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Microwave-assisted santalin extraction from *Pterocarpus santalinus* for mordanted woolen yarn dyeing

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ABSTRACT

Natural dyes have attracted the world because of its ayurvedic and biological functioning characteristics. In this research, the functional bio-actives santalin from red sandal wood (RSW) powder has been isolated and exposed to MW treatment for up to 5 min. The extracts and fabrics were stimulated and used to dye at a given condition. The results revealed that 50 mL of red sandal wood extract (RSWE) at 4 pH containing 2g/100 mL of salt was employed at 65 °C for 65 min. After 4 min, MW treatment has given the highest color yield. The surface morphology of the fiber shows that the yarn surface has been modified without any chemical changes. Mordanting with chemical and biological extract at low amounts has improved shade fastness with new tints. It can be calculated that MW ray has the potential to explore colorant from crude powder in a suitable solvent under mild conditions but also reducing dyeing conditions and mordant, revealing that this green tool is cost, energy and time effective.

1. Introduction

A long time ago, the emergence of synthetic dyes promoted their frequent uses in the dyeing and printing industries due to their variety of bright colors, superior fastness properties, and ease of application (Gala et al., 2022). Synthetic dyes are not eco-friendly because of their effluents have distributed aquatic ecosystems by the rising value of water quality and chemical or biological oxygen demand (Sk et al., 2021). These dyes produce organic and inorganic toxins, including heavy metals, sulfur, nitrates, chromium, and sequestering agents (Rahman et al., 2021). These dyes contaminate air, water, and soil by causing disturbances in the ecosystem's equilibrium which, in turn, causes rising global heat that is making lifestyle hard (Jawad et al., 2022). The hazardous consequence of these man-made colorants has forced, the global community to move towards more sustainable products, including organic dyes, in all over the world (Jiang et al., 2022a).

The interest in natural, sustainable, green, and eco-friendly products is gaining worldwide attraction due to rising environmental threats from synthetic dyed products (Lin et al., 2022). Organic dyes are pigments derived from naturally renewable origins such as plants, animals, and minerals. The natural microbial pigments are biosynthesized from the various source of microorganism (Rather

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et al., 2022). The chitosan has also been used as a biological macromolecule on colorimetric measurement of linen fabric using the dyes extracted from the pineapple peel (Butola, 2019). These are highly environmentally friendly, bio-degradable, energy-efficient, and eco-friendly and pose no serious threat to human life and the habitat (Witono et al., 2022). Which are utilized in various applications, including food, leather, and textiles because they produce biocompatible and less harmful effluents (Kannan et al., 2022). Therefore, we have also extracted natural color from gardenia yellow (Jiang et al., 2022b), tulsi leaves (Mia et al., 2021), *Butea monosperma* plants (Adeel et al., 2022a), *Alkanna tinctoria* roots (Adeel et al., 2022b), *Rheum Emodi* plants (Adeel et al., 2023a), Coral Jasmine flower (Adeel et al., 2022c) and neem leaves extractions (Hasan et al., 2023).

Some novel extraction techniques such as microwave (Ticha et al., 2022), ultraviolet (Rather et al., 2021), ultrasonic (Sadeghi-Kiakhani et al., 2021), and gamma radiations (Chirila et al., 2018) have been adopted to extract the natural dyes from plants (Zhang et al., 2022). Microwaves improve dye absorption by rapidly and uniformly heating exposed materials (Mansour et al., 2022). These rays can be utilized in a range of textile treatments, including dyeing, drying, printing, and finishing. These rays absorb the material, modify its surface to promote stronger affinity, and speed up the dyeing process (Jafari et al., 2019). These rays also collide with phytoconstituents of plants rupture the cell walls, a create efficient interactions of functional moiety (pigment) with solvent via the process known as mass transfer kinetic (Khan et al., 2022). On the other hand, these rays not only consume less energy and time to produce high yields, but also utilized less solvent (Adeel et al., 2023b). Natural dyes have been collected from the various sources of nature for the coloration of different fabrics. For example, the leaves of *Limoniastrum monopetalum* were examined as a potential source of eco-friendly dye for cotton fabric dyeing (Ltaief et al., 2022). The cotton fibers also been dyed using the peel extracts of *Cynomorium Coccineum* L. (Sebeia et al., 2019). In another study by the researchers, these fibers were dyed using the aquas extraction of *Citrullus colocynthis* leaves (Ltaief et al., 2023). The wool fabric was functionally colored using rice straw extract (Kadam et al., 2020). However, till now, there was no study which focused on the coloration of wool yarn using sandal wood powder.

While using natural dyes, mordants are needed to set the color. Mordants are used in textiles to stabilize the shade during dyeing or printing, particularly for textiles made from plants (Zhou et al., 2022). Some metal salts, such as Cu^{+2}, Co^{+2}, and Cr^{+3} electrolytes, are considered carcinogenic, and their presence in effluents causes a decrease in soil fertility, deforestation, and destruction of the green beauty (Liu et al., 2023). Now, in place of such toxic anchors, it has been decided to use plant-based bio-anchors called bio-mordants. These potent molecules produce a wide range of colors based on their mode of application, and the fabric used. Their attachment parts are –OH, C = O, –NH (Özomay et al., 2022). Previous studies show that these bio-mordant mostly use the –OH or C = O & –NH group for interactions via additional H-bonding with the fabric and colorant-functional points that furnish colorfast shades (Zhang et al., 2021).

Considering the benefits of microwave rays for isolation and bio-mordants for the aspect of colorfast properties, the present research has been made to explore red sandalwood shown in Fig. 1a (*Pterocarpus santalinus*) as a source of orange-red colorant. The chemical constitute of santalin is displayed in Fig. 1b and the structure of wool yarn is shown in Fig. 1c. It is a famous timber for its color. Its extract is used to cure ulcers, eye diseases, vomiting, and mental aberrations (Arunakumara et al., 2011; Khan et al., 2021). The heartwood also has anti-inflammatory, hyperglycaemic activity, antipyretic, hemorrhage, anti-anthelmintic, aphrodisiac, aphrodisiac, dysentery, and diaphoretic actions, and is also used as a heat transferring agent (Gafner et al., 2023). The red color is due to santalin (C.I. Natural Red 22), which is anthraquinone in nature and is used as a coloring agent in textiles, pharmaceutical preparations, and foodstuffs. It is used for the coloration of jute, leather, skin, wool, silk, etc. (Sivakumar et al., 2017). Wool is one of the famous animal-based fibers which contains keratin. Keratin is composed of amides units that are linked through the peptide bonds (Haque et al., 2022).

Given the whole aspects of MW rays and bio-mordants, the objective of the present research is.

i. To find out the dyeing potential of santalin dye on wool yarn under the influence of microwave irradiation.
ii. To optimize dyeing variables through central composite design under statistical analysis.
iii. To optimize the concentration of pre- and post-mordanting of bio and chemical mordants under specified conditions.
iv. To assess the finishing rating of selected dyed fabric as per ISO standards.

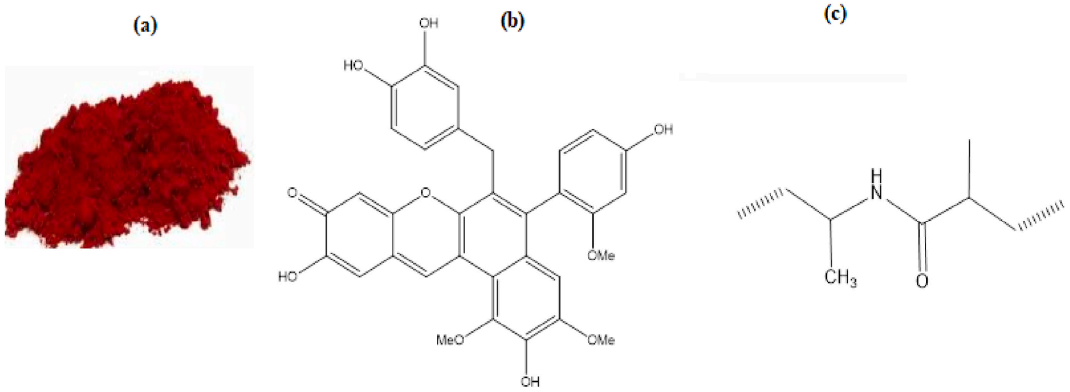


Fig. 1. Sandal wood powder (a) Santalin (b) Structure of wool yarn (c).

2. Experimental details

2.1. Material collection

Red sandalwood powder (*Pterocarpus santalinus*), along with different bio-mordants such as (*Punica granatum* L.) pomegranate rinds and bark of (*Acacia nilotica*) acacia, were acquired from the local market of the Faisalabad, Pakistan. After sieving through a 25 mesh, these samples were crushed finely to produce powders with similar particle size. The university of Sestan and Baluchestan, Zahedan, Iran, provided the pre-treated wool yarns. The source of chemical mordants such as electrolytes of aluminum sulfate ($Al_2(SO_4)_3$, purity of 99.0%; CAS Number: 10043-01-3), ferrous sulfate ($FeSO_4$, purity of 98.5%; CAS Number: 7720-78-7), copper(II) sulfate ($CuSO_4$, purity of 98.9%; CAS Number: 7758-98-7), cobalt(II) chloride ($CoCl_2$, purity of 99.5%; CAS Number: 7646-79-9), tannic acid (T.A., purity of 96.8%; CAS Number: 1401-55-4), nickel(II) sulfate ($NiSO_4$, purity of 99.0%; CAS Number: 7786-81-4), stannous chloride ($SnCl_2$, purity of 95.4%; CAS Number: 7772-99-8), and chromium(II) chloride ($CrCl_2$, purity of 99.8%; CAS Number: 10049-05-5) were purchased from Paragon Dyes and Chemicals Ltd., Faisalabad, Pakistan.

2.2. Extraction and irradiation process

For extraction purpose different media i.e., aqueous and acidic, were employed to adequately isolate natural dye from red sandalwood powder. Using an aqueous medium, 4 g of finely prepared red sandalwood powder (RSP) was heated with 100 mL of distilled at boiling water for 45 min, filtered, and stored. The extract from an acidic medium (1% HCl solution = v/v%) was obtained following the same procedure. One part of the aqueous and acidic extracts and woolen yarn (WY) were kept in a domestic MW irradiator and heated up to 5 min at high power. In the first series, unirradiated woolen yarn (UWY) was dyed with unirradiated red sandal extract (URSE) at 80 °C. For comparative studies, irradiated woolen yarn (IWY) was used to dye with irradiated red sandal extracts (IRSE) at 80 °C for 45 min. The summary of all the experiments performed is shown in Table 1.

2.3. Optimization of dyeing and mordanting conditions

Response surface methodology was used as the statistical tool for tabulating a trial of 32 trials through a central composite design. The following parameters were used for computer simulation to get the design of various trials (Table 2).

2.4. Mordanting process

The eco-friendly chemicals in natural dyeing are the global demand for getting colorfast coordinates. In this study salts of $Al_2(SO_4)_3$, $FeSO_4$ and tannic acid have been used. The Al mordant solution was prepared by dissolving 1,2,3,4,5 g of $Al_2(SO_4)_3$ into 100 mL of water and employed at 80 °C for 45 min keeping the fabric to the acidic value of 1: 25. The same process was done before and after dyeing using iron salt and tannic acid at a given concentration. Plant extracts as a natural bio-molecule source have been used for comparative studies. For this purpose, crude plant biomolecules like pomegranate peels (P·P.), the bark of acacia (B.A.), and Ludhra (L), were ground and sieved up to 25 mesh; their extract was made ready to bio-mordant by boiling 1–5 g with 100 mL of water for 45 min. The obtained filtrates were applied as pre and post dyeing for 45 min at 80 °C keeping material and bio-mordant ratio of 1:25. The schematic illustration for the dyeing process is shown in Scheme 1.

2.5. Analysis of extract and fabric

Physio-chemical changes of irradiated and unirradiated fabrics were examined using scanning electron microscopy (SEM) images. The structural transformation was observed using FTIR analysis before and after the irradiation of fabrics.

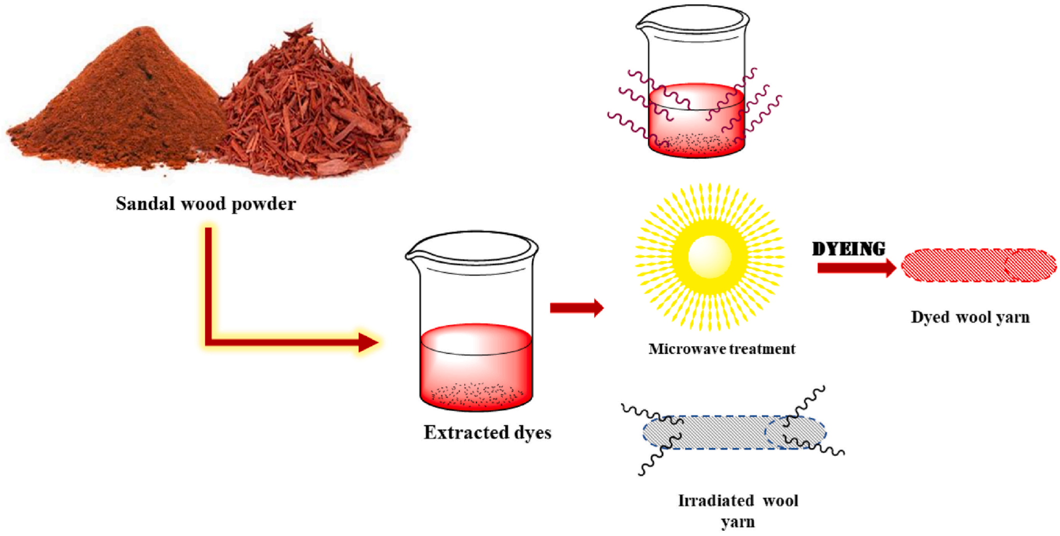
Table 1
Effect of microwave radiation on aqueous extraction of woolen yarn.

Radiation Time	Conditions	K/S	*L**	*a**	*b**
	Aqueous				
	URSE/URWY	50.372	22.31	21.78	22.23
1 min	URSE/RWY	63.314	21.03	20.5	22.05
2 min	URSE/RWY	48.272	21.1	19.21	19.21
3 min	RSE/RWY	48.093	20.17	18.57	17.27
4 min	URSE/RWY	45.093	21.55	19.14	19.04
5 min	MAD	43.901	34.88	19.76	33.16
Acidic					
0 min	URSE/URWY	40.964	29.53	22.68	28.66
1 min	URSE/RWY	57.703	28.47	24.69	30.61
2 min	RSE/URWY	62.394	19.56	18.46	19.89
3 min	RSE/URWY	78.59	17.82	16.21	16.31
4 min	RSE/RWY	81.12	16.82	18.78	17.21
5 min	URE/RWY	62.85	7.88	23.58	10.84

Table 2
Using an irradiation extract of colorant, the dyeing factors are optimized by central composite design (CCD).

Exp. No	A(pH)	B (mL) volume	C(min) Time	D(^{0}C) Temperature	E(g/100 mL) salt	F(K/s) Color strength
1	4	30	45	45	4	59.52
2	4	50	45	45	2	55.32
3	4	30	65	45	2	54.56
4	4	50	65	45	4	46.88
5	4	30	45	65	2	44.14
6	4	50	45	65	4	45.76
7	4	30	65	65	4	73.75
8	4	50	65	65	2	112.35
9	8	30	45	45	2	81.96
10	8	50	45	45	4	50.39
11	8	30	65	45	4	77.23
12	8	50	65	45	2	36.04
13	8	30	45	65	4	65.24
14	8	50	45	65	2	95.26
15	8	30	65	65	2	82.84
16	8	50	65	65	4	69.86
17	2	40	55	55	3	64.58
18	10	40	55	55	3	11.57
19	6	20	55	55	3	92.23
20	6	60	55	55	3	68.25
21	6	40	35	55	3	60.34
22	6	40	75	55	3	82.71
23	6	40	55	35	3	79.09
24	6	40	55	75	3	60.053
25	6	40	55	55	1	13.75
26	6	40	55	55	5	71.27
27	6	40	55	55	3	54.69
28	6	40	55	55	3	62.024
29	6	40	55	55	3	57.32
30	6	40	55	55	3	84.79
31	6	40	55	55	3	83.98
32	6	40	55	55	3	63.35

A = pH. B = volume. C = time. D = temperature. E = salt. F = color strength.



Scheme 1. A schematic illustration of woolen yarn dyeing using red sandal wood powder.

2.6. *Assessment of color characteristics of dyed material*

The dyed fabrics color attributes were investigated CIE Lab system computed in the Colori-spectrophotometer (CS-410) at the department of Applied Chemistry, Government College University Faisalabad, Pakistan. The dyed fabrics' color fastness properties were tested according to ISO standards to determine bio-mordants' role compared to chemical mordants (Chowdhury et al., 2022). For light fastness was rated using (ISO 105 B02) in a fado-meter, washing fastness (ISO 105 C03) was rated using Rota wash, and crocking (ISO 105 X-12) (rubbing) was rated using crock meter (Sk et al., 2022).

3. Results and discussion

Microwave treatment has gained increasing significance in the textile industry due to its cost-effectiveness and rapid heating capabilities for isolating natural products (Jabar et al., 2022). Unlike conventional heating methods, which often require large amounts of energy and solvent, microwave treatment offers the advantage of using less solvent and energy while preserving the chemical integrity of functional moieties (Naveed et al., 2022). This is achieved through the disruption of plant cell walls, facilitating the interaction between the colorant and the solvent (Adeel et al., 2023b). The interaction between microwave rays and the colorant, particularly within a 4 min exposure, promotes efficient transfer of the colorant into the solvent, resulting in a higher yield (Adeel et al., 2023b). Additionally, radiation of the fabric surface has been found to modify the fiber structure and enhance its dye uptake behavior (Adeel et al., 2022d). This improvement is evident in the scanning electron microscope images captured before and after the 4 min radiation treatment of the yarn. The images reveal an enhanced fiber sorption behavior for the colorant, which is further reflected in the increased color strength (K/S).

The spectral graph reveals that the position of –NH (3000–3500 cm^{-1}), –C = O (1500–1700 cm^{-1}), and CH_3 (~1380 cm^{-1}) has not been altered even after being treated up to 4 min, which concludes that these rays did not have potential to alter the chemistry of functional fiber point (amido group) (Fig. 2) (Hosseinnezhad et al., 2021). These rays have shown one of the greatest advantages: the fiber surface is physically modified without changing its chemical nature. The morphology of the woolen yarn is shown in Fig. 3. The investigation sheds light on the woolen yarn's surface properties and structural composition in various environments. The morphology of the woolen yarn is depicted in this photograph prior to radiation treatment (Fig. 3a). It offers a starting point for comparison with the woolen yarn that has been radiated. It was viewed and analyzed the characteristics of the unirradiated yarn, including the fiber arrangement, surface texture, and any obvious imperfections or defects. On the other hand, the morphology of the woolen yarn following radiation treatment is shown in Fig. 3b. It was observed the modifications or changes brought on by the radiation and it enables comparison with the yarn that has not been exposed to radiation. The interaction with the radiation cause changes to the yarn's fiber structure, surface modifications, or increased characteristics.

The results reveal that using a water (neutral aqueous) medium, the irradiation of yarn for 1 min given in Fig. 4a for dyeing with untreated sandal extract has given a high yield (K/S = 63.314). Using an acidic medium, it can be seen that dye irradiation of sandal extract and woolen yarn up to 4 min. It has given excellent calm yield (K/S = 81.12) (Fig. 4b). Hence it is revealed that an effective yield of colorant (santalin) onto woolen yarn can be obtained by irradiating both yarn and acidic extract for up to 4 min. The color coordinates given in Table 1 shown that using the given medium, most shades are dark reddish yellow, where optimal fabric-dyed is darker ($L^* = 21.03$), much ($a^* = 20.05$) redder and yellower in tone, ($b^* = 22.05$). It uses an acidic medium all shades are much darker reddish yellow, but the optimal yarn dyed is highly darker ($L^* = 16.82$) and less reddish yellow in tone ($a^* = 18.78$, $b^* = 17.21$).

Dyeing of yarn with acidic extract after MW rays for up to 4 min was observed the levels of the coloring variable. A trial of 32 experiments were implemented through central composite design as a statistical tool. It was found that dyeing of irradiated yarn with 50 mL of acidic extract of pH having 2g/100 mL of sodium chloride (NaCl), is an exhausting agent at 65 °C for 65 min has given excellent results (Table 2). Dyeing at a low heat level does not cause the shifting of molecules from medium to fabric rapidly, whereas too much heating causes a low yield in fabric. The same case is observed for time; contact of yarn for a low time at a low temperature does not furnish dark shades, whereas, for long-time contact, desorption was occurred (Singh and Sheikh, 2020). Hence at 65 °C for 65 min a high yield is observed. Statistically, it can be seen that model is fit ($P = 0.001$) and linear ($P = 0.008$), whereas the value of temperature ($P = 0.004$), time ($P = 0.049$), and salt ($P = 0.063$) are significant individually (Table 3). For two-way interaction ($P = 0.002$), the rate of pH. with volume ($P = 0.045$) and constant level Lab is significant. Similarly, the rate of temperature with extract volume ($P = 0.003$), time ($P = 0.007$), and salt ($P = 0.041$) is also significant. Side by side, the extract nature also plays a role, and extract volume time is also significant. Hence it is concluded that MW rays have significantly reduced dyeing time and temperature level and minimized the utilization of salt amount and extract volume. The statistical analysis revealed that this MW rays' tool is energy, time, and effective by dyeing wool yarn with red sandalwood extract.

Chemical Mordanting is the art of developing shade. The process depends upon the fabric's nature, weight, the anchor used, reduction power, and mode of application i.e., before and after dyeing. These anchors develop a special type of interaction called coordinate covalent bonding with the functional part of the dye molecule (mostly –OH and –C = O) as well as the binding site of fabric (-OH for cellulose, –CONH for silk/wool), through complex formation (Haji and Naebe, 2020). By this method, before and after dyeing, either shade because brighter and darker or comes out with new excellent colorfast coordinates (Hosen et al., 2021). In this study, three chemical mordants have been used, whereas these are sustainable, i.e., Al, Fe, and Tannic acid. The results revealed that before dyeing 0.5% T.A., and 1.5% of Al Fe, salts had given dark strength (Fig. 5a). Similarly, after dyeing, 0.5% of Fe, 1% of Al, and 2% T.A. displayed dark shades (Fig. 5b). The total variation given in Table 4 revealed that woolen yarn dyed before and after mordants are darker in shades of reddish yellow in hues. The proposed model dye complex formation has been displayed in Fig. 7a. When wool yarn was treated with chemical mordant, the ions of mordant interact with the functional groups present on the wool fibers, such as the hydroxyl (-OH) and carboxyl (-COOH) groups. This interaction is primarily through electrostatic attraction and coordination complexes (Islam and Mohammad, 2018). The positively charged ions form bonds with the negatively charged groups on the wool fibers, resulting in the formation of a complex. This complex facilitates the binding of sandalwood powder dye to the wool fibers, enhancing the dye's affinity and stability on the yarn.

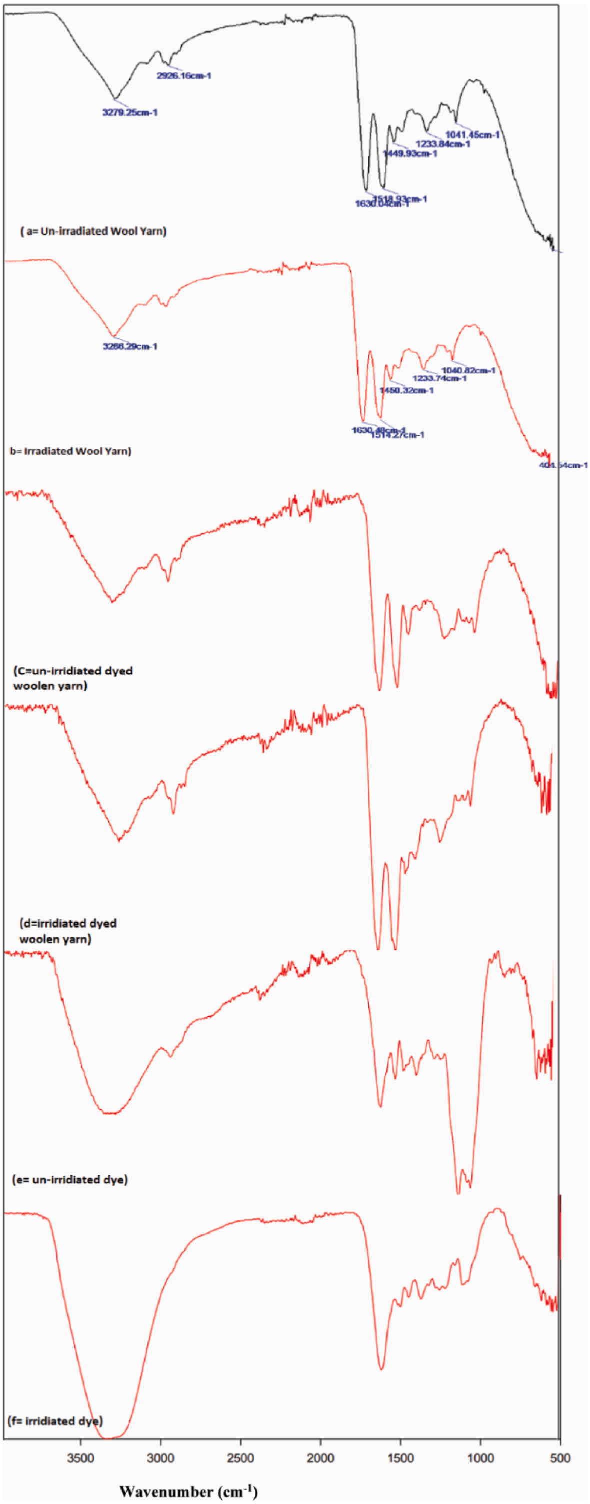


Fig. 2. Spectral analysis of control woolen yarn (a) radiated woolen yarn (b) un-radiated dyed woolen yarn (c) radiated dyed woolen yarn (d) un-radiated dye (e) radiated dye (f).

In understanding the toxicity of chemical mordants such as salt of Co, Cr, Cu, Ni, etc., the researchers have now decided to use plant extracts as a source of green, ayurvedic, and sustainable mordants (Zhang et al., 2021). These extracts have functional molecules which utilize either –OH or –C = O and –OH of bio-colorant and –OH or –CONH of fabric through additional covalent bonding (dos Santos Silva et al., 2020). Through this green process, not only are colorfast shades produced but also biological characteristics of

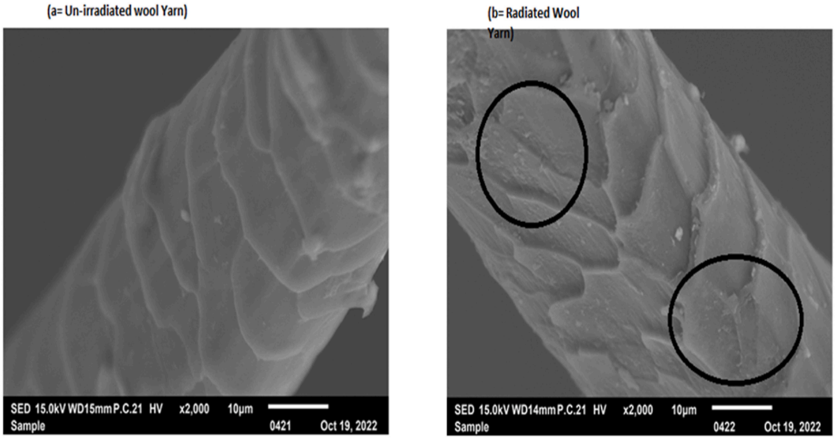


Fig. 3. SEM analysis woolen yarn (a) un irradiated woolen yarn (b) radiated woolen yarn.

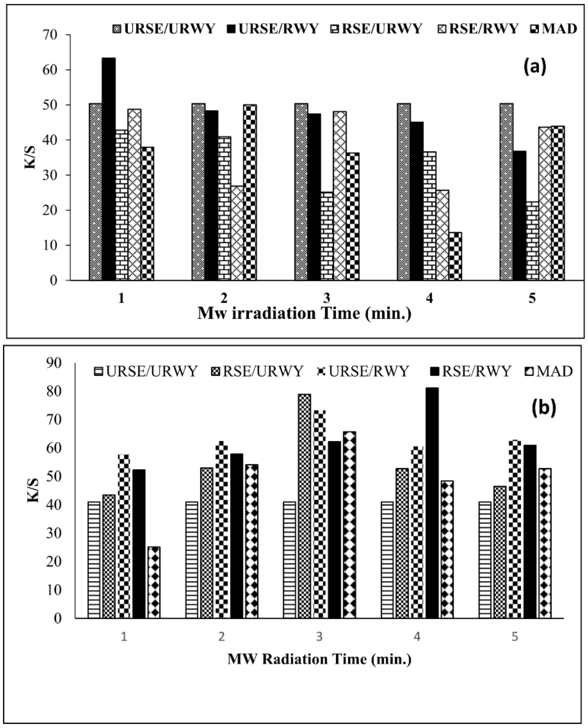
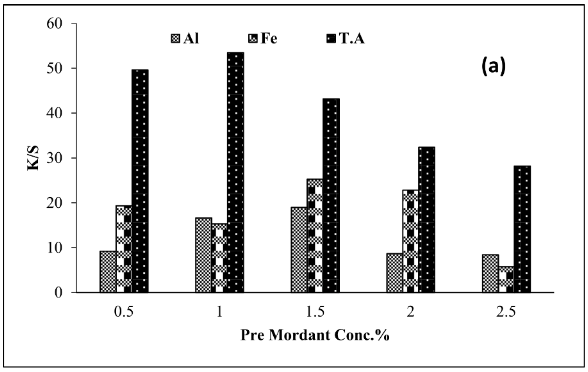


Fig. 4. (a) Using Red Sandal (RSW) powdered aqueous extract for coloring irradiated and unirradiated wool yarns employing microwave radiation, **(b)** Using Red Sandal (RSW) powdered acidic extract (MWI) color irradiated (RWY) and unirradiated wool yarns (NRWY).

green anchors are transferred to the fabric, which makes the coloring process pollution-free and eco-friendly (Özomay et al., 2022). In this study, extracts of acacia, ludhra, and pomegranate plants were used before and after yarn dyeing at selected conditions. The results show that, before dyeing yarn, 1% of acacia, 1.5% of pomegranate, and 2% of ludhra extracts displayed and high yield (Fig. 6a). After dyeing, 1% acacia and 1.5% ludhra and pomegranate extracts displayed high yield (Fig. 6b). The total valuation in Table 5 also revealed that shades made are too much darker and reddish yellow in hue. The proposed bio-mordant, yarn functional group and dye functional site interaction has been drawn in Fig. 7b. There are several ways the sandalwood powder color can interact with the wool yarn, including: Dye may absorb into the surface of the yarn as a result of interactions between the hydrophobic regions of the dye molecules and the hydrophobic sections of the wool fibers. Electrostatic attraction can be used to interact with spots on the wool fibers that are oppositely charged if the dye or bio-mordant has a net positive or negative charge. The dye's ability to adhere to the yarn is aided by this contact. Sandalwood powder dye and the presence of bio-mordants can have synergistic effects that improve the dyeing process (Dhanania et al., 2022). The bio-mordants might enhance the dye's affinity for the yarn, speed up color fastness, and help the dye molecules penetrate the wool fibers. Comparatively, bio-mordanting has given excellent results in place of their chemical

Table 3
Using two-way ANOVA analysis of variance, response surface regression was performed on K/S vs pH, volume, temperature, and salt.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	16	1043.4	651.90	7.37	0.001
Linear	5	2380.6	476.13	5.38	0.008
pH	1	278.1	278.12	3.15	0.102
Volume	1	236.5	236.50	2.67	0.128
Temperature	1	1087.7	1087.67	12.30	0.004
Salt	1	371.9	371.90	4.21	0.063
Square	4	4421.0	1105.26	12.50	0.000
pH*pH	1	3861.2	3861.21	43.66	0.000
Volume*volume	1	247.3	247.31	2.80	0.120
Temp*temp	1	689.3	689.33	7.80	0.016
Salt*salt	1	150.9	150.87	1.71	0.216
2-way interaction	7	4521.8	645.97	7.30	0.002
pH*volume	1	441.6	441.63	4.99	0.045
pH*time	1	751.9	751.86	8.50	0.013
Vol*temp	1	1251.5	1251.48	14.23	0.003
Vol*salt	1	604.2	604.18	6.83	0.023
Time*temp	1	913.2	913.25	10.33	0.007
Time*salt	1	88.8	88.83	1.00	0.0336
Temp*salt	1	463.5	463.54	5.24	0.041
Error	12	1061.2	88.43	–	–
Lack-of Fit	7	175.9	25.13	0.14	0.988
Pure Error	5	885.3	177.05	–	–
Total	28	11491.6	–	–	–



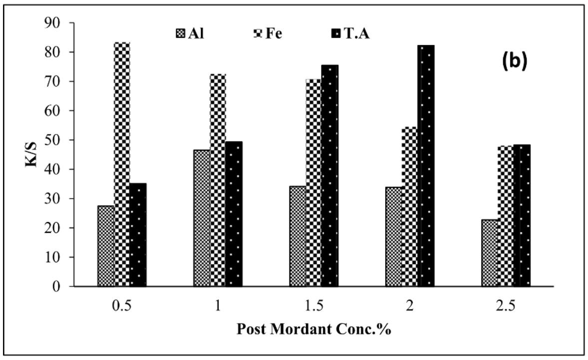


Fig. 5. **(a)** Pre-chemical mordant of wool yarn under optimal conditions of colorant, **(b)** Red sandal wood (RSW) powder post-chemical mordant of wool yarn under optimal conditions.

comparison, and it is revealed that dyeing of woolen yarn with RSW extract should be done before and after bio-mordanting instead of chemical mordant to get eco-friendly colorfast shades.

The fastness properties of naturally dyed yarn rely on mordants, where the surface nature of salt used (in the case of chemical mordants) for plant functional moiety (Table 6), and the mode of application employed (Jabar et al., 2022; Naveed et al., 2022). The function of the dye complex onto fabric added value in fast shades, which resist fading after amendment in fastness methods (Jafari et al.,

Table 4
Parameters determining the shade quality of a particular woolen yarn dyed with colorant with pre and post chemical mordanting.

Mordants used	Mordant Conc.%	K/S	L*	a*	b*
Al	1.5% Pre	18.89	44.37	25.73	42.03
Al	1% Post	46.51	25.56	19.33	25.98
Cu	2% Pre	95.24	7.2	6.69	3.35
Cu	2% Post	98.6	4.93	6.15	3.5
Cr	0.5% Pre	27.44	23.68	15.72	15.45
Cr	0.5% Post	59.90	11.61	9.73	6.43
Co	0.5% Pre	59.79	14.27	11.71	9.71
Co	1% Post	98.5	8.45	13.3	7.48
Fe	1.5% Pre	25.25	19.37	3.24	6.71
Fe	0.5% Post	83.29	6.55	0.52	0.87
Ni	1% Pre	38.29	24.91	16.37	21.61
Ni	1% Post	86.08	6.54	10.23	6.85
Sn	2% Pre	38.92	19.26	14.05	13.29
Sn	1% Post	59.61	16.67	14.52	14.5
TA	0.5% Pre	49.62	18.5	15.39	14.4
TA	2% Post	82.23	11.78	11.5	10.02

L* = dark/lighter; a* = redder/greener; b* = yellower/bluer.

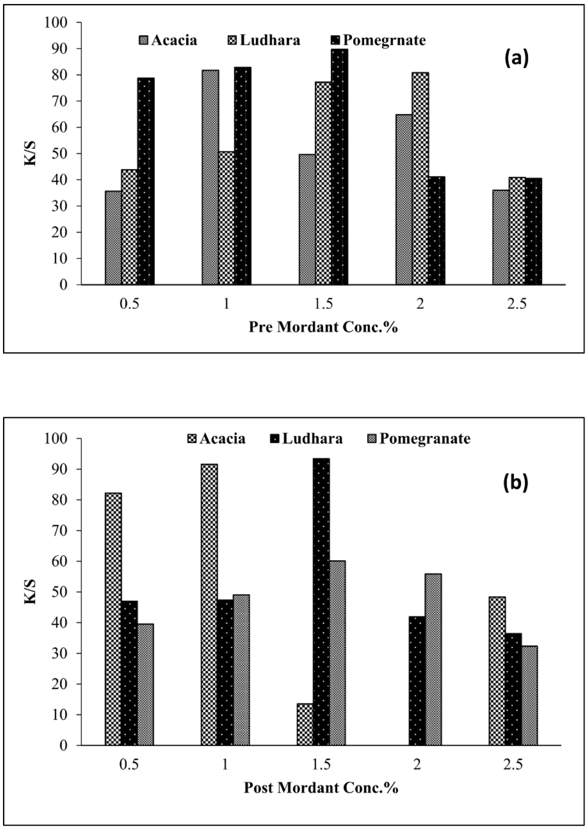


Fig. 6. **(a)** Using red sandal wood (RSW) powder under optimum conditions to pre-bio-mordant wool yarn, **(b)** Using red sandal wood (RSW) powder under optimum conditions to post-bio-mordant wool yarn.

2019). The light, wash and crock-treated dyed chemical mordanted fabric shows good to excellent fastness ratings. In Table 7, using plant functional molecules (bio-mordants), its rationally –OH or –C = O and –OH contributes, but conjugation prevents works well to develop colorfast shades (dos Santos Silva et al., 2020). Hence, along with MW-rays for extraction, the addition of bio-mordants plays an important role in making the dyeing process green and eco-friendly.

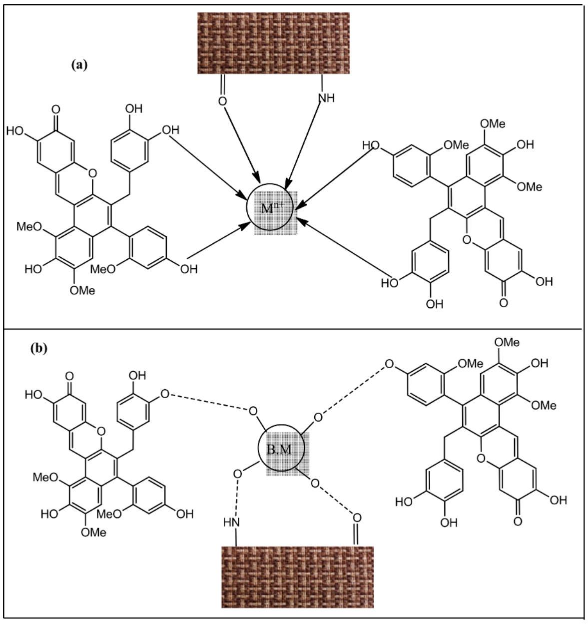


Fig. 7. The proposed chemical (a) and bio (b) interaction of wool with dye structure.

Table 5
Shade quality parameters of a selected woolen yarn dyed with colorant before and after mordanting.

Mordants used	Mordant Conc.%	K/S	*L**	*a**	*b**
Anar phali	0.5% Pre	50.67	18.36	15.55	15.29
Anar phali	1% Post	64.58	16.7	14.39	14.46
Acacia	1% Pre	81.73	12.07	15.02	10.52
Acacia	1% Post	91.56	10.77	15.04	9.15
Amaltas	2% Pre	94.8	15.12	4.92	2.6
Amaltas	1% Post	98.6	16.4	11.01	4.9
Arjun	2% Pre	54.22	23.05	22.91	22.98
Arjun	0.5% Post	85.01	11.71	13.54	10.12
Henna	1% Pre	92.8	20.15	15.53	11.47
Henna	2% Post	86.72	17.01	15.89	18.54
Ludhra	2% Pre	80.8	29.02	19.45	23.91
Ludhra	1.5% Post	93.41	15.24	16.58	16.27
Pomegranate	1.5% Pre	89.71	19.34	12.43	22.18
Pomegranate	1.5% Post	60.12	17.64	10.79	14.88
Turmeric	1% Pre	97.65	19.33	12.09	7.56
Turmeric	1% post	88.17	12.99	13.87	11.84

*L** = dark/lighter; *a** = redder/greener; *b** = yellower/bluer.

4. Conclusion

Natural dyes are acquiring global attention due to their beneficial ayurvedic properties. In the context of these benefits of using natural dyes, the current research was performed to determine the effectiveness of colorant (red sandalwood) as a source of natural dye for woolen yarn. The result shown that irradiation of wool yarn (RWY = 4 min) for dyeing with irradiated acidic extract of red sandalwood (RSW = 4 min) and filtrate containing 2g/100 mL of table salt at 65 °C for 65 min as an exhausting agent. The statistical optimization of the dyeing variable using central composite design (CCD) under the response surface approach reveals that MW treatment lowered both time and temperature, salt quantity as well as extract volume. Therefore, MW procedure is shown to have exceptional long-term effectiveness in separating colorant from red sandalwood for woolen yarn dyeing. On the other hand, adding new bio-mordants has made the process more environmentally friendly and sustainable.

Future research can concentrate on evaluating the woolen yarn dyed with red sandalwood extract and MW treatment's long-term color fastness and durability. To ascertain the dye's resistance to fading and degradation, thorough washing, light exposure, and rubbing tests would be required. It would be beneficial to compare the performance of red sandalwood dye with other natural dyes frequently used in the textile industry. It would aid in establishing the distinctive qualities and benefits of red sandalwood dye, such as its eco-friendliness, variety of colors, and suitability for various fibers. It would also be beneficial to investigate how the red sandalwood dyeing procedure may be scaled up and used in commercial settings. This would entail undertaking larger-scale tests and determining whether it is feasible to use this environmentally friendly coloring technique in the manufacturing of industrial textiles.

Table 6
Fastness of wool yarn treated with optimum extract of colorant before and after chemical mordanting.

Mordants used	Mordant Conc.%	Lightfastness	Washing fastness	Dry rubbing fastness	Wet rubbing fastness
Al	1.5% Pre	5	4–5	4–5	4
Al	1% Post	5	4	4	4
Cu	2% Pre	5	4	5	5
Cu	2% Post	5	4	5	5
Cr	0.5% Pre	5	4	5	4-5
Cr	0.5% Post	5	4	4–5	4-5
Co	0.5% Pre	5	4	5	4
Co	1% Post	5	5	5	4
Fe	1.5% Pre	5	4	4	4
Fe	0.5% Post	5	4	4	5
Ni	1% Pre	5	3	5	5
Ni	1% Post	5	3	5	5
Sn	2% Pre	5	3	5	4
Sn	1% Post	5	4	5	4
TA	0.5% Pre	5	3	4	4
TA	2% Post	5	4	5	4

Table 7
Fastness of wool yarn treated with optimum extract of colorant before and after bio-mordanting.

Mordants used	Mordant Conc.%	Lightfastness	Washing fastness	Dry rubbing fastness	Wet rubbing fastness
Anar phali	0.5% Pre	5	4	4	4
Anar phali	1% Post	5	5	5	5
Acacia	1%Pre	5	3	4	4–5
Acacia	1% Post	5	4	4	5
Amaltas	2% Pre	5	4	5	4
Amaltas	1% Post	5	5	4–5	5
Arjun	2% Pre	5	4	5	5
Arjun	0.5% Post	5	4–5	5	5
Henna	1% Pre	5	4	4	4
Henna	2% Post	5	4	4	4
Ludhra	2% Pre	5	4	5	4
Ludhra	1.5% Post	5	4	4	5
Pomegranate	1.5% Pre	5	3	5	4/5
Pomegranate	1.5% Post	5	4	5	5
Turmeric	1% Pre	5	3	5	4
Turmeric	1% Post	5	4	5	5

Authors contributions

The whole experiments have been conducted by M. Phil student, Maria Mehboob, Dr. Samra Barkaat and Dr Shahid Adeel has supervised and co-supervised the work. And Dr Muhammad Zuber and Dr. Meral Özomay have guided scientifically for smooth running of the work, whereas Rony Mia, Somayeh Mirnezhad, and Tanvir Ahmad has modified the manuscript as per scientific style.

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Author statement

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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