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RESEARCH ARTICLE

Eco-friendly microwave assisted sustainable coloration of silk and wool fabric with Acid Blue 07 dye

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Abstract

Environment-friendly textile processing is the demand of the current global scenario, where the application of sustainable technologies such as microwave radiation has been gaining fame in all global fields due to their green and human-friendly nature. This study has been conducted to employ sustainable technology such as microwave (MW) rays for dyeing polyamide-based proteinous fabric using Acid Blue 07 dye. The fabric before and after MW treatment for up to 10 min has been dyed using an acid dye solution. Spectrophotometric analysis of the dye solution was performed before and after irradiation at a specific selected level. Using selected dyes and irradiation conditions, a series of 32 experiments using a central composite design has been employed. The shades made at selected conditions of irradiation and dyeing were assessed for colorfastness as per ISO standards. It was observed that for dyeing silk, 55 mL of Acid Blue 07 dye solution containing 1 g/100 mL salt solution at 65 °C for 55 min should be employed after MW treatment for 10 min. In comparison, for dyeing wool, 55 mL of Acid Blue 07 dye solution containing 2 g/100 mL salt solution at 65 °C for 55 min should be employed after MW treatment for 10 min. Physiochemical analysis shows that sustainable tool has not altered the chemical nature of fabric but has modified the fabric surface physically to enhance uptake ability. Colorfastness shows that the shades made have offered good resistance to fade and have given good to excellent ratings on the gray scale.

Keywords Colorfastness · MW radiation · Silk · Sustainability · Textile effluent · Wool

Introduction

Worldwide growing sustainable developmental processes have not only influenced life in an efficient manner but also engendered side effects related to biosphere pollution. Sustainability is a main objective in most of the industrial sectors, and sustainable practices require the use of less harmful chemicals and low effluent discharge. In recent years, sustainable practices have been gaining importance in the textile sector due to increased environmental awareness and stricter global legislations. The textile industry makes extensive use of energy and water, which is also causing greenhouse gas emissions (GHG), which in turn along with carcinogenic effluents are destroying the environment badly. It is well recognized that the use of microwave treatment reduces the requirement for large amounts of energy and also improves the entire process of dyeing.

Synthetic dyes are now being used to color fabrics and other materials. Pollutants from all sorts of industries especially from textile industries generate huge amounts of hazardous waste (Mia et al. 2019; Donkadokula et al. 2020). Textile effluents usually consist of several toxic and carcinogenic chemicals (Liu et al. 2021) which also raise the chemical oxygen demand (COD), biochemical oxygen demand (BOD), and suspended solid (SS) parameters of water (Chen et al. 2021). The process of dyeing textiles uses a lot of water and produces a lot of

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effluents, which is hazardous for the aquatic ecosystem and agricultural land. Due to the use of environmentally hazardous chemicals and the buildup of textile waste, the textile sector is the most polluting industry in the world (Sivaram et al. 2019; Nayak et al. 2020).

Effluent treatment plants are the most widely accepted approaches for achieving environmental safety. However, no single treatment approach is appropriate or generally applicable for treating all forms of wastewater. According to the level of emissions, several procedures, such as physical, chemical, and biological treatment, are used to treat the waste stream. Hence, there is a dire need for such technologies that are clean, green, and sustainable in treatment (Abbas and Sağsan 2019). The effluent load in textiles is a major challenge that requires a variety of methods for treatment (To et al. 2019). Different methods are employed to change textile processing based on conventional methods, such as mercerization, cationization, bleaching, and desizing, but modern techniques, such as the use of radiation in textile dyeing, are gaining popularity. There are different techniques employed for effluent treatment, including ultrasonic (Maheshwari et al. 2020), ultraviolet, microwave (Sadiqa et al. 2021), and plasma techniques (Pandiyaraj et al. 2021). However, using microwave treatment to enhance textile processing and decrease effluent discharge from textile industries is a value addition process. The use of microwave radiations modified the surface of the fabric in such a way that less amount of dye effluent is produced with excellent color strength. Microwave radiations are a potential and environmentally friendly heating source (Zhou et al. 2021) because it provides uniform, effective, controlled, and rapid heating to the coloring system (Abdelileh et al. 2021; Keraani et al. 2021). Microwave radiations can reduce textile effluent and improve dyeing behavior (Al-Etaibi and El-Apasery 2022). This tool enables colorant molecules to diffuse into the fabric more strongly (Muneer et al. 2018). Microwave-assisted dyeing of the fabric also helps enhance color characteristics (Popescu et al. 2019; Kamran et al. 2021). Many researchers have used the microwave radiation technique to dye a variety of textiles, achieving higher exhaustion rates, increased dyeing rates, and excellent colorfastness properties (Sharma et al. 2020; Sutar et al. 2022; Tănase et al. 2021; Lara et al. 2022).

Synthetic textile dyes are organic compounds that bring bright and firm colors to the fabric (Ayele et al. 2021). These dyes have introduced a wide range of colorfastness along with different alluring hues. These are less expensive, more readily available, and easier to apply to fabrics (Jamee and Siddique 2019). Among these dyes, acid dyes have unique applications. These dyes are synthetic being anionic, soluble in water, and can be applied directly from a dye bath. The majority of acid dyes have – SO_3Na groups which are water-soluble and capable of binding fibers (Choi et al. 2019). These dyes are attracted by positively charged amino groups in polyamide fibers such as silk, wool, and nylon. The strong binding of dye molecules to the material leads to better color characteristics in dyed fabrics. Among acid dyes, Acid Blue 07 is a greenish-blue powder that imparts a dark blue to violet shade onto polyamide fabrics. Among polyamide fabrics, silk and wool are natural proteinous fibers where silk fibroin and wool keratin contain amide units as functional parts and are utilized for a firm and stable interaction with dye binding sites (Benkhaya et al. 2020; Adeel et al. 2021). Structures of functional groups of fabric and Acid Blue 07 are given in Fig. 1.

Keeping in view the advantages of MW for dyeing and surface modification of fabrics, the current study has aimed to.

i. Explore the dyeing behavior of proteinous fabrics under the influence of microwave-assisted heating.
ii. Study physiochemical changes of fabrics before and after radiation treatment.
iii. Examine the absorption maxima (λ_{max}) of Acid Blue 07 dye.
iv. Observe the effect of different salts and acids on the dyeing of proteinous fabrics dyed with Acid Blue 07 dye.
v. Optimize dyeing variables using central composite design as a statistical tool under response surface methodology.
vi. Rate the colorfastness properties of wool and silk fabrics dyed with Acid Blue 07 dye.

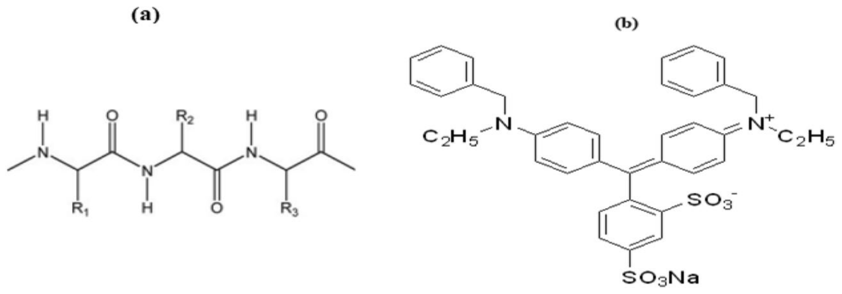


Fig. 1 Functional unit of proteinous fabric silk and wool (**a**) and Acid Blue 7 dye (**b**)

Table 1 Irradiation and dyeing conditions for silk and wool using Acid Blue 07 dye

Fabrics used	Sample code	Microwave irradiation time	Dyeing conditions
Silk	RDS/RF	2–10 min	Dye Solution = 55 mL Salt as leveling agent = 1 g/100 mL Temperature = 65 °C Time = 55 min
Wool	RDS/RF	2–10 min	Dye solution = 55 mL Salt as leveling agent = 2 g/100 mL Time = 55 min pH = 4

RF, radiated fabric; *RDS*, radiated dye solution

Material and method

Materials

Silk and wool fabric have been purchased from Jhelum Cloth House, Faisalabad. Acid Blue 07 (C.I. 42,080) was purchased from Kukdacolor, Karachi, Pakistan. All the chemicals employed during the dyeing process such as table salt (NaCl), sodium sulfate (Na_2SO_4), hydrochloric acid (HCl), sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3), and neutral soap were of commercial grade (Pakistan made).

Irradiation process and dyeing

A dye solution was prepared by dissolving 0.5 g of Acid Blue 07 (AB 07) dye into 100 mL of lukewarm distilled water. The dye solution and fabrics were irradiated for up to 10 min with an interval of 2 min using a domestic-based Dawlance microwave oven at high power (2450 MHz, 700 W). The dyeing was carried out under various microwave-treated and untreated conditions, as described in Table 1.

Statistical optimization of dyeing condition

A set of 32 experiments using the central composite design (CCD) as a statistical tool under response surface methodology were conducted. Various dyeing parameters such as temperatures, pH, table salt, and a selected volume of dye bath have been inserted and utilized (Table 2). The dyeing of silk and wool has been carried out at 55 ℃ to 95 ℃, pH (3 to 7), table salt (0.5 to 2.5 g/100 mL), and selected volumes (25, 35, 45, 55, and 65 mL) of dye bath was employed.

Table 2 Tonal variation and colour characteristics of silk and wool fabrics dyed at selected irradiation conditions

Irradiation time (min)	Sample code	λ_{max}	*K*/*S*	*L**	*a**	*b**	*C**	*h**
Silk at neutral pH								
Control (without radiation)	NRDS/NRSF	630	21.955	34.90	25.12	27.69	37.39	227.79
2	RDS/RSF	620	23.163	38.04	29.39	28.70	41.08	224.31
4	NRDS/RSF	620	24.482	34.84	26.09	28.21	38.43	227.24
6	NRDS/RSF	620	23.343	37.54	28.75	29.53	41.21	225.77
8	RDS/NRSF	630	35.497	32.42	27.09	26.18	37.67	224.01
10	RDS/NRSF	630	20.133	45.34	37.58	22.49	43.79	210.91
Wool at neutral pH								
Control (without radiation)	NRDS/NRSF	640	34.638	26.92	20.76	23.28	31.20	224.14
2	RDS/NRWF	640	39.547	31.49	25.80	23.33	34.78	222.12
4	RDS/RWF	620	36.812	33.12	28.24	26.43	38.68	223.11
6	RDS/RWF	640	38.885	32.45	26.24	26.97	37.63	225.79
8	NRDS/RWF	640	41.265	31.13	26.94	26.01	37.45	223.99
10	NRDS/RWF	640	38.339	32.89	28.03	26.25	38.40	223.12

NRDS, non-radiated dye solution; *NRF*, non-radiated fabric; *NRF*, non-radiated fabric; *RF*, radiated fabric; *RDS*, radiated dye solution; *MAD*, microwave assisted dyeing

Analysis of fabric and dye solution

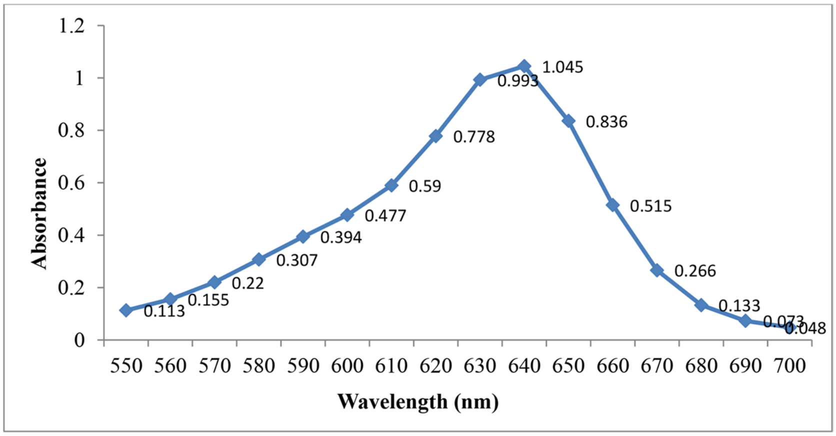
The absorption spectrum of the dye was measured using a UV–Visible spectrophotometer (Peak Instruments, Model C-7200, USA), and the dye showed high average absorption values at a wavelength of 640 nm (Fig. 2). Finally, the shade made at selected conditions has been assessed for colorfastness ratings using ISO standard methods. ISO standards for washing (ISO 105 C03), light fastness (ISO 105 B02), and rubbing (ISO 105-X12) have been employed. The FTIR analysis of untreated and MW treated (2–10 min) proteinous fabric was done using a PerkinElmer-based Fourier-transformed infrared spectrometer (USA), and the SEM analysis of fabrics was done using a scanning electron microscope (SEM-model Tescan; 5 kV). The color characteristics of all dyed fabrics (before and after irradiation) have been investigated in the CIE Lab system using COLORISPECTROPHOTMETRE CS 410 China with an illuminant D65 at 10° observer at the Department of Chemistry, Government College University, Faisalabad, Pakistan.

Results and discussion

Extensive use of synthetic dyes in textile industries elutes such pollutants which are not only carcinogenic but also destroy the eco-balance of the globe (Javaid and Qazi 2019). Due to such harmful effects, these dyes and dyed products are under strict observation on account of their toxicity and hazardous effects (Samsami et al. 2020). In our studies, microwaves have been used to modify the acid dyeing of proteinous fabrics. The results of color characteristics show that untreated silk fabric (NRSF) and radiated dye solution (RDS), up to 8 min, have excellent color depth ($K/S = 35.497$) as compared to untreated dye solution used for coloration of untreated fabric ($K/S = 21.955$) (Fig. 3a, b). For untreated fabric and dye solution, the color coordinates show that shades are darker ($L^* = 34.90$) with a reddish-yellow hue ($a^* = 25.12$, $b^* = 27.69$) (Table 2). But when the dye solution is treated using microwave radiation, a prominent change in shades occurs, i.e., shades become darker ($L^* = 38.04$) with a more reddish-yellow appearance ($a^* = 28.75$, $b^* = 29.53$). On the same pattern using wool fabric, the dyeing behavior of Acid Blue 07 (AB 07) has been observed. The color characteristics indicate that untreated dye solution (NRDS) and radiated wool fabric (RWF), up to 8 min, have excellent color depth ($K/S = 41.265$) as compared to untreated dye solution used for coloration of untreated fabric ($K/S = 34.638$) (Fig. 3c, d). The color coordinates show that shades obtained under controlled conditions (NRDS/NRWF) are darker ($L^* = 26.92$) and have a reddish yellow hue ($a^* = 20.76$, $b^* = 23.28$) (Table 2). But the shades obtained by dyeing fabric under optimal conditions (RDS/RWF) are darker ($L^* = 33.12$) with a reddish-yellowish tone ($a^* = 28.24$, $b^* = 26.43$).

Good results have been observed because MW treatment via its unique mode of action modifies the surface of the fabric to enable effective dye molecule absorption to achieve maximum dyeing rates (Hu et al. 2020). When fabrics are irradiated with microwave radiation, they undergo physical changes and, open the voids of fabrics as a result, absorb much more dye molecules (Shaw et al. 2021). Microwave radiations increase the reaction rate which yields high productivity of dyes through even or constant heating (Verma and Samanta 2018; Palma et al. 2020; Ewis and Hameed 2021). Wool has more substantivity towards Acid Blue 07 (AB 07) dye as compared to silk fabric. In wool fabric, peptides and disulfide linkages have been observed, which require a lot of energy to improve their substantive nature. Hence, it is recommended that for silk dyeing, both the dye solution and fabric need to be treated using microwave radiations. Similarly, for wool dyeing, both the dye solution and fabric need to be treated using microwave radiations.

Fig. 2 Absorption spectrum of Acid Blue 07 dye



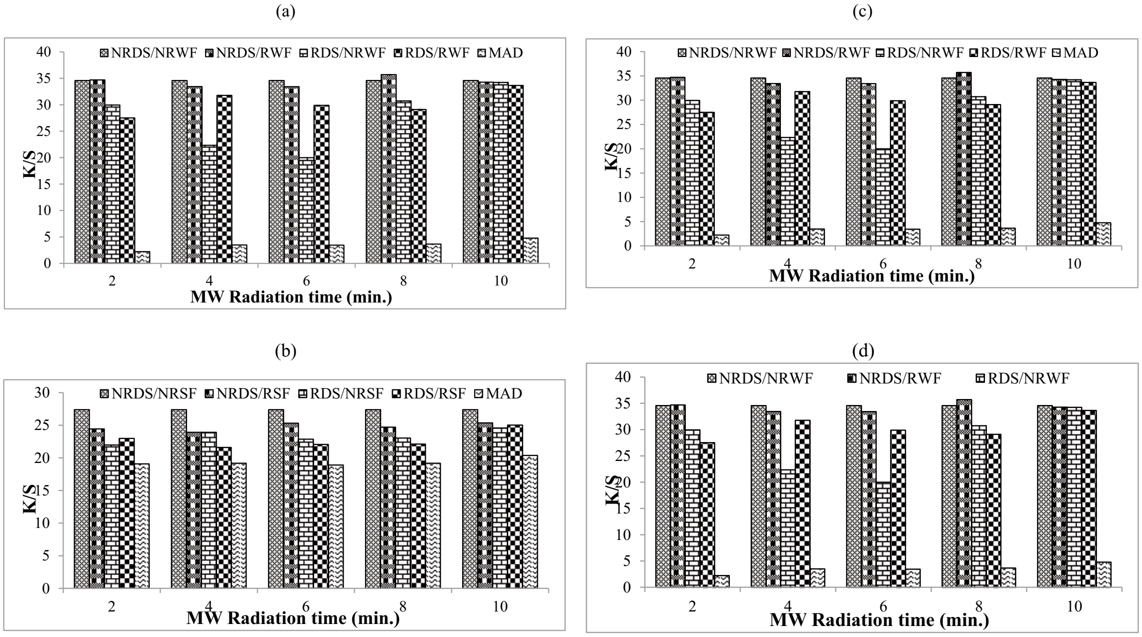


Fig. 3 Color strength values of silk fabric at aqueous pH (**a**), at acidic pH before and after MW radiation (**b**), wool fabric at aqueous pH (**c**), and at acidic pH before MW treatment after MW treatment (**d**)

Table 3 shows the statistical analysis for silk coloration which shows that the results are not significant ($P = 0.760$). Similarly, for wool coloration, a two-way ANOVA analysis (Table 3) shows that the selection of irradiation of both solution and fabric is not significant ($P = 0.287$).

The existence of different functional groups and linkages in proteinous fabrics such as silk and wool has been confirmed by FTIR analysis (Guha 2019). In untreated silk, as observed in Fig. 4a, intense peaks appeared at 1750–1720 cm^{-1} (C = O), 1510 cm^{-1} (CONH), NH (3270 cm^{-1}), and 1390–1365 cm^{-1} for CH_3 groups respectively (Peets et al. 2019). MW radiations do not change the chemical nature of silk (Fig. 4b). In treated wool fabric, a broad peak was observed at 3270 cm^{-1} which shows the presence of the CH_2 group (Fig. 4c, d). Similarly, for wool fabric, functional peaks found at about 1750–1720 cm^{-1} (C = O), 1510 cm^{-1} (CONH), NH (3270 cm^{-1}), and 1390–1365 cm^{-1} for CH_3 groups have been found (Machnowski and Wąs-Gubała 2021; Gurumurthy and Ramesh 2018). SEM analysis revealed that the surface of silk and wool fabric is scratched when it was treated with MW radiations. The peeled surface of fabrics shows that substantive behavior might have been increased which was observed in terms of excellent color strength. Thus, if silk is dyed with AB 07, only the dye solution needs to be MW treated for 8 min, whereas for wool, the fabric needs to be MW treated for 8 min to obtain good color strength. Table 4 displays the optimization of dyeing parameters through RSM.

Table 3 Two-way ANOVA for the statistical analysis of microwave-treated silk and wool fabrics with Acid Blue 07 dye versus *K/S* value

Source	Type III sum of squares	Df	Mean square	*F*	Sig
For silk dyeing					
Corrected Model	49.600^a	8	6.200	0.606	0.760
Intercept	12,873.762	1	12,873.762	1257.305	0.000
Time	39.681	4	9.920	0.969	0.451
Sample code	9.919	4	2.480	0.242	0.910
For wool dyeing					
Corrected Model	541.995^a	8	67.749	1.354	0.287
Intercept	29,451.132	1	29,451.132	588.727	0.000
Time	128.816	4	32.204	0.644	0.639
Sample code	413.179	4	103.295	2.065	0.133

Role of acids in the dyeing of proteinous fabric

Figure 5 shows the SEM analysis of radiated and irradiated silk and Fig. 6 shows the role of acids on color strength of silk and wool. It is evident that when silk was dyed using Acid Blue 07 in a dye bath containing 1.5 mL Conc.HCl, a good color yield ($K/S = 25.040$) was obtained. For 25 mL of acetic acid color strength ($K/S = 24.067$), 1.0 mL of formic acid ($K/S = 24.64$),

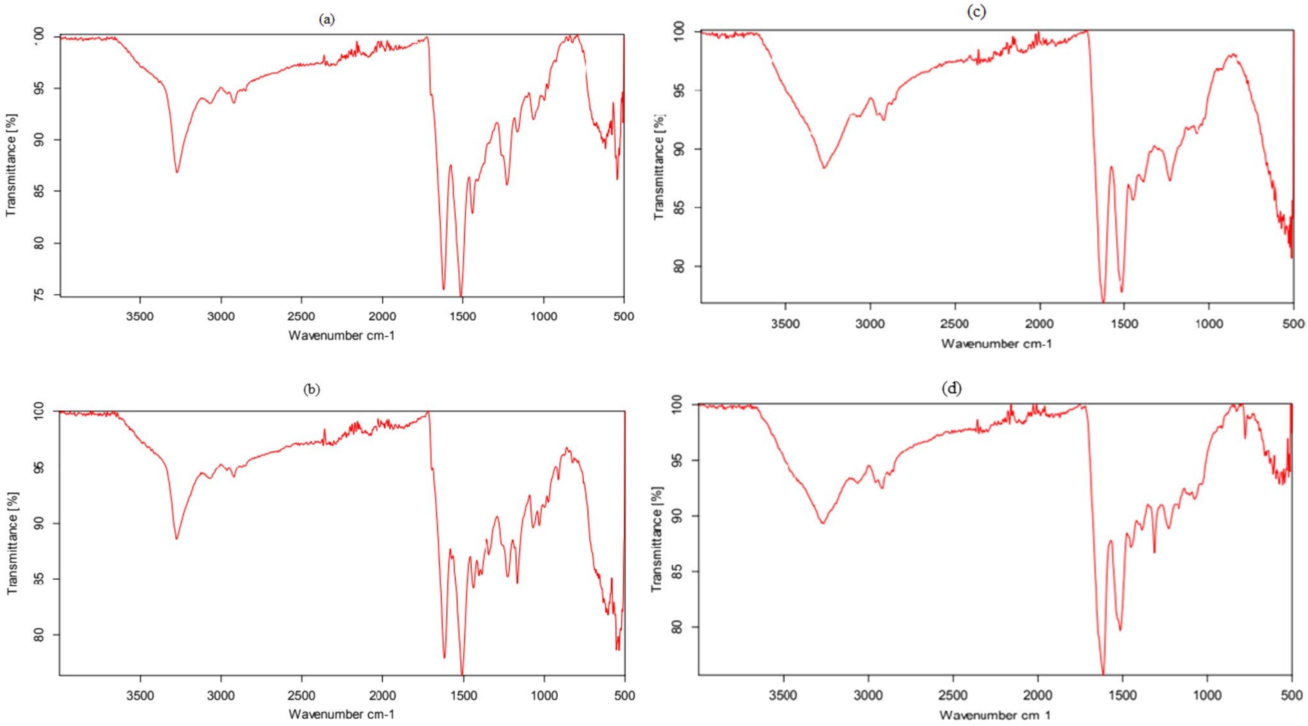


Fig. 4 FTIR spectra of control (**a**), microwave-treated silk (**b**), FTIR spectra of control (**c**), microwave-treated wool (**d**)

2.0 mL of oxalic acid gives $K/S = 23.050$, and 0.5 mL of citric acid gives color strength (K/S) up to 24.392. Overall, for silk dyeing, 1.5 mL of HCl solution is good to use for making the dye bath viable for maximum color yield. Low pH helps to form hydrogen bonds that help dye attach to proteinous fibers. For wool fabric, maximum color yield ($K/S = 38.802$) was obtained when 0.5 mL of citric acid solution was used for dyeing with AB-07 dye (Fig. 6b). For acetic acid, 2 mL has given ($K/S = 34.779$), 1 mL of formic acid gives K/S up to 36.68, 2 mL of oxalic acid solution has given color strength 38.101, and 1.5 mL of HCl acid has shown color yield up to 36.863. Higher acidic dye bath conditions might have weakened the proteinous fibers, causing a less firm bond between dye and binding molecules to the fabric's functional sites and, thus, producing fabrics with weaker colors. Amino and carboxyl groups present in protein fibers are mostly ionized to (NH_3^+) and (COO^-). The addition of acid (HX), which makes silk fiber positively charged ($+H_3N$-S-COOH) causes the carboxyl ions of the fiber molecule main chain to be converted to unionized carboxyl groups in the acidic dye bath. This allows the silk fiber to absorb an appropriate amount of the acid anions X- (Akhtar et al. 2018).

The order of color strength produced by using different acids is as follows:

HCl > formic acid > citric acid > acetic acid > oxalic acid

The order of color strength achieved by using different acids is as follows:

Citric acid > oxalic acid > HCl > formic acid > acetic acid

Role of salts in the dyeing of proteinous fabric

The effect of salts on the color strength of silk and wool is evident from Fig. 7. It is clear that the dyeing process needs inorganic electrolytes, typically in the form of salts of sulfates, to be added to the aqueous dye bath to promote dye uptake. Salt is necessary for the process of dyeing as it drives dye into textiles during the dyeing process. The amount of added inorganic electrolytes used in exhaust dyeing processes varies according to the kind of dye, polyamide fiber type, liquor ratio, dyeing auxiliaries, etc. Acid dyes need salts to dye textile fabrics, to obtain excellent fastness to color, washing, rubbing, and leveled dyeing. These salts act as a catalyst that facilitates dyeing action (Burkinshaw and Salihu 2019). Too high concentration of salt causes aggregate formation onto fabric due to excessive exhaustion. This exhaustion results in difficult penetration into the voids of fibers of dye molecules thereby making

Table 4 Optimization of dyeing parameters for silk and wool fabrics using Acid Blue 07 dye through central composite design under response surface methodology (RSM)

Exp no	A	B	C	D	E	F
For silk						
1	4	35	1	35	85	25.451
2	6	35	1	35	65	23.023
3	4	55	1	35	65	28.155
4	6	55	1	35	85	23.847
5	4	35	2	35	65	27.95
6	6	35	2	35	85	26.557
7	4	55	2	35	85	25.383
8	6	55	2	35	65	24.428
9	4	35	1	55	65	25.918
10	6	35	1	55	85	23.583
11	4	55	1	55	85	22.198
12	**6**	**55**	**1**	**55**	**65**	**31.05**
13	4	35	2	55	85	26.156
14	6	35	2	55	65	24.463
15	4	55	2	55	65	28.224
16	6	55	2	55	85	23.389
17	3	45	1.5	45	75	23.435
18	7	45	1.5	45	75	24.573
19	5	25	1.5	45	75	24.19
20	5	65	1.5	45	75	24.13
21	5	45	0.5	45	75	23.389
22	5	45	2.5	45	75	23.206
23	5	45	1.5	25	75	24.175
24	5	45	1.5	65	75	23.078
25	5	45	1.5	45	55	22.79
26	5	45	1.5	45	95	24.31
27	5	45	1.5	45	75	25.371
28	5	45	1.5	45	75	25.423
29	5	45	1.5	45	75	23.61
30	5	45	1.5	45	75	25.946
31	5	45	1.5	45	75	24.44
32	5	45	1.5	45	75	22.9
For wool						
1	4	35	1	35	85	34.704
2	6	35	1	35	65	24.494
3	4	55	1	35	65	35.179
4	6	55	1	35	85	27.955
5	4	35	2	35	65	36.861
6	6	35	2	35	85	25.095
7	4	55	2	35	85	33.562
8	6	55	2	35	65	31.433
9	4	35	1	55	65	36.686
10	6	35	1	55	85	29.452
11	4	55	1	55	85	35.668
12	6	55	1	55	65	27.549
13	4	35	2	55	85	34.382
14	6	35	2	55	65	29.357
15	**4**	**55**	**2**	**55**	**65**	**38.291**
16	6	55	2	55	85	32.989
17	3	45	1.5	45	75	23.463

Table 4 (continued)

Exp no	A	B	C	D	E	F
18	7	45	1.5	45	75	20.373
19	5	45	2.5	45	75	22.431
20	5	45	1.5	25	75	14.979
21	5	45	1.5	65	75	28.711
22	5	45	1.5	45	55	25.01
23	5	45	1.5	45	95	26.025
24	5	45	1.5	45	75	20.224
25	5	45	1.5	45	75	26.504
26	5	45	1.5	45	75	26.786
27	5	45	1.5	45	75	26.351
28	5	45	1.5	45	75	26.201
29	5	45	1.5	45	75	26.025
30	5	45	1.5	45	75	26.41
31	5	45	1.5	45	75	27.12
32	5	45	1.5	45	75	25.87

A, pH; *B*, Volume; *C*, Salt; *D*, Time; *E*, Temperature; *F*, *K*/*S* value

loose bonding between functional sites of dye and fabric (Kabir and Koh 2018; Zhang et al. 2019; Adegoke et al. 2022). In this part of the manuscript, the effect of inorganic salts including zinc sulfate ($ZnSO_4$), sodium sulfate (Na_2SO_4), copper sulfate ($CuSO_4$), iron sulfate ($FeSO_4$), and aluminum sulfate ($Al_2\ (SO_4)_3$ has been reported. For silk fabric, maximum color yield ($K/S = 26.841$) was obtained using 2 g/100 mL aluminum sulfate ($Al_2\ (SO_4)_3$ (Fig. 7a).

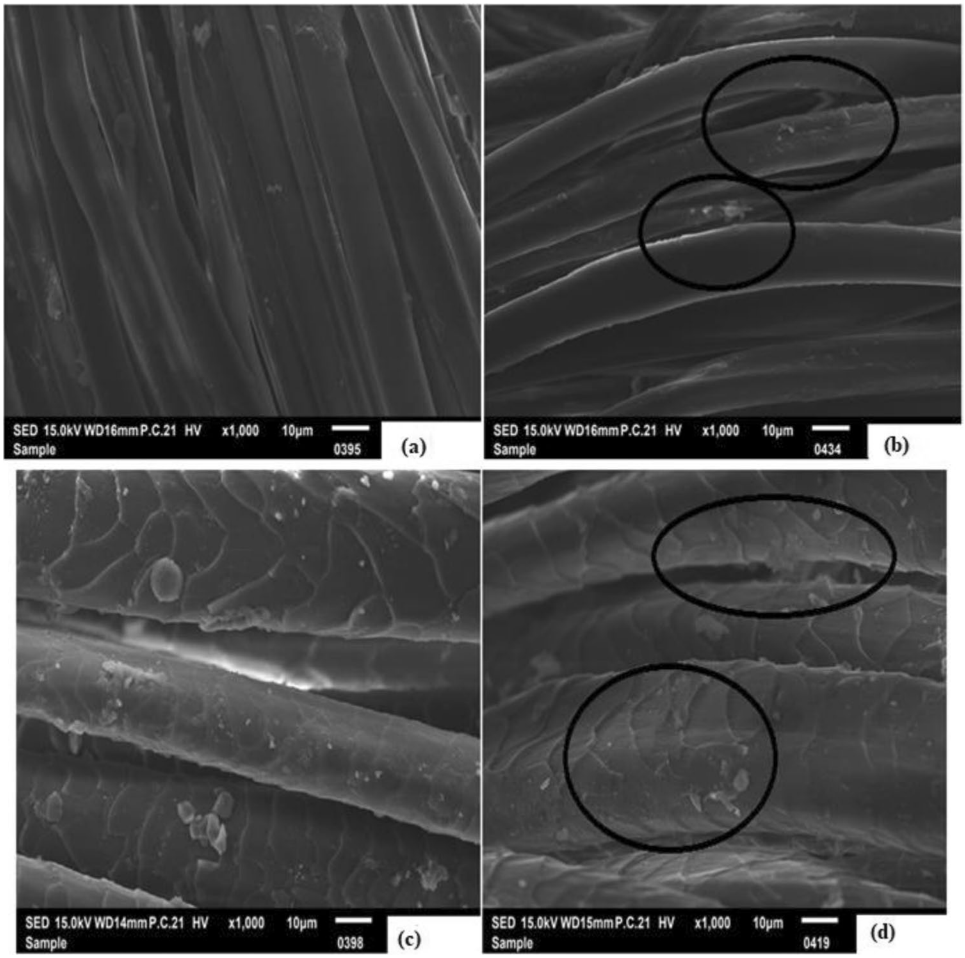


Fig. 5 SEM analysis of un-irradiated silk (**a**), radiated silk (**b**), SEM analysis of un-irradiated wool (**c**), and radiated wool (**d**)

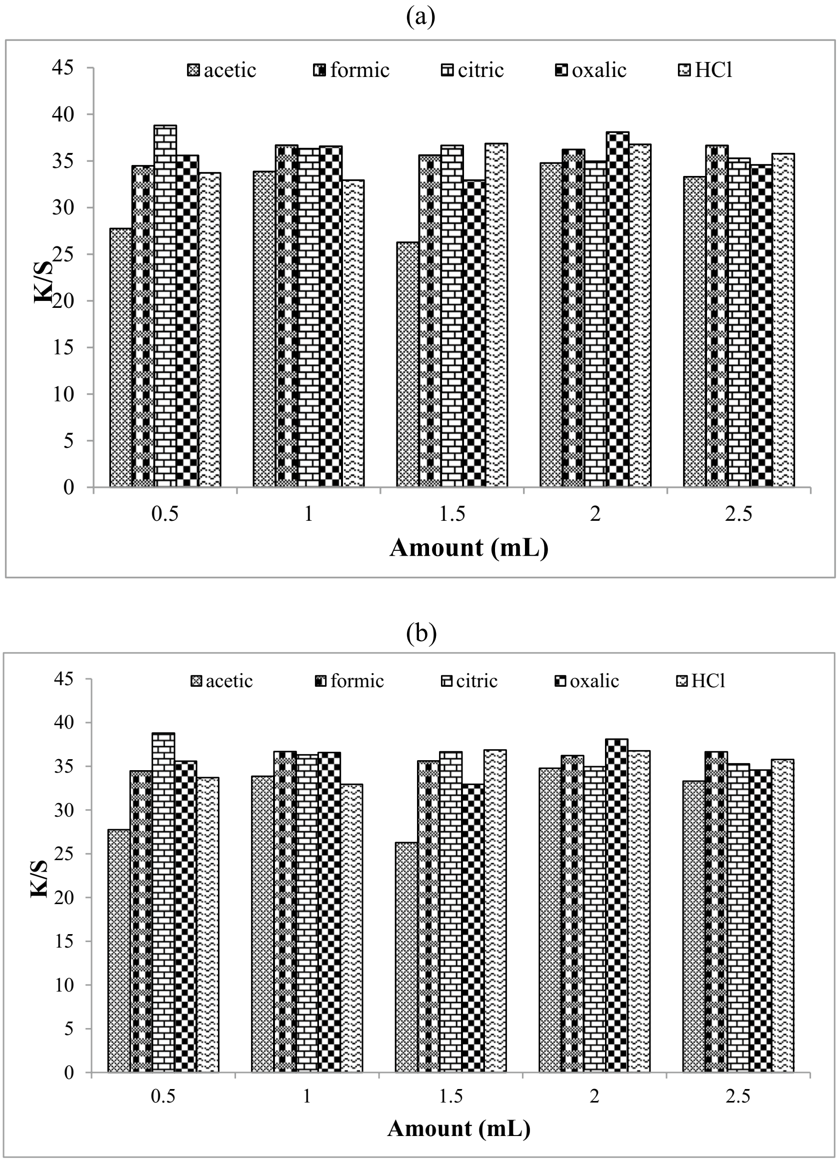


Fig. 6 Role of different acids on color strength of silk (**a**), wool (**b**)

For copper sulfate 2 g/100 mL gives ($K/S = 21.216$), 1 g/100 mL iron sulfate gives ($K/S = 24.353$), 2.5 g/100 mL sodium sulfate gives ($K/S = 20.343$), and 0.5 g/100 mL of zinc sulfate gives ($K/S = 23.217$). Similarly, for wool fabric, maximum color yield ($K/S = 38.834$) was obtained using 2.5 g/100 mL aluminum sulfate $Al_2\ (SO_4)_3$. For copper sulfate 2.5 g/100 mL gives ($K/S = 32.567$), 2.5 g/100 mL iron sulfate gives ($K/S = 34.861$), 1 g/100 mL sodium sulfate gives ($K/S = 21.267$), and 0.5 g/100 mL of zinc sulfate gives ($K/S = 31.955$). Salt as an exhausting agent helps the colorant penetrate the fabric in close proximity, enabling bonding through short attractive forces.

The order of salts regarding color strength when silk fabric was dyed with AB 07 is as follows:

Aluminum sulfate > iron sulfate > zinc sulfate > copper sulfate > sodium sulfate

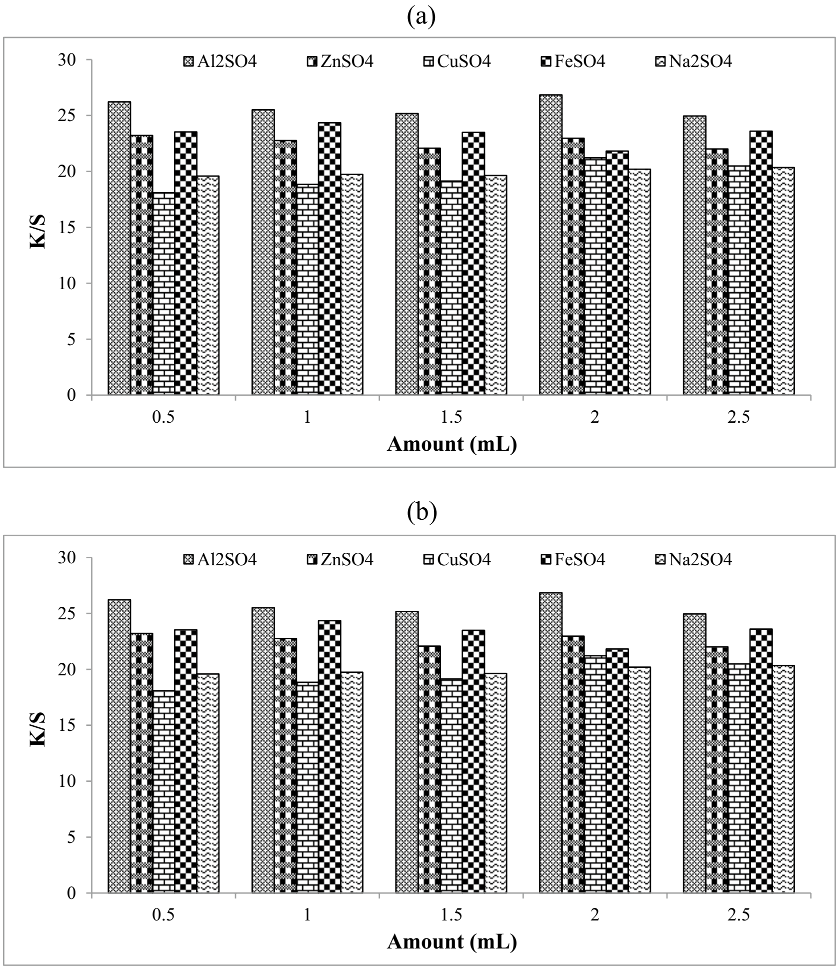
The order of salts regarding color strength when wool fabric was dyed with AB 07 is as follows:

Aluminum sulfate > iron sulfate > copper sulfate > zinc sulfate > sodium sulfate

Hence, excellent color yield was obtained for wool fabric when 2.5 g/100 mL of aluminum sulfate was used for dyeing with Acid Blue 07 (AB07) dye. The results are reported in Fig. 7b.

Different dyeing variables have different roles in fabric dyeing. The pH of the dye bath is important for silk or wool fabric because under acidic conditions, the amine linkage gets protonated, where it becomes equally available for dyeing with a functional site of dye. In the case of acid dyeing, a low pH helps form the hydrogen bonds that attach acid dyes to protein fibers, such as silk, wool, and nylon. Silk can be dyed at low pH (acidic) or high pH, while

Fig. 7 Role of different salts on color strength of silk (**a**) and wool (**b**)



wool can only be dyed at low pH because it is damaged by high pH. The results show that irradiation of the dye bath at pH 6 for up to 8 min has given good results on non-treated silk fabric, but for wool fabric, irradiation of the fabric for 8 min has given good results with a non-treated dye solution of pH 4. The volume of the dye bath is also a very important variable during the dyeing process of proteinous fabrics. The volume of the dye bath after irradiation also affects color strength. It is observed that 55 mL of an irradiated dye bath of pH 6 for silk has given good results, whereas for wool fabric, 55 mL of a dye bath of pH 4 has given good results (Table 4). Exhausting or leveling agents in any dyeing process play a good role in strong interaction as their particular amount causes the dye to penetrate the voids of fabric and produce high-quality shades (Sundhu et al. 2021; Wolela 2021). Through this particular amount, more colorant is sorbed and less effluent is produced (Talukder et al. 2017).

The same is true of the eco-friendly situation that has been found in our studies. It has been observed that 1 g/100 mL of salt has exhausted well the colorant from the bath towards the fabric. After MW treatment of both dye solution and fabric, more sorbed dye by adding salt shows that this treatment is sustainable and green. Statistically, from Table 5, it can be seen that salt along with pH ($P = 0.066$), dye bath volume ($P = 0.026$), and temperature ($P = 0.047$) for silk dyeing have given significant results. Similarly, for wool, the role of salt with dye bath pH ($P = 0.019$), dye volume ($P = 0.017$), and temperature ($P = 0.044$) has been found to be significant. Thus, salt addition to get a high yield onto fabric with less effluent is necessary for the greener dyeing process. The role of pH ($P = 0.026$) and temperature ($P = 0.001$) is significant. In two-way interactions, the role of pH with salt ($P = 0.066$) and pH with time ($P = 0.056$) is significant. In two-way interactions, the role of volume with temperature ($P = 0.002$) is highly significant. The role of salt with temperature ($P = 0.047$) is significant. The role of time with temperature ($P = 0.017$) is also significant. Hence, selecting 55 mL of solution of Acid Blue 07 (AB 07) at pH 6 using 1 g/100 mL of salt at 65 ℃ has given significant

Table 5 Analysis of variance for silk fabric according to obtained results

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	19	98.000	5.1579	4.70	0.008
Linear	5	31.933	6.3867	5.82	0.009
pH	1	7.456	7.4560	6.80	0.026
Volume	1	0.497	0.4968	0.45	0.516
Salt	1	0.365	0.3648	0.33	0.577
Time	1	0.168	0.167	0.15	0.704
Temperature	1	21.840	21.8399	19.91	0.001
Square	4	16.827	4.2067	3.84	0.039
pH*pH	1	4.533	4.5326	4.13	0.069
Salt*Salt	1	1.192	1.1919	1.09	0.322
Time*Time	1	0.430	0.4300	0.39	0.545
Temperature*Temperature	1	7.844	7.8440	7.15	0.023
2-way interaction	10	58.961	5.8961	5.38	0.007
pH*Volume	1	2.725	2.7250	2.48	0.146
pH*Salt	1	4.684	4.6840	4.27	0.066
pH*Time	1	5.145	6.1450	4.69	0.056
pH*Temperature	1	1.871	1.8707	1.71	0.221
Vol*Salt	1	7.581	7.5309	6.87	0.026
Volume*Time	1	2.182	2.1823	1.99	0.189
Voumel*Temperature	1	18.994	18.9943	17.32	0.002
Salt*Time	1	1.188	1.1876	1.08	0.323
Salt*Temperature	1	5.625	5.6262	5.13	0.047
Time*Temperature	1	9.017	9.0165	8.22	0.017
Error	10	10.968	1.0968		
Lack of fit	8	3.990	0.7980	0.57	0.723
Pure error	5	6.970	1.3956		
Total	29	108.968			
Model summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	1.04728	89.93%	70.81%	0.00%	

Table 6 Analysis of variance for wool fabric according to obtained results

Source	DF	Adj SS	Adj MS	*F*-value	*P*-value
Model	19	840.304	44.227	7.61	0.003
Linear	5	226.325	45.265	7.79	0.006
pH	1	0.031	0.031	0.01	0.944
Volume	1	72.395	72.395	12.46	0.008
Salt	1	3.162	3.162	0.54	0.482
Time	1	118.358	118.358	20.37	0.002
Temperature	1	20.326	20.326	3.50	0.098
Square	4	515.018	128.755	22.16	0.000
pH*pH	1	19.296	19.296	3.32	0.106
Volume*Volume	1	443.352	443.352	76.30	0.000
Salt*Salt	1	41.241	41.014	7.10	0.029
Time*Time	1	20.116	20.116	3.46	0.100
2-way interaction	10	105.995	10.599	1.82	0.203
pH*Vol	1	57.756	57.756	9.94	0.014
pH*Salt	1	50.237	50.237	8.65	0.019
pH*Time	1	43.196	43.195	7.43	0.026
pH *Temperature	1	57.482	57.482	9.89	0.014
Volume*Salt	1	52.774	52.774	9.08	0.017
Volume*Time	1	26.599	26.599	4.58	0.066
Volume*Temperature	1	34.066	34.066	5.86	0.042
Salt*Time	1	33.160	33.160	5.71	0.044
Salt*Temperature	1	9.840	9.840	1.69	0.229
Time*Temperature	1	47.018	47.018	8.09	0.022
Error	8	46.482	5.810		
Lack of fit	3	14.631	4.877	0.77	0.560
Pure error	5	31.852	6.370		
Total	27	886.786			
Model summary	S	R-sq	R-sq(adj)	R-sq(pred)	
	2.41046	94.76%	82.31%	*	

results for silk dyeing (Table 4). The statistical model shows that it is fit and linear (Table 6). The table shows that the roles of volume ($P = 0.008$) and time ($P = 0.002$) are highly significant. In two-way interaction, the role of pH with volume ($P = 0.014$), salt ($P = 0.019$), time ($P = 0.026$), and temperature ($P = 0.014$) is significant. The interaction of volume with time ($P = 0.066$), temperature ($P = 0.042$), and salt ($P = 0.017$) is also significant. The role of salt with time ($P = 0.044$) is also significant. The role of time with temperature ($P = 0.022$) is also significant. Hence, wool dyeing using 55 mL of dye solution containing 2 g/100 mL salt at 65 ℃ for 55 min has given good results.

Washing, light, dry, and wet rubbing fastness properties are displayed in Table 7, and it is noticed that the MW-treated wool fabric (RWF) and non-treated silk fabric (NRSF) when dyed with radiated dye solution (RDS) of AB 07 have improved colorfastness properties. This is because microwave treatment has modified the surface of

Table 7 Rating of fastness properties of fabric dyed at optimal conditions using Acid blue 07 dye

Shade (%)	Light fastness	Washing fastness		Rubbing fastness	
Silk fabric					
		c.c	c.s	Dry	Wet
0.5	5	4/5	4/5	5	4/5
1.0	5	4/5	4/5	5	4/5
1.5	5	4/5	4/5	5	4/5
2.0	5	4/5	4/5	5	4/5
2.5	5	4/5	4/5	5	4/5
Wool fabric					
0.5	5	4/5	4/5	5	4/5
1.0	5	4/5	4/5	5	4/5
1.5	5	4/5	4/5	5	4/5
2.0	5	4/5	4/5	5	4/5
2.5	5	4/5	4/5	5	4/5

fabrics in such a way that color fading parameters such as washing, light, and crocking do not affect the shade. The type of dye, the specific shade used, the depth of shade, and how effectively the dyeing process has been conducted may all affect colorfastness properties. Most dyes change or lose their shade when exposed to light, as light causes the degradation of dye. In washing fastness, the staining of fabric observed is because of color migration from the fabric to the dye bath. Good light, washing, and rubbing fastness can be attributed to the presence of conjugation systems, benzenoid rings, auxochromes, and modes of bonding. Hence, all this fastness jointly adds value to the coloration of fabrics.

Conclusion

The dyeing process needs to be sustainable as the conservation of water resources and the environment become key issues of concern in textile manufacturing. By using environmentally friendly technology such as microwave radiation, the dyeing process can be made more clean, effective, and rapid. From our study, it is recommended that dyeing MW-treated silk and wool fabrics with MW-treated dye solution, in the presence of salt as an exhausting agent, has provided excellent results. Hence, it is concluded that MW radiations improve the color characteristics of fabrics without altering their molecular structure. MW treatment also reduces dyeing time and temperature by making the process sustainable, cost-effective, and energy efficient. Employing the MW radiation method helps reduce waste products and toxic components and makes the dyeing process eco-friendly for the global community.

Author contribution Dr. Muhammad Usman has supervised where Dr. Shahid Adeel has co-supervised the work of M.Phil studies. Ms. Hira Akram has performed experiments and Dr. Tanveer Hussain Bokhari has technically and scientifically guided the work for smooth running of experiments. Dr. Meral Ozomay has analyzed fabrics through FTIR and SEM techniques. The significance of the method utilized in this study was statistically analyzed by Mr. Aftab Ahmad.

Data availability The whole data is present in M.Phil. thesis of Miss Hira Akram.

Declarations

Ethical approval We approve that this manuscript is part of M.Phil studies of Miss Hira Akram.

Consent to participate N/A.

Consent for publication We give consent to publish our work of M.Phil studies that is jointly contributed by all authors.

Competing interests The authors declare no competing interests.

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