures of flavonoids (a), tannins (b) and the cellulosic unit of cotton (c)

EXPERIMENTAL

Materials

Agricultural residues, such as jashir leaves (*Prangos ferulacea* = JL) and pomegante peels (*Punica granatum* = PP) were ground finely and sieved up to 20 mesh. Pretreated cotton fabric (GSM 100 g/m^2) was washed with a neutral soap solution. Commercial grade mordants, such as tannic acid (TA), salts of Al^{+3} and Fe^{+2}, neutral soap, sodium carbonate and formic acid were purchased from a local chemical market. Tannin-based bio-mordant sources, such as red sumac (*Rhus typhina* = SU) and myrobalan (*Terminalia chebula* = MB) were provided by Yazd University (Yazd, Iran), and were ground finely, sieved up to 20 mesh and saved for future processes.

Isolation of the colorant

2 g of dried and ground jashir leaves (JL) and pomegranate peel (PP), mixed in the ratio of 1:1, were added to 100 mL of distilled water and boiled for 60 minutes. The same process of isolation was used for different concentrations of the mixed powder of jashir and pomegranate: 4, 6, 8 and 10 g, mixed in the same ratio and boiled in 100 mL of water, as given by the central composite design (CCD). The binary extracts of each concentration were filtered and stored until the dyeing process.

Optimization of dye bath parameters

The central composite design (CCD) through response surface methodology (RSM) was used to select dyeing variables and find out the significance of their interaction.[25] The following ranges were introduced into Minitab software for the construction of the design: pH (8-12), time (25-65 min), temperature (50-90 °C), amount of binary powder (2-10 g/100 mL) and salt (1-5 g/100 mL). A design of 31 experiments was created and each experiment was run separately (Table 1). The results were analyzed using two-way analysis of variance and the significant interactions between dyeing variables were observed.[26-27]

Use of microwave treatment

To achieve more promising dyeing results, the role of microwave (MW) treatment in cotton dyeing using the binary extract of JL and PP was investigated. Three distinct approaches were evaluated to observe the effects of MW irradiation for up to 10 min using a high-power (700 W, 500 Hz) microwave source.

In the first series, the binary extract of the selected concentration and the fabric were subjected to MW treatment for 2, 4, 6, 8, and 10 min; subsequently, dyeing after irradiation (DAR) of these materials was performed under statistically optimized conditions.

In the second series, extracts from pomegranate peel and Jashir leaves were prepared separately and then mixed. After mixing, this combined extract and the fabric were simultaneously irradiated for 2, 4, 6, 8, and 10 min (radiation after mixing – RAM), followed by dyeing under optimum conditions.

For comparative purposes, in the third series, the separate extracts of PP and JL were individually exposed to microwave radiation for up to 10 min. After irradiation, these extracts were mixed (radiation before mixing – RBM) and then used to dye the fabric under the specified conditions.

Mordanting of dyed fabric

Additives (both synthetic and ecological) were used to enhance the colorfastness rating and to develop new shades of high strength. In the chemical mordanting process, the salts of Al^{+3} (alum), Fe^{+2} (iron sulfate) and tannic acid (TA) were used before, after and during the dyeing of cotton fabric under optimum conditions. For this purpose, a stock solution of each chemical mordant (1-3 g/100 mL) was prepared and 25 mL of each mordant was used to treat 1 g of fabric at 60 ℃ for 45 minutes, maintaining a liquor ratio (LR) of 25:1. For bio-mordanting, plant based functional molecules from red sumac (SU) and myrobalan (MB) were extracted and applied to cotton fabric by the same pre-, post-, and meta-mordanting techniques under the same conditions.[28] The bio-mordant stock solutions were prepared by boiling 1-3 g of SU powder and MB with 100 mL of water for 45 min. After filtration, 25 mL of extracted bio-mordant was used to treat (mordant) 1 g of cotton fabric under the same conditions (60 ℃ for 45 min, at a liquor ratio of 25:1).

Characterisation of the extract and dyed fabrics

To identify functional groups, the spectral analysis of the binary colorant system of JL and PP was done using an ATR-FTIR spectrophotometer in the range of 500-4000 cm^{-1}.

SEM images of the cotton samples were taken before and after MW treatment. For determining the color strength (K/S) and tonal expressions (L^*, a^*, b^*, c^* and h) of dyed cotton samples, the CIE Lab system using Data Color SF600 was used. The Kubelka Munk equation was used to determine color strength (Eq. 1):

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \qquad (1)$$

Colorfastness against rubbing (dry and wet) was evaluated by rubbing dry and wet dyed fabric up to 10 turns and the results were compared to the grey scale according to ISO 105-X12 standard. Washing fastness tests were done by washing dyed fabrics with neutral soap according to ISO 105-C03, and the changes in color were assessed by comparing to the grey scale. Light fastness was assessed by exposing the dyed fabric to a Xeon arc lamp by the ISO 105-B02 method and the results were assessed on the blue scale.

RESULTS AND DISCUSSION

For the extraction of natural colorants, the amount of binary plant powder is a key factor. Based on a series of preliminary experiments, the extract of 8 g (composed of 4 g/100 mL of JL and 4 g/100 mL of PP) was selected as it yielded the maximum color strength (K/S) of 4.86 (Table 1). In contrast, the smallest amount of binary powder (2 g/100 mL) resulted in the lowest color strength (K/S = 2.43), while the highest amount (10 g/100 mL) also led to a decline in color strength, reaching only 2.87.

Cellulosic fabrics require a specific medium for dyeing with plant-derived natural colorants. At pH 11, the binary extract produced the highest color strength. Under these alkaline conditions, the terminal hydroxyl groups (–OH) of the fabric are readily deprotonated, facilitating firm bonding with the –OH groups of the binary colorants. Statistically, the effect of the dyebath pH was found to be highly significant ($p = 0.008$). Furthermore, two-way interaction analyses revealed that dyebath pH had highly significant interactions with both dyeing time ($p = 0.000$) and dyeing temperature ($p = 0.000$). Consequently, the selected dyebath pH exerts a critical influence on the dyeing performance of cotton with this binary extract.

The addition of salts is necessary when dyeing cotton with plant-derived binary colorants, as a specific amount of salt helps establish stable interactions between the dye and the fiber.[29] When cotton fabric is immersed in an aqueous solution, it develops a negative surface charge that repels the anionic sites of the colorant. The addition of a 2 g/100 mL salt solution helps overcome this electrostatic repulsion, thereby facilitating firm bonding and yielding high color strength. Statistically, the effect of salt concentration as an individual factor was found to be highly significant ($p = 0.000$), and its interaction with dyebath pH (pH 11) was also highly significant. Furthermore, in combination with the selected dyeing time and temperature, the optimum salt concentration demonstrated a highly significant impact ($p = 0.000$) on the dyeing process. Therefore, a dyebath at pH 11 containing 2 g/100 mL of salt as an exhausting agent should be utilized for dyeing cotton with the binary extract of JL and PP.

Cotton dyeing using this binary mixture is also highly dependent on contact time. Prolonged dyeing times may lead to thermal degradation of the colorant, while excessive heat can promote dye desorption due to a shift in equilibrium toward retardation rather than exhaustion. Under these conditions, hydrolyzed dye products are more likely to sorb onto the fiber instead of the actual colorant, resulting in shades of low color strength. Conversely, short dyeing times limit the dyeing rate because the dye molecules are adsorbed as aggregates and remain strictly on the fiber surface.[30] Consequently, cotton dyeing with this binary mixture must be conducted for a specific duration to achieve efficient color strength.

Table 1
Color strength (K/S) values of cotton dyed with the binary extract of jashir leaves and pomegranate peel using CCD

Powder amount (g/100 mL)	Dyeing time (min)	Dyeing temperature (°C)	Salt amount (g/100 mL)	Extract pH	Colour strength (K/S)
4	35	60	2	11	1.85
8	35	60	2	9	1.65
4	55	60	2	9	2.24
8	55	60	2	11	2.73
4	35	80	2	9	2.07
8	35	80	2	11	4.86
4	55	80	2	11	2.20
8	55	80	2	9	3.84
4	35	60	4	9	1.83
8	35	60	4	11	2.38
4	55	60	4	11	1.58
8	55	60	4	9	1.36
4	35	80	4	11	1.88
8	35	80	4	9	3.33
4	55	80	4	9	1.79
8	55	80	4	11	4.07
2	45	70	3	10	2.43
10	45	70	3	10	2.87
6	25	70	3	10	3.12
6	65	70	3	10	2.12
6	45	50	3	10	1.80
6	45	90	3	10	3.14
6	45	70	1	10	1.81
6	45	70	5	10	0.75
6	45	70	3	8	1.61
6	45	70	3	12	1.12
6	45	70	3	10	0.99
6	45	70	3	10	1.02
6	45	70	3	10	1.26
6	45	70	3	10	1.23
6	45	70	3	10	1.25

Table 2
Analysis of variance (two-way ANOVA) for process optimization of cotton dyeing with JL/PP binary extract

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	20	24.2685	1.21342	50.32	0.000
Linear	5	7.4856	1.49712	62.09	0.000
Powder	1	0.2480	0.24797	10.28	0.012
Time	1	0.6110	0.61097	25.34	0.001
Temperature	1	1.9334	1.93337	80.18	0.000
Salt	1	1.7613	1.76132	73.04	0.000
pH	1	0.2930	0.29297	12.15	0.008
Square	5	8.2437	1.64875	68.37	0.000
Powder*Powder	1	3.7843	3.78429	156.94	0.000
Time*Time	1	3.6346	3.63458	150.73	0.000
Temperature*Temperature	1	2.9313	2.93135	121.56	0.000
Salt*Salt	1	0.0290	0.02902	1.20	0.305
pH*pH	1	0.0787	0.07867	3.26	0.109
2-Way Interaction	10	5.7707	0.57707	23.93	0.000
Powder*Time	1	1.0923	1.09230	45.30	0.000
Powder*Temperature	1	0.0442	0.04422	1.83	0.213
Powder*Salt	1	1.1799	0.17992	48.93	0.000
Powder*pH	1	0.0886	0.08857	3.67	0.092
Time*Temperature	1	0.3423	0.34227	14.19	0.005
Time*Salt	1	0.5288	0.52877	21.93	0.002
Time*pH	1	1.2076	1.20756	50.08	0.000
Temperature*Salt	1	0.3736	0.37359	15.49	0.004
Temperature*pH	1	0.8094	0.80940	33.57	0.000
Salt*pH	1	1.0401	1.04006	43.13	0.000
Error	8	0.1929	0.02411	-	-
Lack-of-Fit	4	0.1219	0.03048	1.72	0.307
Pure Error	4	0.0710	0.01775	-	-
Total	28	24.4614	-	-	-
Model summary					
	S	R^2	R^2 (adj)	R^2 (pred)	-
	0.155286	99.21%	97.24%	74.60%	-

The experimental results demonstrate that dyeing cotton with the binary extract at pH 11, with 2 g/100 mL of salt at 80 °C for 35 min, yielded the highest color strength. Statistical assessment confirmed that the effects of dyeing temperature ($p = 0.000$) and dyeing time ($p = 0.001$) were highly significant. Similarly, the interaction of time and temperature in the presence of the optimized salt concentration (2 g/100 mL), plant powder amount (8 g/100 mL), and pH 11 was also found significant (Table 2). Hence, based on CCD, the optimum results for dyeing cotton with the binary extract can be obtained at pH 11, with 2 g of salt at 80 °C for 35 min to obtain high color strength.

Role of MW treatment

The influence of microwave (MW) irradiation on the cotton dyeing process using the binary extract was evaluated through three distinct methods: dyeing after irradiation (DAR), irradiation of the combined mixture after mixing (RAM), and irradiation of each extract separately before mixing (RBM). The results indicated that a 2 min MW treatment applied to the materials prior to dyeing (DAR) yielded a lower color strength of 1.32 (K/S). Also, treating the combined binary extract for up to 6 min after mixing (RAM) produced slightly improved color strength of 1.38. However, separate MW irradiation of each plant extract for 4 min, followed by mixing and subsequent dyeing of cotton (RBM), yielded an exceptional color strength of 2.99 (Fig. 2). This enhancement occurs because the 4 min MW treatment effectively breaks down the colorant aggregates into smaller molecular clusters, which significantly improves dye uptake upon dyeing.

Microwave irradiation serves as an eco-friendly heating source for isolating natural colorants. It causes dipole rotation of water molecules, generating sufficient internal pressure and heat within the plant cell walls to cause their rupture. This localized thermal energy facilitates the rapid release of colorant compounds without thermal degradation, leading to high color strength when applied to cotton. Additionally, MW irradiation modifies the cotton fiber surface, which enhances dye accessibility and maximizes exhaustion. Consequently, accelerated mass transfer into the aqueous medium combined with MW-induced surface modification of the cotton fabric (for 4 min) favored high-quality dyeing.[31-32] Therefore, when using 8 g of binary powder for dye isolation (4 g/100 mL of *Jashir* + 4 g/100 mL of pomegranate), separate MW irradiation of both extracts and the fabric for 4 min represents the optimal condition to achieve excellent color strength.

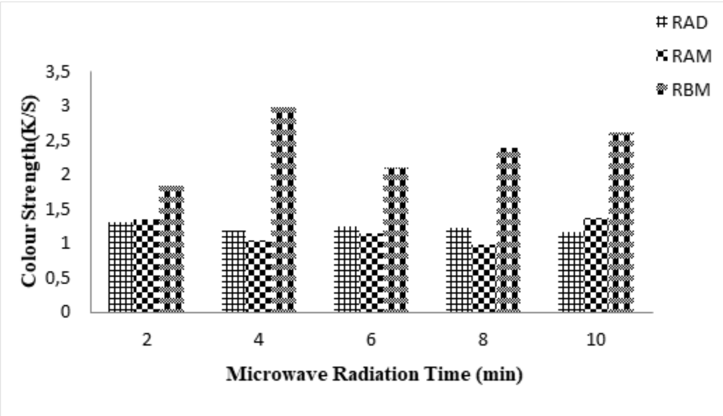

Figure 2: Effect of microwave (MW) radiation on color strength of cotton fabric died with JL/PP binary colorant

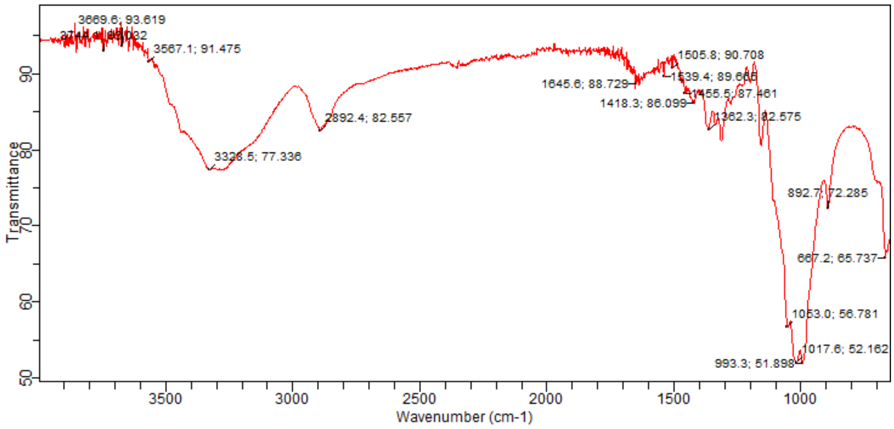

Figure 3: FTIR analysis of binary extract of jashir and pomegranate

FTIR analysis of the extract

The broad absorption bands identified at about 3689 cm^{-1} and 3567 cm^{-1} show the presence of hydroxyl groups belonging to the phenolic compounds present in the binary extract. The absorption peak at about 3336 cm^{-1} also indicates the existence of intermolecular hydrogen bonding between phenolic constituents of the jashir and pomegranate extracts. A specific band appearing at 2922 cm^{-1} is due to C–H stretching vibrations of aliphatic $-CH_2$ groups present in the binary extract.[23] The peak at 1645 cm^{-1} is due to the presence of C=O (carbonyl) groups characteristic of flavonoids. The characteristic peaks at 1053 and 1017 cm^{-1} indicate C–O stretching vibrations typical of alcohols, ethers, or carbohydrates. Thus, FTIR analysis confirms the presence of colorant compounds within the prepared binary mixture.

Morphological observation of cotton

The SEM images of cotton fibers present their surface appearance before (Fig. 4a) and after MW radiation (Fig. 4b). The images reveal some changes on the fiber surfaces in response to MW treatment.[32] The cotton fibers before radiation (a) look smooth and well-defined, with very little surface irregularities. Meanwhile, Figure 4b illustrates the effects of MW treatment on the fiber surface appearance – a modified texture is noted, which can lead to improved sorption behavior.[34]

Hence, the MW treatment can induce a rougher fiber surface, which can alter the behavior of the fabric towards colorants.

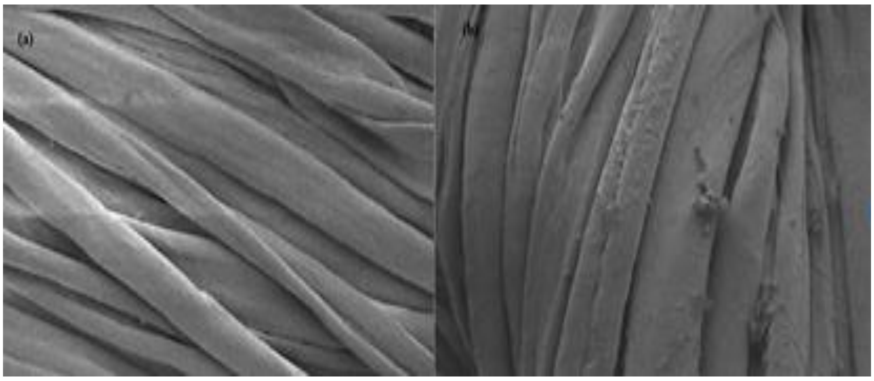

Figure 4: SEM images of cotton before (a) and after (b) MW radiation

Mordanting of dyed fabric

The dyeing of cotton with the binary extract from JL and PP was performed using eco-friendly mordants to enhance color strength and fastness. When applied before, after, or during the dyeing process, mordants have the potential to develop stable shades; however, shade fastness depends on the MW treatment time, dyeing conditions, and the nature of the fabric.[35] The Al^{3+} and Fe^{2+} salts used formed a dye complex with the hydroxyl (-OH) groups of the fabric and the binary colorant via coordinate bonding, yielding excellent results. Additionally, the organic mordant tannic acid (TA) enhanced the coloring behavior of the binary dyes by introducing supplementary hydrogen bonding between the colorant and the fabric.[36]

The results indicate that dyeing after the treatment of cotton with 2.5% TA, 1% Fe^{2+} salt, and 2% Al^{3+} solution produced excellent color strength. Among these variants, pre-mordanting (coating) the cotton with 1% Fe^{2+} salt developed the highest color strength (K/S = 3.79) under optimum dyeing conditions. Also, post-treatment with 1% TA, 2.5% Fe^{2+}, and 1% Al^{3+} salts gave high color strength; but among these options, post-treatment with a 1% TA solution achieved the maximum strength (K/S = 3.10) under optimum conditions. Furthermore, simultaneous addition (meta-mordanting) of 2.5% TA, 2.5% Fe^{2+} salt, and 1.5% Al^{3+} salt solutions during the dyeing process with the JL and PP binary extract resulted in high color strength (Fig. 5 a, b, c). Specifically, the addition of a 2.5% Fe^{2+} salt solution during the dyeing process yielded the overall highest shade strength (K/S = 6.32) recorded in this study. Consequently, these eco-friendly additives improved the shade depth through ionic interactions between the mordants, dye, and fabric.[37] Based on these results, it is recommended to use the optimized concentrations of eco-friendly mordants when dyeing cotton with this binary extract to achieve maximum shade strength (Fig. 5a-c).

The color coordinates given in Table 3 shows that meta-mordanting of cotton with a 3% TA solution during dyeing with the binary extract furnishes dark reddish-yellow shades having good chromaticity and high hue saturation (L^* = 69.44, a^* = 3.42, b^* = 22.72, C* = 22.97, h = 81.45). Also, the addition of the Fe^{+2}-salt solution (2.5%) during dyeing of cotton with the JL and PP binary extract developed a much darker shade, with reddish yellow tones, having good chromaticity and hue saturation (L^* = 44.56, a^* = 2.69, b^* = 11.55, C* = 11.86, h = 76.89). The use of 2% Al^{+3}-salt solution before dyeing (pre-mordanting) of cotton yielded a bright reddish yellow shade, having good chromaticity and hue saturation (L^* = 69.91, a^* = 4.15, b^* = 30.31, C* = 30.59, h = 82.2).

The effects of bio-mordents were also examined when added before, during and after the dyeing of cotton with the JL/PP binary colorant. Pre-mordanting of cotton with a 1.5% extract of red sumac (RS) or a 2.5% of myrobalan (MB) yielded excellent results. Similarly, post-mordanting treatment with 2% RS or 1% MB produced favorable results. Also, the addition of 1.5% of red sumac (RS) extract before dyeing led to K/S=3.24, and the addition of 3% of myrobalan extract during dyeing of cotton under selected conditions yielded K/S=3.28.

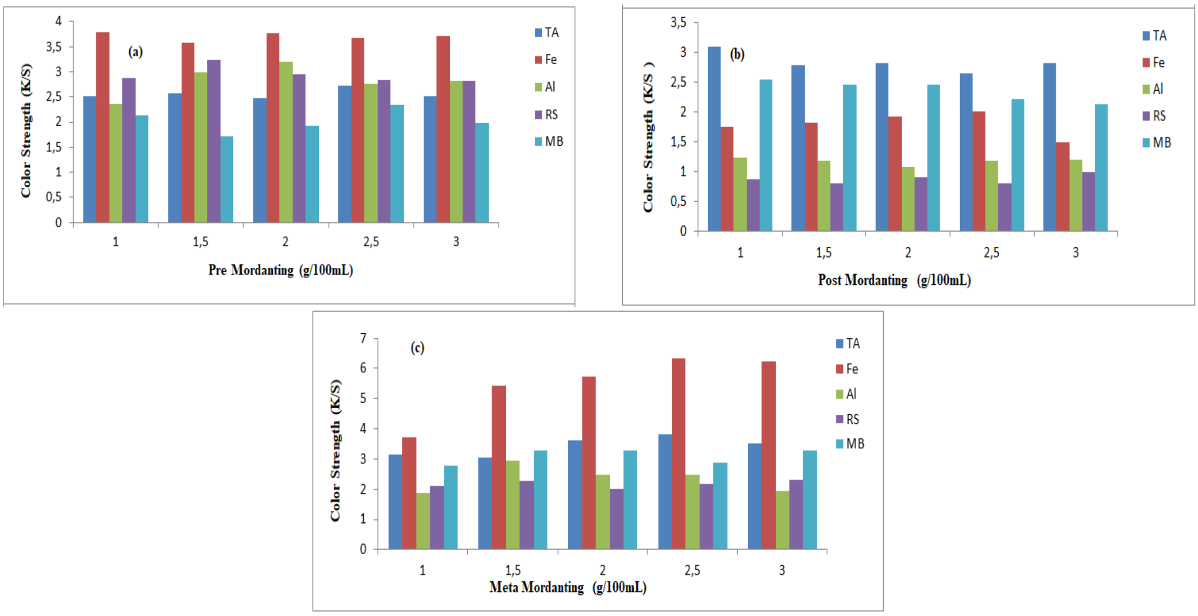

Figure 5: Shade development using chemical and bio-mordants before (a), after (b) and during (c) dyeing of cotton with JL/PP binary colorant

Table 3
K/S values and tonal variation of mordanted cotton and dyed with JL/PP binary colorant

Mordant used	*K/S*	*L**	*a**	*b**	*C**	*h*	Shade
Without mordant	2.99	71.53	3.59	27.47	27.77	82.65	
TA pre 2.5%	2.72	70.35	3.72	27.26	27.52	82.22	
TA post 1%	3.1	69.44	3.42	22.72	22.97	81.45	
TA meta 2.5%	3.83	65.08	3.23	22.09	22.32	81.68	
Fe^{+2} pre 1%	3.79	63.67	4.22	25.96	26.3	80.77	
Fe^{+2} post 2.5%	2.02	60.56	0.77	9.53	9.56	85.41	
Fe^{+2} meta 2.5%	6.32	44.56	2.69	11.55	11.86	76.89	
Al^{+3} pre 2%	3.2	69.91	4.15	30.31	30.59	82.2	
Al^{+3} post 1%	1.24	77.59	0.01	20.07	20.07	89.98	
Al^{+3} meta 1.5%	2.95	76.43	0.5	33.83	33.83	89.15	
Red Sumac pre 1.5%	3.24	69.76	1.87	28.94	29	86.31	
Red Sumac post 3%	0.99	75.73	6.77	17.01	18.3	68.3	
Red Sumac meta 3%	2.31	72.97	3	26.26	26.43	83.49	
Myrobalan pre 2.5%	2.35	73.93	2.19	27.88	27.96	85.51	
Myrobalan post 1%	2.55	72.36	2.06	23.54	23.63	84.99	
Myrobalan meta 3%	3.28	68.39	3.23	25.33	25.54	82.74	

Therefore, utilizing specific concentrations of MB and RS extracts for the bio-mordanting of cotton is recommended to achieve firm and stable shades. The application of these bio-mordants produced a variety of shades; specifically, bio-coating with 1.5% RS followed by dyeing furnished a dark shade with a less reddish and more yellowish tone, characterized by lower chromaticity and higher hue saturation (L^* = 69.76, a^* = 1.87, b^* = 28.94, C^* = 29, h = 86.31). The addition of 3% of MB extract as bio-mordant during dyeing of cotton also yielded a dark yellow, less reddish-yellow shade, having good chromaticity and high hue saturation (L^* = 72.36, a^* = 2.06, b^* = 23.54, C^* = 23.63, h = 84.99). This variation in shade development is attributed to the phenolic nature of both the colorants and the mordants used. Overall, the formation of metal–dye complexes and hydrogen bonding between the hydroxyl (–OH) groups of the bio-mordant, colorant, and cellulosic units contributed to the stable tonal values and tint behavior. Consequently, the optimized concentrations of these mordants successfully provided high-quality, stable shades.

Colorfastness

The colorfastness properties of naturally dyed fabrics depend on the nature of the dye, the fabric pretreatment, the type of mordant used, and the specific dyeing conditions.[38]

In this study, the dyeing conditions optimized via a central composite design made the process more viable for mordanting to achieve colorfast shades. Additionally, MW treatment modified the fabric surface, enhancing its sorption behavior toward the binary colorant from JL and PP extracts, which subsequently enabled the eco-friendly additives to develop colorfast shades.[39] Unmordanted dyed cotton fabric exhibited low fastness ratings for light, washing, and rubbing (4-3/4). However, when cotton was mordanted before, after, or during dyeing with the binary colorant, the inclusion of inorganic and organic additives improved the fastness properties due to the strong interactions established among the additive, dye, and fabric.

Table 4
Fastness rating of mordanted cotton fabric dyed with JL/PP binary colorant

Mordant used	Light fastness	Wash fastness		Dry rubbing fastness	Wet rubbing fastness
		Color stain	Color change		
Without mordant	4	4	3/4	4	3/4
TA pre 2.5%	6	4/5	4/5	5	5
TA post 1%	5	4/5	4/5	5	4/5
TA meta 2.5%	5	4/5	4/5	5	4/5
Fe^{+2} pre 1%	6	4/5	4/5	5	5
Fe^{+2} post 2.5%	5	4/5	4/5	5	4/5
Fe^{+2}meta 2.5%	5	4/5	4/5	5	4/5
Al^{+3} pre 2%	5	4/5	4/5	5	5
Al^{+3} post 1%	6	4/5	4/5	5	4/5
Al^{+3} meta 1.5%	5	4/5	4/5	5	4/5
Red Sumac pre 1.5%	5	4	5	5	4/5
Red Sumac post 3%	6	4/5	4/5	5	4/5
Red Sumac meta 3%	6	4/5	4/5	5	5
Myrobalan pre 2.5%	5	4/5	4/5	5	4/5
Myrobalan post 1%	6	4/5	4/5	5	5
Myrobalan meta 3%	6	4/5	4/5	5	5

CONCLUSION

The present study demonstrates that the binary mixture of Jashir leaves and pomegranate peel extracts serves as an effective and sustainable natural dye system for cotton. The results highlight the promising role of microwave treatment in improving dye uptake. Furthermore, the tannins and flavonoids present in JL and PP played a crucial role in achieving deeper, high-strength shades with enhanced fastness properties on cellulosic fibers.

Thus, this work emphasizes the importance of reintroducing natural dyes as viable alternatives to synthetic colorants. Jashir and pomegranate are renewable, biodegradable, and easily accessible sources, making them highly suitable for eco-conscious textile production. By utilizing agricultural by-products, such as pomegranate peel, this approach also contributes to waste valorization and circular economy practices. Overall, the findings suggest that binary natural dye mixtures can reduce dependence on synthetic dyes and lower the ecological footprint of the textile sector, representing a significant step toward greener and more sustainable coloration processes. Future research focusing on process optimization and scale-up will further strengthen the industrial feasibility of such eco-friendly dyeing methods.

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