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Enhancement of Polyester Dyeing Performance Integrating Ecological and Cost-Effective Auxiliaries

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Article

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ABSTRACT

Disperse dyes, primarily used for dyeing synthetic fibres like polyester, are characterized by their poor solubility in water, which necessitates the use of dispersing agents; however, environmental concerns arise due to their low biodegradability and potential toxicity, thus posing significant challenges in waste management and pollution control. This study explores the dyeing performance of knitted polyester with dispersed dyes, employing natural auxiliaries as substitutes for conventional commercial chemicals to promote an environmentally friendly approach. Citric acid (derived from lemon), sodium citrate (prepared from citric acid and sodium bicarbonate), and glucose (extracted from date fruits) replace commercial acetic acid, dispersing agent, and hydrolyze. Dyeing is conducted using the high-temperature and high-pressure methods with consistent parameters. A comparative study of the dyeing performance of the natural auxiliaries with the existing commercial chemicals was assessed concerning colour strength, different fastness properties, and the FT-IR diagram. Proton NMR is utilized for the structural determination of date fruit and lemon components. UV-Vis spectral data show that adding sodium citrate to the dispersed dye solution drops the absorbance value from 1.1457 to 0.58916, confirming sodium citrate's efficacy as a dispersing agent. With lower recipe costs, the environmentally friendly approach using natural auxiliaries exhibits comparable dyeing performance and excellent fastness properties, providing a sustainable alternative to traditional methods.

KEYWORDS

knitted polyester, natural auxiliaries, disperse dye, colour strength, colour fastness

INTRODUCTION

The most important class of synthetic fibres, polyester, is coloured primarily with dispersion dyes, which were developed in the early 1920s to colour secondary cellulose acetate fibres. Disperse dyes are aromatic, non-ionic compounds with anthraquinone or azo as a chromophore group. The fibres are dyed using a stable aqueous dispersion that includes high-temperature dispersants and other auxiliaries [1]. Due to stringent laws and increased ecological concerns, environmental factors are

being considered more and more in the textile dyeing and finishing processes [2,3]. Therefore, natural auxiliaries are far more convenient than synthetic auxiliaries when dyeing polyester materials. In the dyeing process, acetic acid, which is toxic in high concentrations, is typically used to adjust the pH value of the dye bath, although a buffer system containing formic acid and ammonium sulfate can be used as well [4–6]. Citrus fruits and vegetables, in particular, contain citric acid, a weak organic acid. Because of its low toxicity, it is safer for the general public's health and the environment. It is a cheap, safe, biodegradable, and multipurpose chemical that can be used for cleaning, wetting, buffering, and sequestering. Carmo et al. explored the possibility of using citric acid in place of acetic acid in the dyeing processes for polyester and polyamide [7]. The study found that citric acid can be used as a levelling agent for dispersing dyestuffs, with no significant differences in colour dyeing and good colour fastness to water. Sodium citrate, a dispersing agent, plays a crucial role in the dyeing process. It can enhance the dispersion of dispersed dyes, leading to improved dyeing properties [8–10]. Citric acid, when combined with sodium bicarbonate, produces sodium citrate. Zouhaier et al. examined using glucose as a reducing agent when using sulfur dyes for dyeing [11]. Comparing glucose with sodium dithionite in natural indigo dyeing and found that glucose has the potential to be applied as a green reducing agent. Bhuiyan et al. dyed polyester fibre with henna dye at an elevated temperature to enhance dye uptake and depth of shade [12]. Elnagar et al. described an eco-friendly method for dyeing synthetic fabrics with natural dyes using UV/ozone pretreatment to activate fibre and improve dyeability of polyester [13]. Tambi et al. applied natural dyes on polyester fabric displayed good colour values and satisfactory colour fastness, with additional functional properties such as antibacterial, antioxidant, and UV protection [14].

Some works have been found in literature related to polyester dyeing using natural dye [12,13,15–18]. However, there is a lack of investigation of polyester dyeing with dispersed dye using natural auxiliaries. Polyester dyeing with dispersed dyes along with natural auxiliaries may be good substitutes for conventionally synthesized auxiliaries. In addition, a large number of commercial auxiliaries have negative effects on the environment, including toxicity, foul odours, and pollution. Here, the main objective is to find an alternative to conventional chemicals and introduce a sustainable dyeing environment. Also, the motive is to investigate the feasibility of natural auxiliaries and to evaluate the behaviour of dispersed dye with natural auxiliaries. So, natural auxiliaries are used, which will be eco-friendly, easily available, and sustainable and will give an acceptable performance.

EXPERIMENTAL

Materials and Methods

Materials

100% knitted polyester fabric (constructional structure: single jersey) that has an areal density of 150 gm/sqm and Terasil Red W-4BS-01 150% (Huntsman, UK) disperse dye were used in this research work. Commercial chemicals such as Univadine DFM (dispersing agent), Univadine Top (levelling agent), Albatex AB-45 (acid buffer), acetic acid (CH_3COOH), hydrolyze ($Na_2S_2O_4$) and caustic soda (NaOH) were used. Fabrics, dyes, and chemicals were sourced from Magpie Textile Composite Ltd., Dhaka, Bangladesh. All the chemicals were laboratory-grade and used without any purification.

Lemon and glucose were used in this research as sources of natural acids and natural reducing agents, respectively. Sodium bicarbonate or baking soda ($NaHCO_3$) was used for preparing sodium citrate along with natural citric acid. These components were purchased from Mugda Market, Dhaka, Bangladesh.

Extraction of citrus lemon juice

Taking raw, fresh lemons, cleaning them thoroughly, cutting them into pieces, and manually squeezing them with a wooden squeezer. Pure citrus lemon juice was obtained from raw lemons by filtering them with a nylon filter. In place of commercial inorganic acetic acid, the filtered citrus lemon juice provides an abundant source of citric acid, which was used to maintain the pH of the dye bath. Figure 1 (a) indicates the schematic illustration of the citrus lemon juice extraction process.

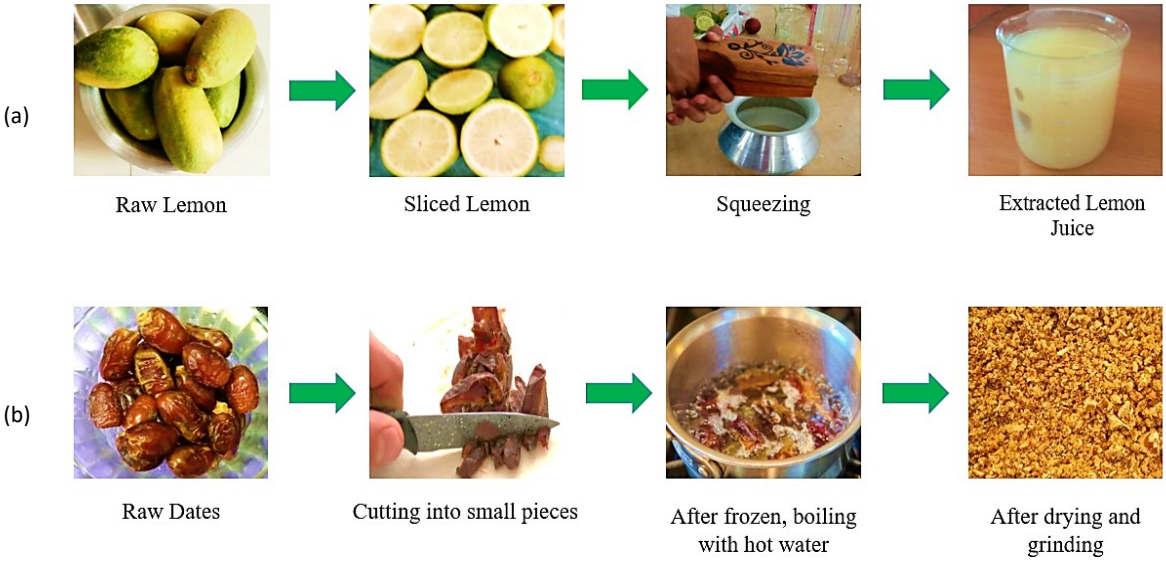

Figure 1. Citrus lemon juice extraction process (a) and glucose extraction process from dates (b)

Extraction of Glucose from Dates

The dates were frozen after being cut into tiny pieces. The dates were in contact with a hot water solution to extract the glucose from them. The sugar-enriched water solution was filtered through milli-screens. After drying and grinding, glucose was obtained, which was used instead of hydrolysed for reduction cleaning purposes. Figure 1 (b) indicates the schematic illustration of the glucose extraction process from dates.

Preparation of Sodium Citrate

For preparing sodium citrate, 8 grams of citric acid were mixed with 9.5 g of baking soda, and then 12.5 ml of water was added. It will foam, and after the foam subsides, the liquid will contain almost 10 g of sodium citrate. By maintaining the ratio, sodium citrate can be prepared.

Dyeing Procedure

All the samples were dyed according to the recipe described in Table 1 concerning natural and commercial auxiliaries with Terasil Red W-4BS-01 150% dispersed dye. The beakers (including dye solution and fabric samples) were set in the dyer and raised to 130 °C (5 °C/min) for dyeing. Continue at this temperature for 45 minutes before cooling down to room temperature. After that, the dye liquor was drained, and samples were prepared for washing. For reduction clearing, similarly, the chemical solutions were taken into the beakers along with the dyed samples, set into the dyer, raised to 95 °C, continued for 20 minutes, cooled down to room temperature, dropped out, and the samples were prepared for washing. The dyeing and reduction cleaning procedures are shown in Figure 2.

Table 1. Recipe for dyeing with Terasil Red W-4BS-01 150% disperse dyes

Dyeing by using commercial chemicals					Dyeing by using natural auxiliaries				
Dyeing Process									
Name of the Dyes	Concentration								
Terasil Red W-4BS-01 150%	0.5%	1%	1.5%	2%	3%	4%	5%	6%	7%

Name of the Chemicals	Concentration	Name of the Chemicals	Concentration
Univadine DFM	0.6 g/L	Sodium Citrate	1 g/L
Univadine Top	0.6 g/L	Citric Acid	10 g/L
Albatex AB-45	1.0 g/L		
Acetic Acid	1.2 g/L		
Temperature	130 °C	Temperature	130 °C

Name of the Chemicals	Concentration	Name of the Chemicals	Concentration
Time	45 minutes	Time	45 minutes
pH	4.5	pH	4.5
M:L	1:10	M:L	1:10
	Reduction Clearing Process		
Hydroze	2 g/L	Glucose (from Dates)	2 g/L
Caustic Soda	2 g/L	Caustic Soda	2 g/L
Temperature	95 °C	Temperature	95 °C
Time	20 minutes	Time	20 minutes
M:L	1:10	M:L	1:10

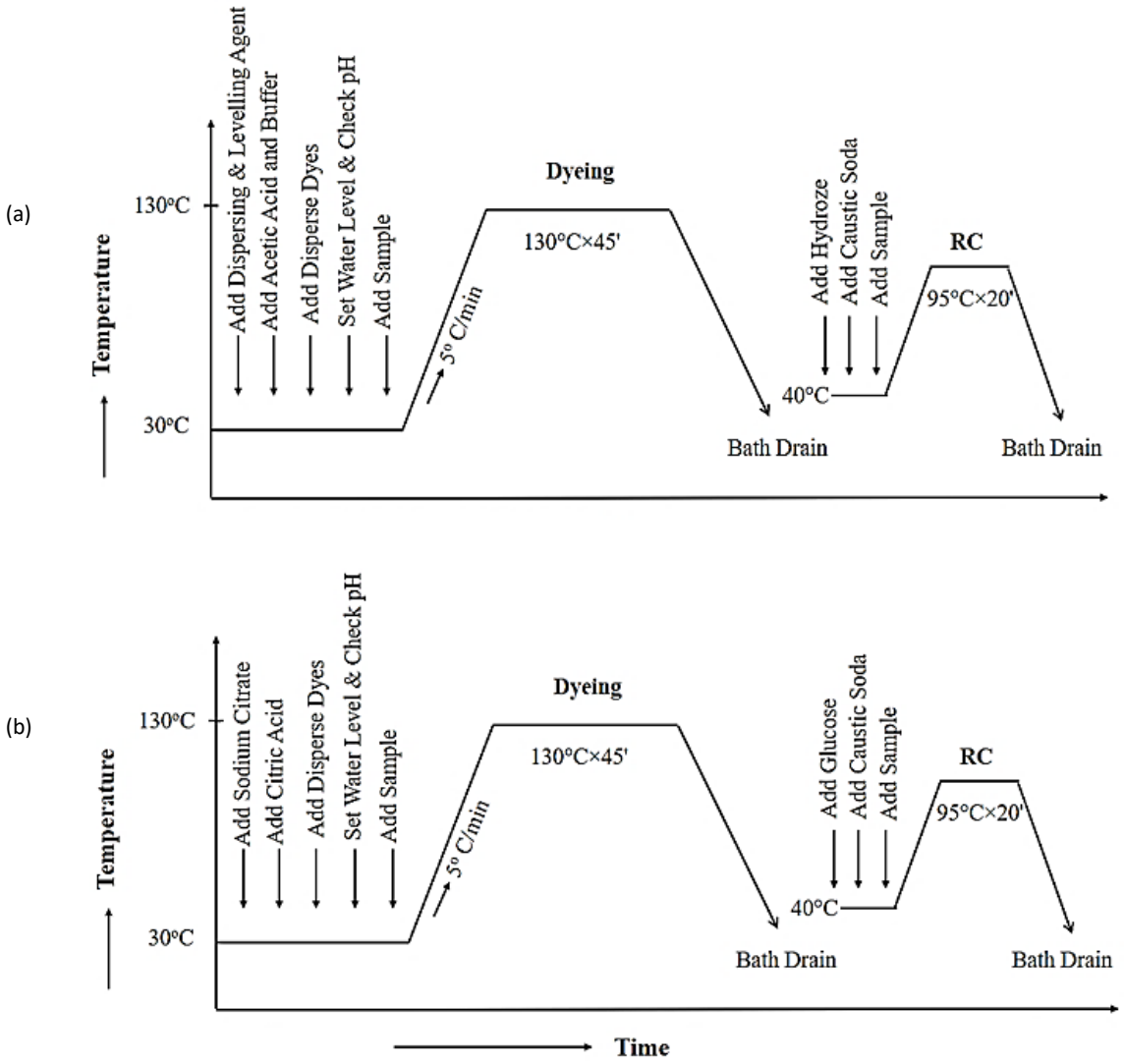

Figure 2. Process curve for dyeing and RC using commercial auxiliaries (a) and natural auxiliaries (b)

Measurement of reflectance%, colour strength and dye uptake%

The reflectance% of the dyed samples was measured using the colour measuring spectrophotometer (Brand: Hunter Associates Laboratory, Inc.) with the illuminant D-65 and 10° observers. The dyed samples colour strength (K/S) was obtained from the reflectance values by using the following equation [19]:

$$\frac{K}{S} = \frac{(1 - \mathrm{R})2}{2\mathrm{R}} \quad (1)$$

Where, R = Reflectance, K = Absorption co-efficient and S = Scattering co-efficient

Dye uptake% was calculated by expressing the K/S values in percentage when considering 100% dye uptake during dyeing with commercial auxiliaries.

Evaluation of colour fastness properties

The ISO 105-C06 [20] standard method was followed for the assessment of colour fastness in the washing of dyed samples. Rubbing fastness was assessed by following ISO 105 X-12:2002 [21] and perspiration fastness properties were assessed through ISO 105 E04 [22] method. The rating was determined using the grey scale for all the test methods.

FT-IR, NMR and UV-Vis analysis

Fourier-Transform Infrared Spectroscopy (FT-IR) (Brand: MIRacle ATR and Model: MB3000 PIKE MIRacle) was utilized to measure spectral data of different natural and commercial auxiliaries as well as dyed and undyed fabric samples to determine their functional groups where every spectrum was obtained at a resolution of 4 cm^{-1}, with a sample and background data collection time of one minute each. The functional group region, which covers the wavelengths from 4000 cm^{-1} to 2000 cm^{-1}, and the fingerprint region, which covers the wavelengths from 4000 cm^{-1} to 600 cm^{-1}, are the typical ranges for an IR spectrum (2000 cm^{-1} to 600 cm^{-1}) [23–25]. For characterization and structural determination of natural auxiliaries (dates and lemons) Proton Nuclear Magnetic Resonance (Brand: BRUKER) was used. Two distinct NMR tests were conducted for dates and lemons where D_2O (Deuterium Oxide) was used as the solvent in both cases. A UV-Vis spectrophotometer ranging from 190 to 900 nm was used to determine the absorption of dye solution of Terasil Red disperse dye, solution of dye and dispersing agent, and solution of dye and sodium citrate.

Evaluation of the Environmental impact of waste-water

COD was measured by using a COD reactor and COD spectrophotometer with a suitable test kit. For BOD measurement, firstly DO was measured using colourimetric value and then BOD was calculated by following the formula [26].

$$BOD = (DO_{initial} - DO_{final}) \times \text{dilution factor} \quad (2)$$

RESULTS AND DISCUSSION

Evaluation of reflectance%, colour strength and dye uptake%

The sample dyeing with existing commercial auxiliaries and the sample dyeing with natural auxiliaries were considered standard samples and trial samples, respectively. Table 2 denotes that the minimum reflectance values fell between 510 nm to 540 nm wavelength. It was also discovered that when the shade percentage was increased, the reflectance value decreased by up to 4% shade, and then different outcomes were achieved for the trial and standard samples (as reaching nearly saturation level, so differences are obtained). Once more, a decrease in reflectance results in an increase in the K/S value, which indicates a rise in colour strength due to an increase in shade% [27]. Except for the 6.0% shade, the trial sample's K/S value was lower for every shade% when compared with the standard sample.

Considering that the dye uptake% for the standard samples was 100% for each shade, considering that the trial sample's dye uptake% was significantly lower for 0.5% shade. As the shade% increased, so did the dye uptake%. The trial sample's dye uptake% for 6.0% shade is higher than the standard sample's, while the dye uptake% for 3.0%, 4.0%, and 7.0% shade is nearly equal for both the standard and trial samples. So, it can be concluded that dye uptake% is higher when dyeing with dispersed dyes using commercial auxiliaries than when dyeing with dispersed dyes using natural auxiliaries.

Fastness properties analysis

Wash, rubbing, and perspiration fastness properties (Table 2) were evaluated on grayscale and found that the fastness properties were identical or even better when dyed with natural auxiliaries in each fastness. Here, the wash, rubbing, and perspiration fastness performance for all the samples is mostly at an excellent level. In clarification of the colour bleeding and colour staining, satisfactory results were obtained for both properties during wash fastness. Again, satisfactory results were obtained for dry rub and wet rub during rubbing fastness and for acidic and alkaline for perspiration fastness. The dye uptake percentage was lower when using natural auxiliaries for dyeing; consequently, fastness properties were found to be better or similar when compared to dyeing methods using commercial auxiliaries.

Table 2. Evaluation of reflectance %, colour strength and dye uptake % of the dyed samples

Shade %	Used auxiliaries	Reflectance, %	K/S	Dye uptake, %	Wash Fastness (C.C.)	Fastness				Dyed samples
						Rubbing		Perspiration		
						Dry	Wet	Acidic	Alkaline	
0.5	Comm.	5.08	8.87	100	4	4-5	4	4-5	4-5	
	Natural	9.39	4.37	49	4-5	4-5	4-5	4-5	4-5	
1.0	Comm.	2.99	15.74	100	4	4-5	4-5	4-5	4-5	
	Natural	4.18	10.98	70	4-5	4-5	4-5	4-5	4-5	
1.5	Comm.	2.41	19.76	100	4	4-5	4	4	4	
	Natural	2.87	16.44	83	4	4-5	4	4-5	4	
2.0	Comm.	1.83	26.33	100	4	4-5	4	4	4	
	Natural	2.26	21.14	80	4	4-5	4-5	4	4	
3.0	Comm.	1.79	26.94	100	4	4-5	4	4	4-5	
	Natural	1.88	25.61	95	4	4-5	4	4-5	4-5	
4.0	Comm.	1.68	28.77	100	4	4-5	4	4-5	4	
	Natural	1.75	27.58	96	4	4-5	4	4-5	4	
5.0	Comm.	1.57	30.85	100	4	4	3-4	4-5	4	
	Natural	1.86	25.89	84	4	4-5	4	4-5	4-5	
6.0	Comm.	1.70	28.42	100	4	4	3-4	4	3-4	

Shade %	Used auxiliaries	Reflectance, %	K/S	Dye uptake, %	Wash Fastness (C.C.)	Fastness				Dyed samples
						Rubbing		Perspiration		
						Dry	Wet	Acidic	Alkaline	
7.0	Natural	1.63	29.68	105	4	4-5	3-4	4-5	4	
	Comm.	1.63	29.68	100	4	4-5	4	4	3-4	
	Natural	1.68	28.77	97	4	4-5	4	4-5	4	

Note: Comm.= Commercial; C.C.= Colour Change

FT-IR data analysis

Figure 3 shows the infrared spectrum of sodium citrate, dispersing agent, citric acid, acetic acid, glucose, and hydrolyze, with the vertical axis denoting transmittance percentage and the horizontal axis denoting wave number per centimetre.

Sodium citrate showed a sharp peak located below 700 cm^{-1}, indicating a sodium ion-related band that ensures the presence of Na^+ in sodium citrate. By comparing the FTIR diagram of sodium citrate with the dispersing agent, it can be seen that almost similar peaks were obtained at the same wavenumber. Again, almost similar peaks were obtained at the same wavenumber both for citric acid and acetic acid. No significant variation was found here. When comparing the FTIR diagrams of hydroze (sodium dithionite) and glucose, a sharp peak was obtained below 700 cm^{-1} that denoted the metal ion (Na^+) and another sharp peak at 1095.5 cm^{-1} denoted S-O stretching for hydroze [28]. Since glucose doesn't have these functional groups, peaks were not obtained at those wavenumbers. The remaining peaks were identical for hydrolyze and glucose, as were those obtained at almost the same wavenumbers. Hence, FT-IR data revealed that the comparable components have almost the same functional groups in their structures [29].

The FTIR spectra display characteristic signals for polyester material in the following regions: 1700 cm^{-1} denoted -C=O bond vibrations, 1200 cm^{-1} denoted the aromatic ring, 1100 cm^{-1} denoted O=C-O-C stretching, 967 cm^{-1} indicated C=C stretching, and 869 cm^{-1} from hydrogen in benzene [30]. Figure 4 shows the infrared spectrum of dyed shades with natural auxiliaries and dyed shades with commercial chemicals. Both dyed samples exhibit sharp peaks at identical wavenumbers, such as 725.18 cm^{-1}, indicating methylene -(CH_2)n- rocking (n>3); 1018.34 cm^{-1}, representing C-C vibration for carbon-carbon bonds; 1095.48 cm^{-1}, denoting C-O stretching of alkyl-substituted ether; 1249.78 cm^{-1}, indicating C-O bonds in the carboxylic acid functional group; and 1712.66 cm^{-1}, signifying C=O stretching in the carbonyl group [31,32]. Hence, distinct functional groups and wavenumbers were

observed in the undyed and dyed polyester fabric samples. However, there are no significant differences between the samples dyed with commercial chemicals and those dyed with natural auxiliaries.

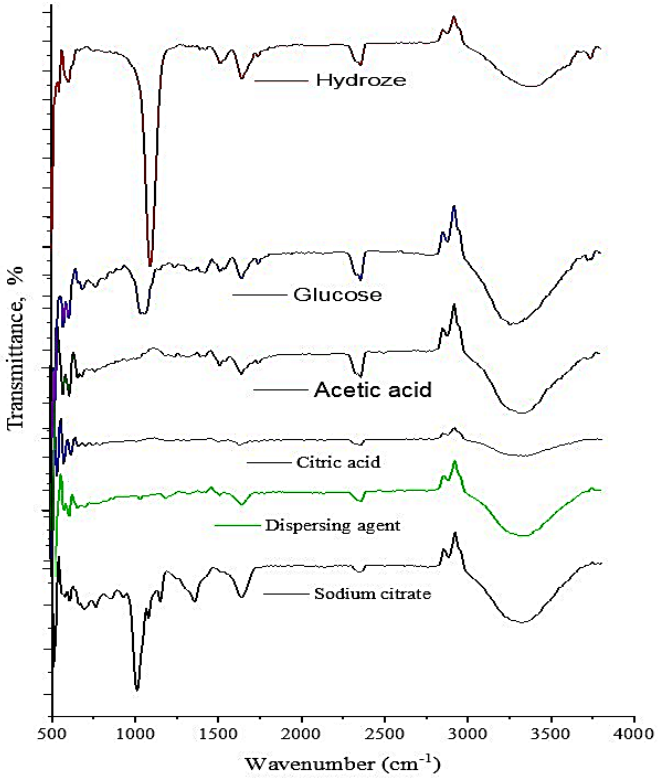

Figure 3. FTIR diagram of sodium citrate, dispersing agent, citric acid, acetic acid, glucose and hydrolyze

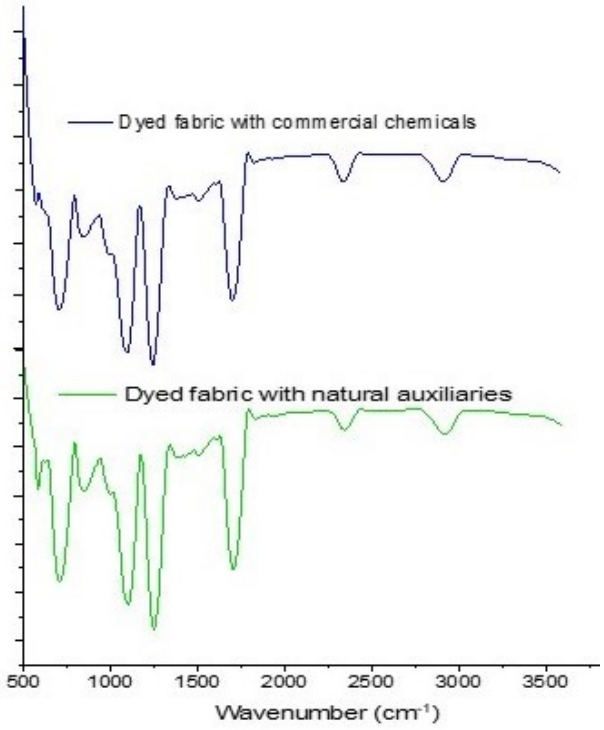

Figure 4. FTIR diagram of dyed shades with natural auxiliaries and dyed shades with commercial chemicals

From the above discussion, it can be inferred that the FTIR analysis revealed variable functional groups for both dyed and undyed samples. This indicates that the dyeing process modifies certain functional groups in the fabric. Additionally, the analysis showed that dyed samples treated with natural auxiliaries exhibited similar functional groups to those treated with commercial chemicals. This suggests that natural auxiliaries can potentially serve as effective substitutes for commercial chemicals in the dyeing process, achieving comparable results in terms of the functional groups present on the fabric.

NMR data analysis

For the 1H NMR spectrum analysis of glucose extracted from date fruits, Deuterium Oxide (D_2O) was used as the solvent. Again, for the 1H NMR spectrum analysis of citric acid extracted from lemons, Deuterium Oxide (D_2O) was also used as the solvent. Two distinct NMR tests were conducted for dates and lemons, and the spectral results are illustrated in a single figure (Figure 5).

In the 1H NMR spectra of glucose, 23 peaks ranging from 3.402 ppm to 3.998 ppm were observed, along with a doublet peak at 4.790 ppm. Protons in the -CH_2OH groups are generally found in the range of 3.4 - 3.8 ppm, and because of coupling with nearby protons, they frequently appear as multiplets. The protons in the methylene (-CH_2-) groups are usually found in multiple patterns and appear at 3.3 - 3.6 ppm on average. Similar to the -CH_2OH groups, protons in the -CHOH groups (secondary alcohol groups) are generally observed in the range of 3.4 - 3.8 ppm and may also appear as multiplets as a result of coupling. Based on the spectral result above, multiplets within the specified range (3.3 ppm to 3.8 ppm) are obtained; consequently, the glucose in the experimental date fruit has the same primary alcohol groups, methylene groups, and secondary alcohol groups as regular glucose. Anomeric protons (H_1 and H_1') in the ring are attached to the anomeric carbon (C_1) of glucose and exhibit chemical shifts around 4.5 - 5.3 ppm. They appear as a doublet (2H, d) because of their coupling with the oxygen atom. As we also found a doublet at 4.79 ppm, it can be said that experimental date fruit (glucose) also has anomeric protons [33].

The exact number of distinct proton signals can vary but generally ranges from 10 to 20 or more, depending on the complexity and concentration of the compounds present in the lemon juice [34]. Hydrogens in the methylene (-CH_2-) groups adjacent to the -COOH groups usually appear in the range of 2.8 ppm - 3.0 ppm, and because of coupling, they often appear as a quartet (2H, q). Quartets are also obtained at the mentioned range (2.8 ppm to 3.0 ppm) from the above spectral result; thus, the experimental lemon (citric acid) has the methylene (-CH_2-) groups adjacent to the -COOH groups, just like regular citric acid [35,36].

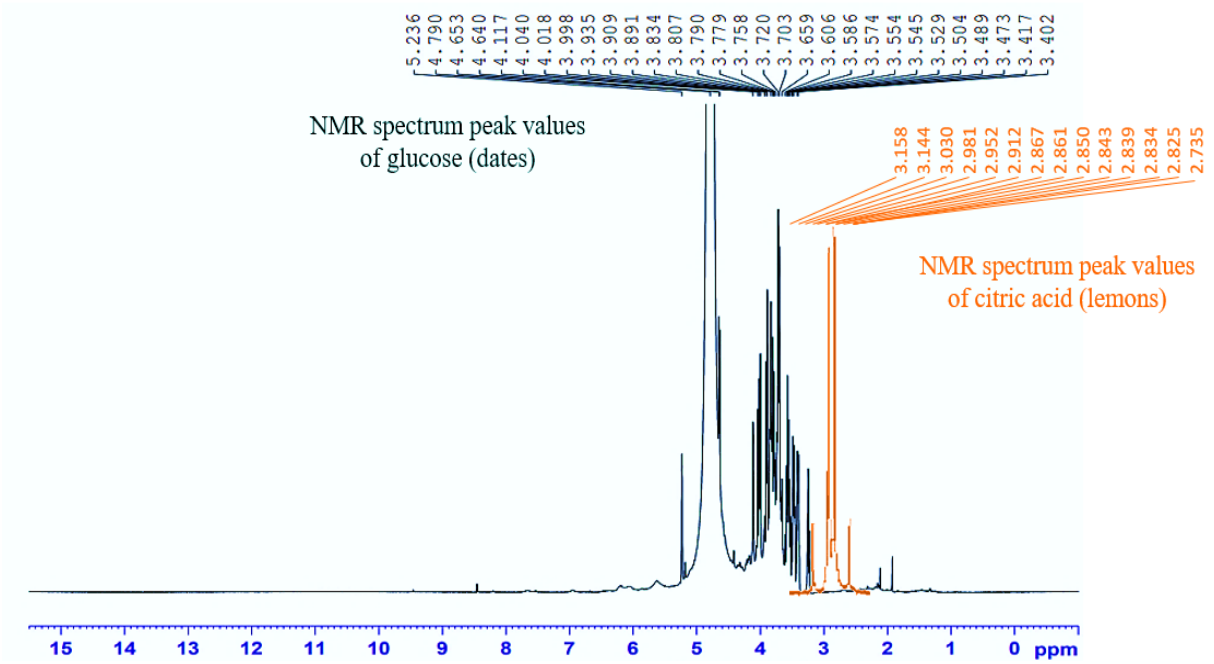

Figure 5. 1H NMR spectra of glucose (dates) in black colour and citric acid (lemons) in orange colour

UV-Vis spectra data analysis

The absorbance values for the solution of disperse dye (Terasil Red W-4BS-01 150%), the solution of dye and dispersing agent, and the solution of dye and sodium citrate were determined using UV-VIS spectroscopy across a wavelength range of 380 nm to 750 nm. These absorbance values were then plotted against the wavelengths to create the absorbance curve shown below in Figure 6. The absorbance curves offer valuable insights into the behaviour of the dye solution and its interactions with different agents.

From Figure 6, it can be seen that the pure dispersed dye solution exhibits a sharp peak at 590 nm with a maximum absorbance value of 1.1457. When a dispersing agent was added to the dye solution, a peak appeared at 540 nm with an absorbance value of 0.5318. Similarly, the addition of sodium citrate to the dye solution resulted in a peak at 590 nm with an absorbance value of 0.58916. The pure dye solution displayed the highest peak absorbance, highlighting the intrinsic absorption characteristics of the dye. Introducing a dispersing agent caused a significant drop in the absorbance peak, indicating that the dispersing agent substantially alters the dye's absorption, likely due to complex formation or dilution effects [37]. The addition of sodium citrate also led to a reduction in absorbance, although to a lesser extent compared to the dispersing agent. This suggests that both additives reduce the absorbance value, thereby facilitating the dispersion of the dye throughout the dye bath.

The data revealed that while sodium citrate exhibits a slightly higher absorbance value than the commercial dispersing agent, it is still effective as a dispersing agent. This implies that sodium citrate can disperse the dyes effectively throughout the dye bath [38,39].

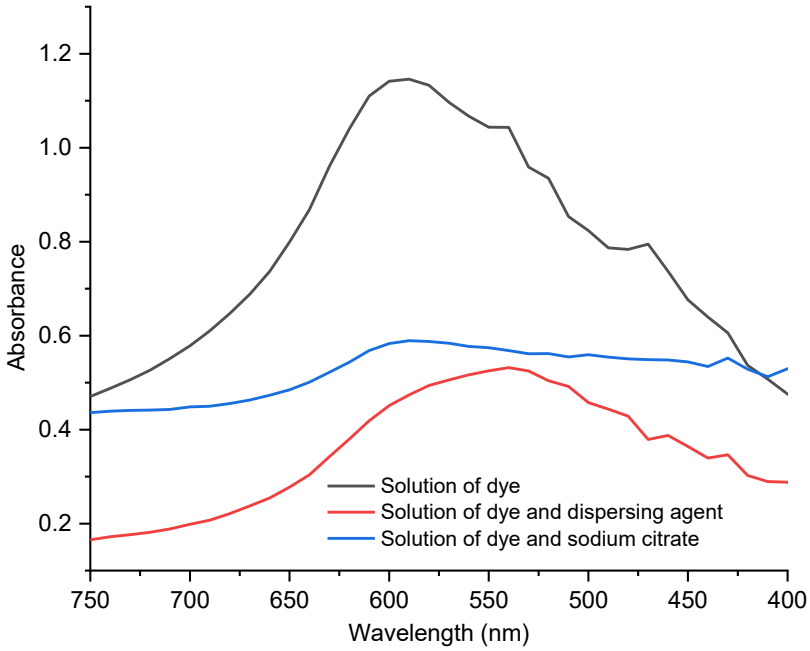

Figure 6. Absorbance curves for solution of dye; solution of dye and dispersing agent; solution of dye and sodium citrate

Dye bath wastewater analysis

The BOD and COD values were determined by mixing the wastewater from the dye bath and reduction clearing bath together. Table 3 illustrates the wastewater parameter for dye baths using natural auxiliaries and existing commercial chemicals. The complex molecular structures and residuals of commercial auxiliaries can contribute to the organic load and, consequently, higher COD and BOD values, as they may be less biodegradable than the simpler compounds found in natural auxiliaries. Lemon juice and its pills also have the capability of lowering the amount of effluent load; hence, the COD and BOD values are lowered for natural auxiliaries.

Table 3. Wastewater parameter for dye bath using natural auxiliaries and existing commercial chemicals

Parameter	Unit	Natural auxiliaries	Commercial auxiliaries	Standard discharge level
BOD	mg/L	408	535	150
COD	mg/L	1500	2240	200

Cost analysis

In this study, dyeing was performed by following the same procedure and the same process parameters, so other costs will remain the same. Hence, the cost of the recipe was analyzed, as only the auxiliaries differ.

Table 4. The recipe cost analysis for dyeing knitted polyester with dispersed dyes using natural auxiliaries and existing commercial chemicals

Chemicals/Auxiliaries Name	Unit Price/Kg (BDT)	Using Natural Auxiliaries		Using Commercial Auxiliaries	
		Amount/1 kg fabric processing	Price (BDT)	Amount/1 kg fabric processing	Price (BDT)
Terasil Red W-4BS-01	1077	10 g	10.77	10 g	10.77
Univadine DFM	522	-	-	6 g	3.132
Univadine Top	418	-	-	6 g	2.508
Acetic Acid	79	-	-	12 g	0.948
Albatex AB-45	196	-	-	10 g	1.96
Citric Acid (Lemon)	80	100 g	8	-	-
Baking Soda	150	10 g	1.5	-	-
Hydroze	357	-	-	20 g	7.14
Glucose (Dates)	180	20 g	3.6	-	-
Caustic Soda	100	20 g	2	20 g	2
Total Cost			25.87 BDT ≈ 0.24 $		26.46 BDT ≈ 0.26 $

As the cost of lemons and dates differs very much in Bangladesh, both in terms of quality and season, a concrete comparison of the natural auxiliaries and commercial auxiliaries dyeing processes is not possible in great detail. From Table 4, it can be seen that the natural auxiliary dyeing process required less cost than the commercial auxiliary dyeing process. Hence, employing natural auxiliaries can reduce expenses.

CONCLUSION

In this study, knitted polyester samples were dyed with dispersed dye using both natural and commercial auxiliaries, maintaining identical process parameters. K/S values were analyzed for fabric surface colour characterization, revealing higher values with commercial auxiliaries. Much more variation was obtained up to 2.0% shade, and after that, by raising the shade%, almost similar K/S values were obtained. Colour fastness tests—wash, rubbing, and perspiration—demonstrated excellent performance, comparable to or better when dyeing with natural auxiliaries. FT-IR analysis revealed similar functional groups between substitute natural auxiliaries and commercial chemicals, as well as the dyed samples containing both commercial and natural auxiliaries. Proton NMR spectra analysis of glucose and citric acid extracted from date fruits and lemons, respectively, showed identical curves to their regular counterparts. UV-Vis spectrum data confirms sodium citrate's role as a dispersing agent. Natural auxiliaries result in lower BOD and COD values in dye bath wastewater, indicating environmental sustainability. Additionally, dyeing with natural auxiliaries proved more cost-

effective compared to commercial chemicals. These outcomes confirm that polyester fabric can be dyed using natural auxiliaries in place of commercial chemicals. Possible applications of the treated fabrics include eco-friendly fashion and sportswear, sustainable home textiles like curtains and upholstery, and environmentally-conscious automotive interiors. In conclusion, dyeing knitted polyester with dispersed dyes using natural auxiliaries offers an innovative, sustainable, and economically viable approach to textile production.

Author Contributions

Conceptualization – Islam MK, Uddin Z and Repon MR; methodology – Islam MK, Uddin Z and Repon MR; formal analysis – Islam MK and Repon MR; investigation – Islam MK; resources – Uddin Z and Repon MR; writing original draft preparation – Islam MK and Repon MR; writing-review and editing – Uddin Z and Repon MR; visualization – Repon MR; supervision – Uddin Z. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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