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Research Article

Introduction of Pan as a New Natural Dye for Eco-Friendly Wool Dyeing

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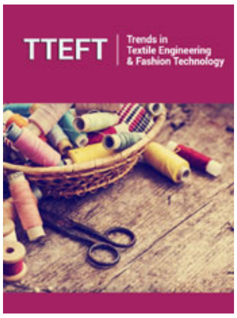

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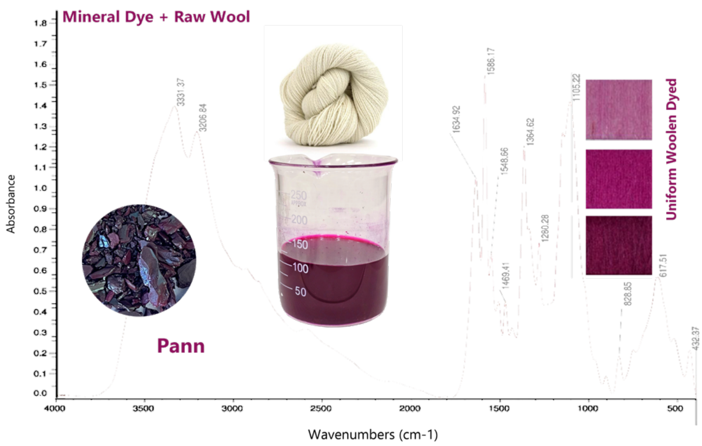
Abstract

Natural dyes have been used in textile dyeing for centuries, and their importance has recently increased due to growing concerns about the environmental impact of synthetic dyes. Natural dyes are biodegradable and environmentally compatible, offering a sustainable alternative for the textile industry. Mineral dyes, a subgroup of natural dyes, play a crucial role in natural dyeing, as they often serve as mordants, particularly in wool dyeing. This study introduces Pan, a mineral dye, as a new natural source capable of producing purple hues. Initially, X-ray and infrared scattering spectra were used to identify the dye content. We also evaluated how mordant type, mordanting method, dyeing pH, and temperature influence color hue, color strength, fastness properties (washing, staining, and light), and mechanical properties of dyed wool yarns. The results show that Pan produces various purple tones even at low concentrations of dye. The dyed samples exhibited moderate light and washing fastness. Using bio-mordants significantly improved washing fastness, though enhancing light fastness requires further investigation. Overall, this research highlights the potential of Pan as a sustainable and high-value mineral dye that can provide eco-friendly coloration for wool textiles (Graphical Abstract).



Keywords: Natural Dyeing; Mineral Dye; Pan; Wool Dyeing; Eco-friendly

Introduction

In recent year's textile dyeing process, especially woollen yarns with natural dyes, have been developed for various reasons such as environmental protection, non-toxicity, renewability, various color hues, antimicrobial and anti-allergy properties, and compatibility. Among these, the most common sources of natural dyes are plants. Many scientists in their research have introduced new natural resources for dyeing textiles. Shahid et al. [1], Guha [2], and Sohrabi et al. [3] have documented numerous plant sources used as natural dyes. Mineral dyes, derived from naturally occurring earth pigments, also exhibit good affinity for textiles and acceptable fastness. Their tinctorial properties arise from oxides or hydrated oxides of metals such as manganese. Common mineral dyes include chrome yellow, iron buff, Prussian blue, Nankin yellow, and manganese brown. Many minerals serve as mordants to fix or enhance vegetable dyes, while some minerals can directly impart color. Examples of such natural mordants include serum, cow urine, cow dung, and egg albumin. Extensive research has also explored the use of alternative sources of natural dyes, including residues from the food industry, for textile dyeing. Mortazavi et al. [4] and Adeel et al. [5] demonstrated that even plant residues from industrial processes can serve as viable sources for natural dyeing, with acceptable dyeing performance. Historically, red has been a prominent color in Iranian textiles, often combined with blue and yellow to create diverse hues. Traditional natural red dyes in Iran include cinnabar as a mineral mordant, madder, cochineal, and iron oxide, while more recent studies have introduced herbs such as red onion skin and beetroot. However, these alternatives often produce colors that deviate from pure red and exhibit poor fastness, limiting their economic viability. Some natural dyes containing anthocyanins are capable of producing shades within the purple color spectrum. Examples include dyes extracted from eggplant skin, onion skin, and beet. Abdul Daim [6], Pranta and Das [7], Ahmadi et al. [8], and Gumrukcu et al. [9] have successfully used dyes extracted from eggplant skin, sunflower seed skin, and red onion skin to dye wool and cotton products. These plant-derived dyes share an anthocyanin-based chemical structure. Dyes with the chemical structure of anthocyanin are sensitive to pH and their color changes with the pH of the dyeing bath, and their dyeing fastness was good to moderate. In both studies, the dyeing fastness of the dyed products was improved by using a mixture of tannic acid and metal mordant or other bio-mordant. Researchers have reported that the light fastness of dye yarn samples is not very satisfactory. Ahmad Khan et al. [10] used calico leaves to obtain red color on textile products. They used Copper mordant and tannic acid to increase the dyeing fastness, and gamma radiation was used on cotton products to increase dye absorption.

In another study, researchers used dyes extracted from bacterial culture to produce red color on textiles. In this study [11], a water-soluble dye obtained from a red pigment-producing microorganism (fungus) called *Penicillium purpurogenum* was used to obtain a red color. The results showed that the color of the dyed silk product was reddish-brown, and in dyeing cotton products, a pink color was observed. The extracted dye had a high affinity for silk and cotton and also showed more fastness to pH changes compared to natural dyes with anthocyanin structure. In another similar study [12] of 11 types of bacteria that were cultured with H-acid (1- naphthol-8-amino-3, 6-disulfonic acid) as a precursor for dye production, which were cultured at different temperature conditions and in a neutral environment, a dye with a red to brown hue was obtained. The extracted dyes were used for dyeing woollen products. Washing fastness showed good results, but light fastness had poor values. Despite the great advantages of natural dyes, the use of natural dyes has problems such as the complexity of the dyeing process, the problems of reproducing a color and the non-reproducibility of the process, poor dyeing fastness, and occupying a large volume of the dye bath with pulp. Plants are unavailable in different seasons of the year and there are limitations in terms of color shade variation [13]. To solve the mentioned problems, scientists have done a lot of research to simplify the method of using natural dyes, including the use of various extraction methods and the use of extracted dye powder instead of whole plants [14]. Nevertheless, metal mordants remain essential for enhancing fastness, though they can increase processing time, costs, and environmental concerns [15,16]. Therefore, if a natural material with dyeing properties that minimizes the above problems and can dye textile products with acceptable general fastness, it will be a valuable event in the field of natural dyeing. This study investigates Pan, a mineral substance with medicinal and dyeing properties, as a natural dye for textiles, aiming to optimize dyeing parameters and achieve acceptable fastness while minimizing environmental impact.

Experimental Materials and Equipment Required

Materials

We collected a naturally colored soil from the Sistan and Baluchistan province in southeastern Iran, known locally as Pan, which has traditionally been used for medicinal purposes. Pan appears dark, multi-component, non-dense, and polished. When immersed in water, it separates into soluble and insoluble fractions: the soluble fraction produces a purple color, while the insoluble fraction remains suspended. Heating the water to 60 °C or adding acid accelerates dissolution Figure 1.

Figure 1: Physical appearance of Pan.

Merinos two-ply wool yarn with a fineness of 20 metric was used. Auxiliary chemicals included acetic acid (CH_3COOH), lactic acid ($C_3H_6O_3$), oxalic acid ($C_2H_2O_4$), alum ($KAl(SO_4)_2 \cdot 12H_2O$), tin chloride ($SnCl_2 \cdot 2H_2O$), zinc sulfate ($ZnSO_4$), copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), iron sulfate heptahydrate ($FeSO_4 \cdot 7H_2O$), nickel chloride ($NiCl_2$), and potassium dichromate ($K_2Cr_2O_7$), all of Merck laboratory grade.

Equipment

Samples were analyzed using a Nicolet IS50 FTIR spectrometer, a Neicus 670 light fastness tester, a Color-Eye 7000A spectrophotometer, an energy-dispersive X-ray (EDX, TTE-

SCAN) analyzer, and an X-ray fluorescence (XRF, IXF-W-504-01) spectrometer. Mechanical properties were evaluated with an Instron 5566 universal testing machine.

Infrared spectroscopy (FTIR), EDX, and XRF analyses were performed in accordance with ISO/IEC 17025:2005 standards to determine the elemental composition of the Pan material. Energy-dispersive X-ray microanalysis (EDX) is widely recognized for providing detailed information on the elemental composition of pigments. The Aquaria dissolution method was applied to further identify the constituent components of the Pan substance. Tensile strength measurements of both raw and dyed yarn samples (25cm in length, approximately 1mm in diameter) were conducted using the Instron 5566 device equipped with a 50N load cell.

Dyeing

Dyeing Procedure: We studied the effects of dyeing parameters-including dyeing method, type and concentration of mordant, acid type, liquor ratio, temperature, and solvent-on color hue and fastness. Mordanting and dyeing diagrams are shown in Figure 2, and bath conditions are summarized in Tables 1-3.

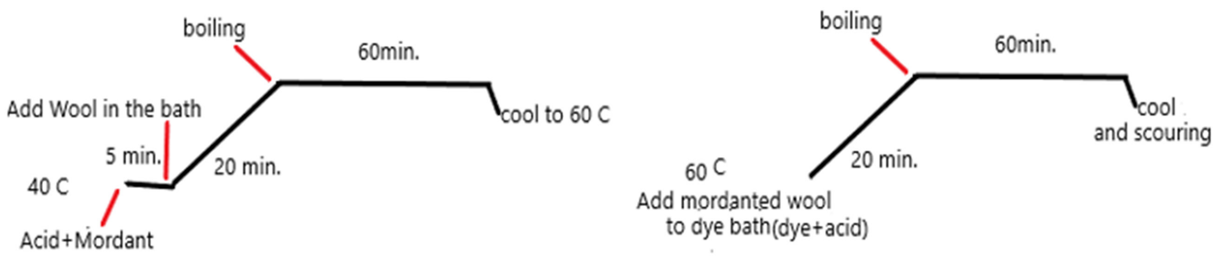


Figure 2: (a) - mordanting diagram, (b) - Dyeing diagram.

Table 1: Dyeing Parameters according to Dyeing method, dye, and mordant concentration.

Sample	Acid Con.%	Mordant Con.%	Dye Con.%	Mordanting method
1	Acetic 4%	Alum.8 %	1	Pre-mordanting
2	Acetic 4%	Alum%8	1	Meta mordanting
3	-	Alum%8	1	Meta mordanting
4	Acetic 4%	Alum%8	1	Post mordanting
5	Acetic 4%	Alum%12	1	Meta mordanting
6	Acetic 4%	Alum%12	1	Meta mordanting
7	Acetic 4%	Alum%12	1.5	Meta mordanting
8	Acetic 4%	Alum%12	3	Meta mordanting
9	Acetic 4%	Alum%12	5	Meta mordanting
10	Acetic 4%	Alum%15	1	Pre-mordanting
11	Acetic 4%	Alum%15	1	Meta mordanting
12	Acetic 4%	Alum%15	1	Post mordanting
13	Acetic 3%	Alum%15	0.7	Pre-mordanting
14	Acetic 6%	Alum%15	0.7	Pre-mordanting
15	Acetic 6%	Alum%10	0.7	Pre-mordanting
16	Lactic 6%	Alum%10	0.7	Pre-mordanting
17	Oxalic 6%	Alum%10	0.7	Pre-mordanting
18	Acetic 6%	Alum%15	1	Pre-mordanting
19	Acetic 6%	Alum%10	1	Pre-mordanting
20	Lactic 6%	Alum%10	1	Pre-mordanting
21	Acetic 6%	Alum%15	1.5	Pre-mordanting
22	Acetic 6%	Alum%10	1.5	Pre-mordanting
23	Lactic 6%	Alum%10	1.5	Pre-mordanting
24	Lactic 6%	$CuSO_4$ 2%	1	Pre-mordanting
25	Lactic 6%	$FeSO_4$ 2%	1	Pre-mordanting
26	Lactic 6%	$SnCl_2$ 2%	1	Pre-mordanting
27	Lactic 6%	NiCl2 2%	1	Pre-mordanting

28	Lactic 6%	$ZnSO_4$ 2%	1	Pre-mordanting
29	Lactic 6%	$K_2Cr_2O_7$ 2%	1	Pre-mordanting
30	Acetic 6%	Alum%10	1	Meta mordanting
31	Acetic 6%	Alum%10	1	Meta mordanting
32	Acetic 6%	Alum%10	1	Meta mordanting

*: Dyeing temperature of all samples adjusted to boiling, sample No. 30 adjusted to room temp. Sample No. 31 adjusted to 60 °C. L/R of all samples adjusted to 40, except for No.5, which was adjusted to 20.

Table 2: Dyeing parameters according to dye extraction solvents.

Sample No.	Extraction Solution	L/R	Acid Acetic %	Alum. %	Dye%	Method
33	80%methanol+ 20%water	40:1	6	10	1	Pre-mordanting
34	80%ethanol + 20%water	40:1	6	10	1	Pre-mordanting

Table 3: Dyeing Parameters according to mordants.

Sample No	Mordant Con.%	Method
35	Alum10%+ Henna 5%	Pre-mordanting
36	Alum10%+ Eucalyptus 5%	Pre-mordanting
37	Alum10%+ Aloe Vera 5%	Pre-mordanting
38	Alum10%+ wool treatment with chitosan	Meta mordanting
39	Alum10%+ Henna 5%	Post mordanting
40	Alum10%+ Eucalyptus 5%	Post mordanting
41	Alum10%+ Aloe Vera 5%	Post mordanting

All dyeing has been done in the L/R=40, dye concentration of 1%and 6% of acid Lactic.

The fastness properties of the dyed yarns were assessed using the test methods ISO 105-A03:2019 for color fastness to washing and ISO 105-B02:1994 for color fastness to light. The reflectance and color quality of dyed samples were measured using a Color-Eye 7000A spectrophotometer (X-Rite, USA) under D50 illumination. Color values (L*, a*, b*, K/S, C*, h o, λmax) and Relative color strengths (K/S values) were determined by using the Kubelka-Munk equation (1).

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

Where R is the decimal fraction of the reflectance of dyed woollen yarn, K is the absorption coefficient, and S is the scattering coefficient.

Results and discussion

Identification of pan dye

Experiments were performed on the Pan to identify the constituent elements. X-ray energy scattering spectroscopy is a suitable method that is typically used for semi-quantitative analysis of elements that are heavier or equivalent to sodium in weight and contain about half a percent or more of the total sample by weight. The EDX test has little applicability for some specimens that are flat, smooth, and uniform. The Pan sample was also polished and non-powdered, which was easily tested. A comparison of the diagrams shown in Figure 3 with the reference diagrams shows that Fe^{+2}, Fe^{+3} metal elements are present in the Pan material in lines with energies of about 1000 and between 6000 and 7000 electron volts. Na, Mg, Al, Si, S, Ca are present in the lines with energies about 1200,1400, 1600, 1800, 2100, 2500, 3400, respectively. These results are consistent with those reported by the researcher in their study and indicate the presence of metals with carbonyl compounds in the Pan structure [17,18]. The elements carbon, oxygen, and nitrogen are also present in power lines with less than 1000 electron volts. Some other elements, such as magnesium and silica, are found in power lines between 1000 and 2000 electron volts. Therefore, it seems that Pan dye can be used as a dye.

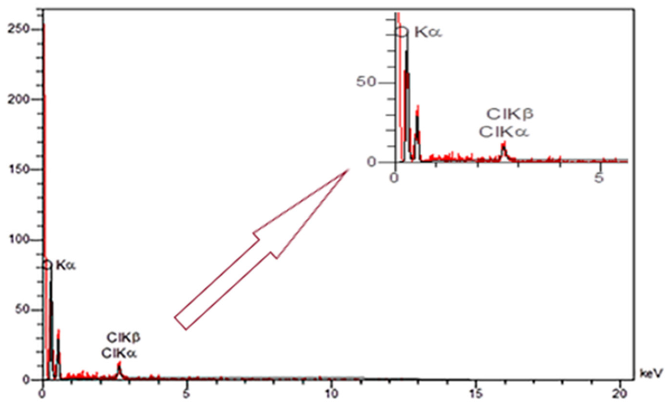


Figure 3: Spectra obtained from X-ray spectroscopy (EDX) of the dye used.

The quantitative results of the EDX test are shown in Table 4.

Table 4: Elements identified in Pan mineral dye by EDX method.

Elt	Line	Int	K	Kr	W%	A%	ZAF	Pk/Bg	L Conf.	H Conf.
C	Ka	35.3	0.7810	0.3118	54.88	61.55	0.5682	162.82	50.13	59.62
N	Ka	1.0	0.0312	0.0124	10.65	10.25	0.1168	7.93	5.29	16.02
O	Ka	13.7	0.1512	0.0604	32.70	27.54	0.1846	49.82	28.16	37.24
Cl	Ka	6.4	0.0366	0.0146	1.77	0.67	0.8284	7.26	1.41	2.12

Table 5: Elements identified in the Pan mineral dye sample by the XRF method.

Test Name	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Fe_2O_3	ZnO
Result	6.67	1.64	1.95	1.02	0.83	79.44	4.16	350	0.40	3.61	650
Unit	w/w%	w/w%	w/w%	w/w%	w/w%	w/w%	w/w%	Ppm	w/w%	w/w%	Ppm

Based on the findings of the XRF test performed using the IXF-W-504-01 method and the data in Table 5, the constituents of the Pan material mainly include iron oxide (Fe^{+2}, Fe^{+3}), aluminum oxides, magnesium, and sodium. Silica, calcium, and zinc. Most of the Pan material is composed of sulphur oxides.

In the infrared spectrum of Pan dye, as shown in Figure 4, the maximum absorptions at wavelength 3330 correspond to the primary NH_2 groups, 3205 at wavelengths belong to the C-OH groups, and absorption at 1106cm^{-1} corresponds to the absorption of the ether groups. The absorption bands observed at 1640cm^{-1} are due to >C=O conjugated with aromatic ring, at 1508 and 1468cm^{-1} corresponding to aromatic C=C, and at 1275cm^{-1} for phenol C-O. These FTIR peaks are most likely cyanidin [18].

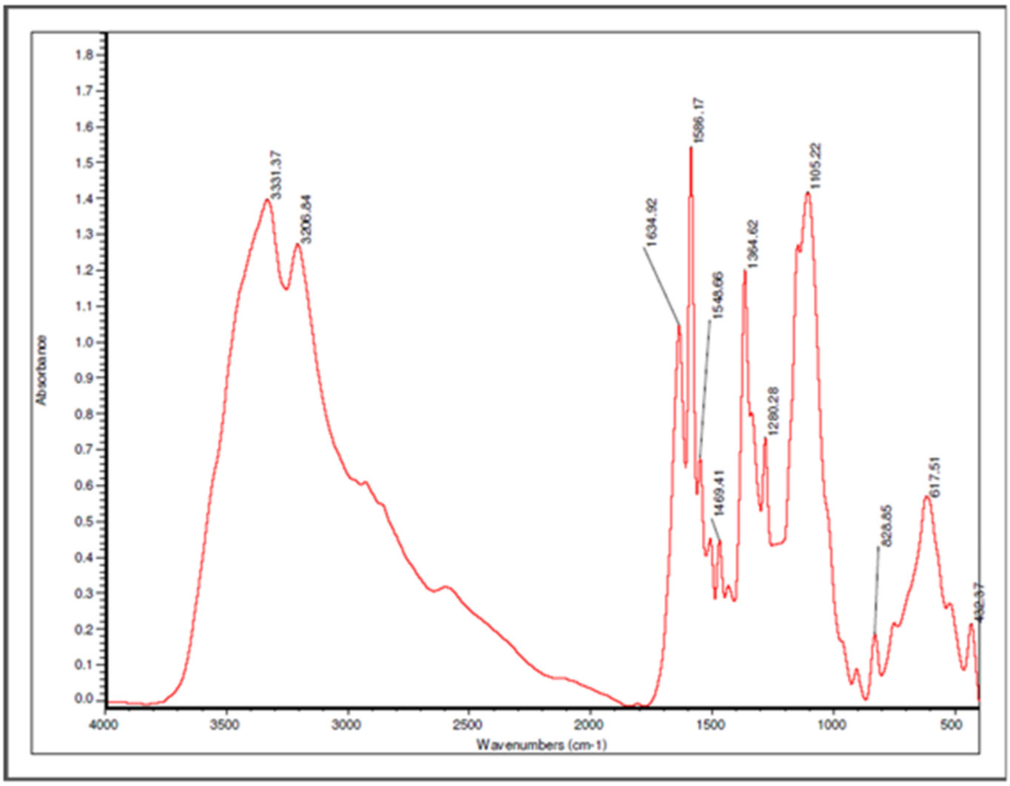


Figure 4: Spectra of infrared spectroscopy (FTIR) of the dye powder.

Dissolution of the pan according to aqua regia

The mineral dye sample was dissolved by the aqua regia, which is the conventional method in non-silica rock samples, and an instrumental measurement. The second test was performed to confirm the type of possible ligands and complexometric of the dissolved samples by ammonia, the acidic solution, and colorimetry of the sample in solution, as shown in Figure 5. The dissolution test showed that the only substance that can hold Fe^{3+} in solution, whether in acidic, alkaline, or neutral states, and also has a specific purple color, is cyanate or thiocyanate, which forms a powerful complex with Fe^{3+}. Aqua regia dissolution tests confirmed that cyanate or thiocyanate forms a stable purple complex with Fe^{3+}, consistent with the acidic purple color observed in dyed yarns (Figure 5).

Dye+ HCl+ $H(NO_3)$ Dye+ $Fe(NH_4)_3$ +$Fe(SCN)_3$

Figure 5: Acid dissolution test.

XRD patterns

Analysis of the X-ray diffraction patterns is a suitable method to identify the crystallinity of the samples. Furthermore, it is used to calculate the phase content and investigate the changes in the phase structure of the samples before and after the dyeing. The XRD Patterns of raw and treated wool are shown in Figures 6&7.

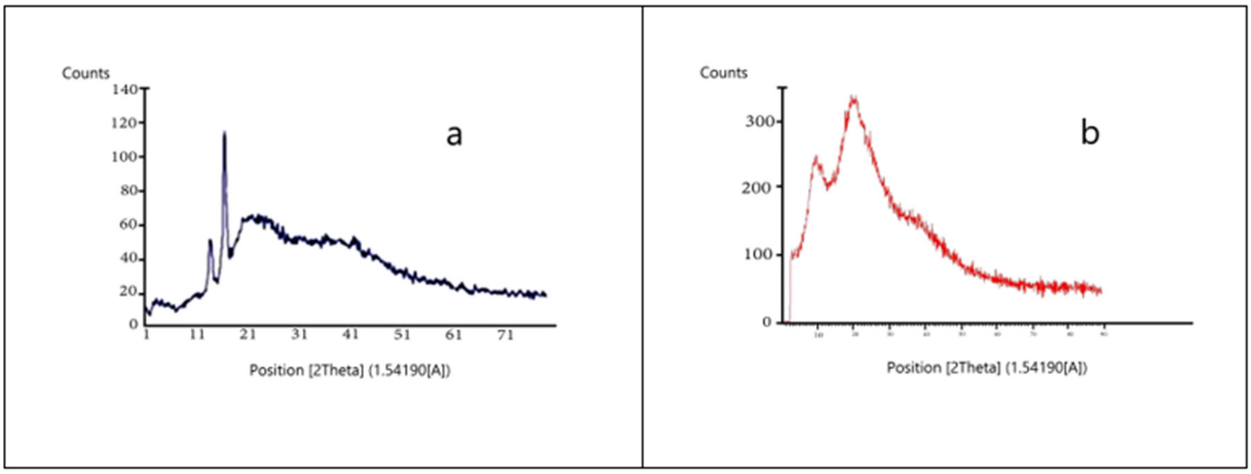


Figure 6: XRD pattern of wool samples: (a) raw, and (b) dyed wool.

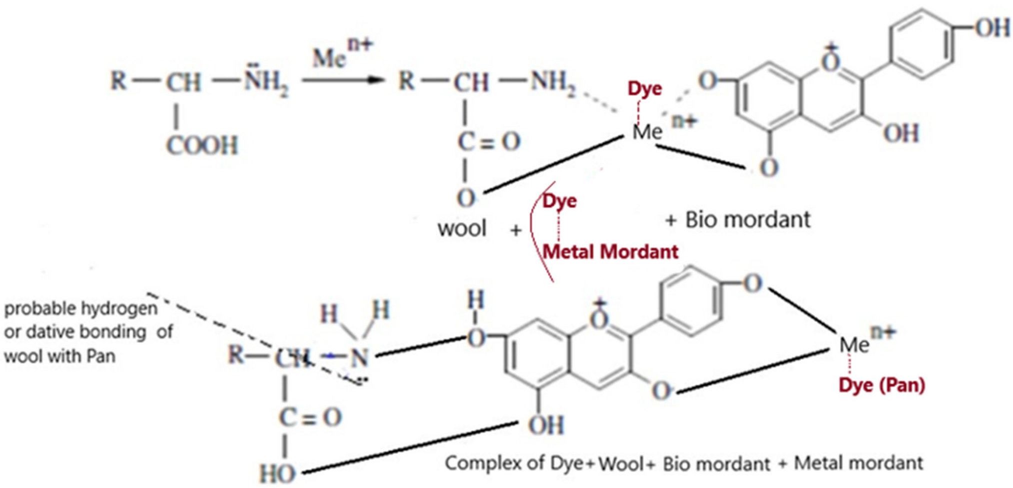


Figure 7: Possible interaction between bio-mordant, (metal mordant, dye) and wool.

Regarding raw wool, two major peaks are observed at 2θ=13.7° and 2θ=16.45°, corresponding to the hydrated crystalline structure of wool and α-keratin, respectively. In the XRD patterns of dyed woollen yarn, no specific additional peaks can be seen. In the dyed sample, the major peaks are observed at 2θ=20.7° and 2θ=1.0°. XRD analysis showed no significant changes in wool crystallinity after dyeing, with characteristic peaks at 2θ=13.7° and 16.45° for raw wool, and minor shifts for dyed samples. In the previous research, XRD analysis revealed that the crystal property of wool yarn did not change significantly when it was dyed with Monascus pigments in non-aqueous medium [19]. Compared with the undyed wool yarn, the crystalline structure of the peak at 13.95° and 2θ=16.45°, changed when the wool yarn was dyed. This might be because of the fact that amorphous regions of wool fiber are susceptible to degradation under high temperature and acid conditions owing to its protein nature, leading to the damage of wool yarn [19].

Dyeing Experiments

Effect of dyeing method

The dyeing results of the samples obtained through different methods (Samples 1-4) are presented in Table 6. The findings indicate that pre-mordanted wool yarn exhibited superior dye uptake and greater color depth compared to the other samples. Accordingly, the pre-mordanting technique can be considered the most effective method for applying Pan dyes. It is also noteworthy that, in the meta-mordanting method (simultaneous dyeing and mordanting), the use of acid did not significantly influence the color depth, as observed from the comparison between Samples 2 and 3.

Table 6: Effect of dyeing- mordanting method on the color of samples.

Sample No.	4	3	2	1
Hue				
PH	4	6	4	4

Effect of Liquor ratio on the color of wool

Table 7 demonstrated the effect of the Pan dye to liquor ratio (water). The liquor ratio affects the availability of dye. In the smaller volume of the dyeing bath, more dye is available directly to the yarn; the color of pan dyed wool yarns decreased with increasing the liquor ratio, and this may be due to a smaller number of dye molecules available with increased quantity of water for the same weight of wool. As visual results show, the change of liquor ratio does not have a significant effect on the color intensity; then, for more uniformity, the use of L/R = 40:1 is recommended.

Table 7: Effect of liquor ratio on the color of samples.

L/R	20:1	40:1
Hue		

The color strength of the dye Pan

The results of different dye concentration hues are given in Table 8. The results show that Pan has a very high dyeing ability; in low concentrations of dye, a suitable and acceptable hue is obtained. The results of Table 8 show purple color for using 0.7% to 1.5% concentration of dye, and crimson shade with 3 and 5% of dye concentration. It means the use of Pan dye more than 3% has had very little change on the hue; therefore, the use of dye concentration greater than 3% is not recommended.

Table 8: Effect of dye concentration on the color of samples.

Dye Concentration (%)	5	3	1.5	0.7
Hue				

Effect of dye bath pH

Table 9: Effect of dyeing bath pH on the color of samples and the washing and staining fastness.

Sample No.		23	22	21	20	19	18	17	16	15	14	13
Hue												
Hue after washing												
pH		3-4	4-5	4-5	3-4	4-5	4-5	3-4	3-4	4-5	4-5	4-5
Staining on the wool												
Staining on the cotton												
Washing fastness		3	3	3	3	3-4	3-4	3	2-3	3-4	3-4	3-4
Staining fastness	wool	2-3	2-3	2-3	2-3	3-4	3	3	2-3	3-4	3-4	3-4
	cotton	4	4	4	4	4	4	4	4	4	4	4

Color strength of different acids and concentrations of acid (pH) on the final shade obtained from Pan dye are shown in Table 9. The color of the samples shows that increasing the concentration of acetic acid (samples 13 and 14) improves the color intensity slightly. Also, the washing fastness results of these samples show that increasing the amount of acid did not have much effect on the washing and staining fastness of wool and cotton yarn.

The results obtained using lactic acid indicate that increasing the acidity of the dye bath produces a darker shade; however, it decreases the washing and staining fastness of wool yarn, while the staining fastness of cotton yarn remains unchanged. A comparison between Samples 19, 20, and Samples 15, 16, reveals that an increase in pH slightly enhances the washing and staining fastness of wool yarn. The findings further demonstrate that the type of acid and the pH of the dye bath have minimal influence on the hue of the dye. Moreover, comparison among Samples 14, 18, and 21 shows that higher dye concentrations lead to a reduction in washing and staining fastness. Overall, the washing and staining fastness of this dye system is not satisfactory. The light fastness results are presented in Table 10. Between Samples 14 and 15, which differ in mordant concentration, Sample 14 appears darker, whereas Sample 15 exhibits stronger blue and red tones. The results also indicate that higher mordant concentrations (as seen in Samples 14, 18, and 21 compared to Samples 15, 19, and 22) enhance color intensity and that an increase in dye concentration leads to greater redness. Negative b_* values reflect the tendency of the Pan dye to produce a purplish-bluish-red hue. Doubling the dye concentration, as in Samples 14 and 22, results in only a minor change in color strength. It can be concluded that increasing the mordant concentration from 10% to 15% has little effect on dye absorption. The corresponding colorimetric data are summarized in Table 11.

Table 10: The effect of type and acid concentration on the color of samples after exposure to the light.

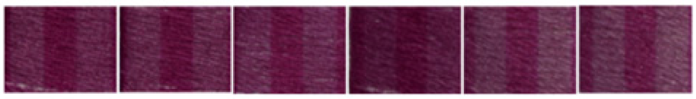
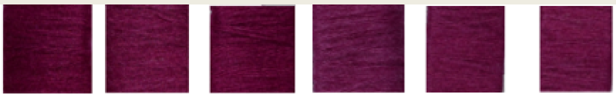
Sample No.	22	21	19	18	15	14
Hue						

Table 11: Influence of dyeing parameters on color characteristics of wool yarn dyed with Pan.

Sample No.	14	15	18	19	21	22
Hue of Sample						
L*	30.8	30.3	34.6	33.6	42.3	38.8
a*	47.5	47	47.9	47.1	43.9	43.1
b*	-8.8	-9.2	-10.4	-10.3	-11.3	-10.1

Effect of mordant

Table 12: Effect of mordant concentration on the color of samples.

Sample No.	Post-mordanting	Post-mordanting	Post-mordanting	Pre-mordanting	Pre-mordanting	Pre-mordanting
Hue						
Mordant%	Alum15%	Alum15%	Alum15%	Alum8%	Alum8%	Alum8%

Preliminary results revealed that the application of 4% mordant in dyeing with Pan dye did not yield satisfactory washing fastness. Subsequently, the concentration of white alum mordant was increased to 8%, 12%, and 15%. However, increasing the mordant concentration from 8% to 12% and finally to 15% did not produce a significant improvement in the washing or staining fastness of the samples. The results concerning variations in mordant concentration and mordanting methods are summarized in Table 12. Comparison of the color shades presented in Table 13 indicates that the use of tin mordant resulted in a bright purple hue, whereas potassium dichromate produced a duller purple tone. A general review of the findings suggests that altering the type of mordant causes only slight variations in color intensity and shade. This behavior is consistent with that of many natural dyes, where the shade produced by Pan dye is similarly influenced by the mordant type. In general, tin mordant has been reported to enhance color luster in natural dyeing [12]. The results further indicate that using higher concentrations of mordant improved light fastness to some extent; however, the overall light fastness of Pan dye remained low. Increasing the concentration of aluminum mordant produced a moderate improvement in light fastness. The use of natural or synthetic light stabilizers could potentially enhance the light stability of Pan-dyed fabrics. Analysis of the washing fastness data shows that variations in mordant type had minimal influence on the washing fastness of the samples. As presented in Table 13, the dye sample treated with potassium dichromate displayed slightly better washing fastness compared with those treated with other mordants.

Table 13: Effect of mordant types on the color of samples and the fastness of washing and staining.

Mordant		$CuSO_4$ 2%	FeO 2%	SnCl 2%	$NiCl_2$ 2%	$ZnSO_4$ 2%	$K_2Cr_2O_7$ 2%
Hue							
Hue after washing							
Staining on the cotton							
Staining on the wool							
Washing fastness		3-4	3	3	3	3	3
Staining fastness	wool	4	3-4	3-4	3-4	3-4	3-4
	cotton	4	4	4	4	4	4

The efficacy of bio-mordant on fastness

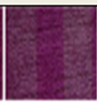
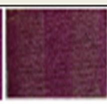
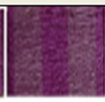
The washing fastness results indicated that the use of metal mordants did not yield satisfactory outcomes for the dyed samples. Therefore, bio-mordants-including henna, aloe vera, eucalyptus, and chitosan-were evaluated to enhance washing fastness. As presented in Table 14, the shade produced by using tannin-rich plant mordants appeared duller, whereas chitosan and aloe vera did not significantly alter the primary hue of the Pan dye. In traditional natural dyeing processes, tannin-containing materials such as pomegranate peel and walnut husk are often employed to reduce color luster; therefore, the softening or dulling of the purple tone observed with henna or eucalyptus mordants may be desirable for certain handicraft applications. Analysis of the washing and staining fastness data in Table 14 shows that plant-based mordants markedly improved the fastness properties of the dyed samples. Similar findings have been reported by other researchers [16,20], who attributed the enhanced fastness to the formation of a more stable complex between the fiber, mordant, and dye molecules. Overall, plant-derived mordants such as henna, aloe vera, eucalyptus, and chitosan improved the washing and staining fastness of the samples, with chitosan and aloe vera maintaining the original shade, while tannin-based mordants slightly subdued the color intensity.

Table 14: Effect of bio-mordant on the dyeing fastness.

Mordanting / Dying properties		Pre mordanting			Meta mordanting		Post mordanting	
Hue								
Hue after washing								
Staining on the cotton								
Staining on the wool								
Washing fastness		4-5	4-5	4-5	4-5	4-5	4-5	4-5
Staining fastness	wool	4-5	4-5	4-5	4-5	4-5	4-5	4-5
	cotton	5	5	5	5	5	5	5

The observed improvement in washing fastness of samples dyed with bio-mordants indicates that bio-mordants have a more pronounced effect than mineral mordants. The stronger fastness can be attributed to the formation of a stable complex between the fiber, mineral and/or bio-mordant, and the dye. The numerous hydroxyl groups and cyclic structures present in eucalyptus, henna, chitosan, and aloe vera likely facilitate the formation of a stable fiber-plant-dye complex, even in the presence of a small amount of mineral mordant, as reported in previous studies [15]. The interaction of tannic acid in henna and eucalyptus with metal mordants (considering Pan dye itself may act as a metal mordant) is illustrated in Figure 7. Similarly, the polyhydroxy structure of aloe vera contributes to an increased number of bonds between the fiber, mordant, and dye, enhancing the overall fastness. Despite the significant improvement in washing and staining fastness, natural mordants exhibited limited impact on light fastness. However, a comparison of the results in Tables 9&14 indicates a slight enhancement in light fastness due to the use of bio-mordants. This observation aligns with previous suggestions that light stabilizers can improve light fastness, as aloe vera, which possesses light-protective properties, was able to enhance light fastness to some extent (Table 15).

Table 15: Effect of light exposure on the Color of bio-mordanted dyed samples.

Sample No.	40	41	42	43	44	45	46
Hue							

The effect of temperature on dyeing

Temperature is a key factor influencing the dyeing process, as it affects fiber swelling and dye uptake. The effect of dyeing temperature on the color shade of the samples is presented in Table 16. At low ambient temperatures (20 °C), Pan dye exhibits low absorption and produces a pale color with minimal depth. As the temperature increases, dye uptake improves, resulting in progressively more intense shades. At room temperature, the dyed samples display a pale pink hue, whereas higher temperatures yield richer, more vibrant colors, culminating in a deep magenta shade near the boiling point. Overall, the data indicate that increasing temperature enhances dye absorption, with the highest color intensity observed at elevated temperatures. Table 16, illustrating the effect of temperature on dyeing.

Table 16: Effect of temperature on the color of samples.

Dyeing Temp.	Room Temp.	60 °C	Boiling Temp.
Hue			

Effect of solvent on the dye extraction process

The effect of different extraction solvents on the color shade of Pan dye is presented in Table 17. The results indicate that extraction with water and methanol yields greater color depth than extraction with water and ethanol. However, both extraction methods produce significantly lower color intensity compared to the direct use of Pan dye powder. Therefore, for optimal dyeing results, the use of the dye powder is recommended. This behavior can be attributed to the higher solubility of metal compounds, such as sodium, magnesium, and aluminum, in polar solvents like water, compared to solvents of lower polarity, such as ethanol or methanol [21].

Table 17: Effect of dye extracted with different solvents on the color of samples.

Sample No.	34	33	19
Hue			

Colorimetric results

Reflection values were measured in the range of 380-720nm at 20nm intervals. The spectrum shown in Figure 8 exhibits two absorption maxima, corresponding to the red and blue components of the dye. Specifically, the maximum at 400nm corresponds to blue, while the maximum at 620nm corresponds to red. The presence of two distinct absorption maxima indicates that Pan dye is sensitive to hue changes, which are likely influenced by bathochromic, hypochromic, and solvatochromic effects. The observed variations in hue and color intensity of Pan dye, resulting from changes in acid type and dyeing temperature, can be attributed to these effects [22].

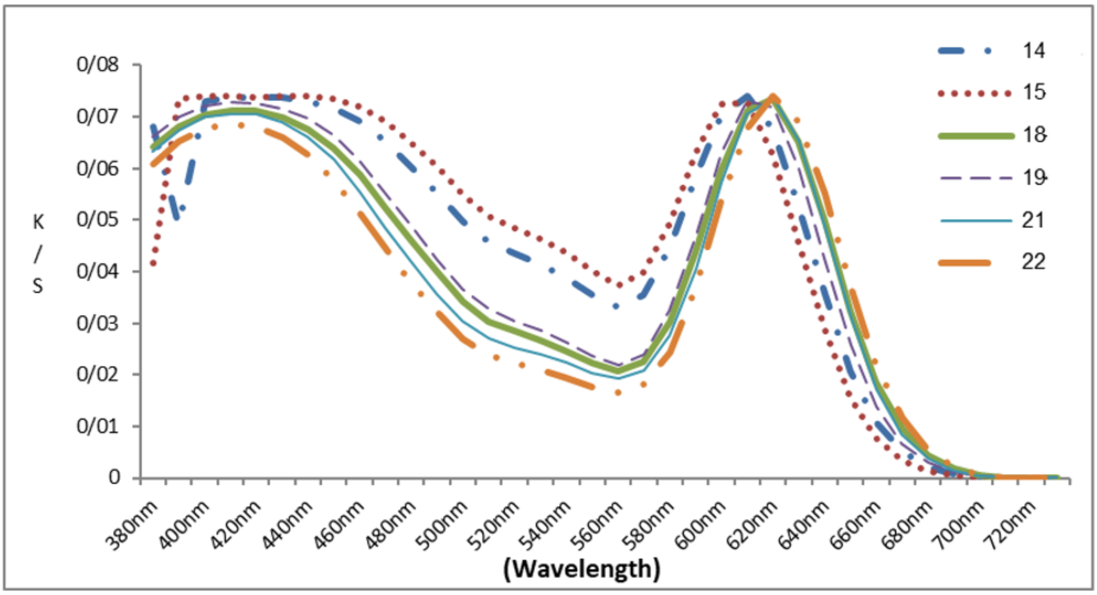


Figure 8: Color strength (K/S) of dyed wool yarns with Pan.

Mechanical measurement results

To study the role of Pan dye used in dyeing on the tensile strength of wool yarn samples, the tensile strength of dyed yarn samples with raw yarn samples was measured and compared. The average of the measurement results, which were repeated 5 times, is shown in Figure 9. As shown in the diagram, the use of a mordant has increased the strength and the amount of elongation. The formation of covalent bonds between the mordant, the dye, and the yarn may have increased the strength of the wool fiber molecular chains. The presence of a complex with a larger molecular size (dye-mordant) in the molecular chain has created a stronger structure that has increased elongation. The results showed that the elongation at break point was 12.66% for the dyed yarn sample and 11.15% for the raw wool yarn sample.

Figure 9: Stress -strain curve of dyed wool yarn and raw wool yarn.

Conclusion

The present study was conducted with the introduction of Pan mineral dye for dyeing textiles. The experimental results showed that, firstly, this dye can be used as a natural dye. In the study of dyeing variables, it was found that with very low dye concentrations, deep shades of purple can be achieved on woollen products. Pan exhibits dyeing performance comparable to cochineal, a traditional animal-based natural dye. Increasing the dyeing temperature to near boiling enhanced color intensity, and aqueous extraction is more efficient as compared to ethanol or methanol, indicating high solubility of Pan in water. Using Pan dye directly in dyeing also improved color uptake compared to solution-based extracts. Increasing mordant concentration from 10% to 15% did not significantly enhance dye absorption, but it improved tensile strength and elongation at break of wool yarns. The presence of two maximum wavelengths in the reflection spectrum demonstrated the dye's color sensitivity and potential for producing diverse purple shades. The use of bio-mordants improved washing and staining fastness to acceptable levels, though light fastness remains limited, suggesting the need for further investigation. Overall, Pan dye, with its eco-friendly characteristics, represents a promising, sustainable, and cost-effective alternative for wool coloration in natural dyeing applications.

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