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REGULAR ARTICLE

Dyeing and Computer-Aided Color Matching (CCM) by Reactive Dyeing of Cotton Fabric with Biodegradable Secondary Ethoxylated Alcohol (SAE) Non-ionic Surfactant-Based Reverse Micelles in Non-aqueous Alkane Solvent Medium

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Abstract
This study investigates the dyeing, computer-aided color matching (CCM), fastness, tensile and surface properties of cotton samples dyed in non-aqueous medium of alkane solvents, including heptane, octane and nonane with the use of biodegradable secondary alcohol ethoxylates (SAE) surfactant-based reverse micelles. Experimental results show that color yield of alkane solvent-dyed batch and standard samples can be 4.7–123.5% and 73.1–91.8% higher than the water-dyed batch and standard samples, respectively. Calibration curves are almost linear in structure and the actual CCM results show less than 30% and 33% difference from the theoretical concentration for aqueous and non-aqueous dyeing, respectively. Reflectance curves are identical in shape. Both samples show good to excellent color evenness, washing, crocking and light fastness and distinctive CIE $L^*a^*b^*$ values, guaranteeing the color quality of the dyed samples. Good tensile and surface properties of the dyed samples were verified by the AATCC test method and scanning electron microscopy (SEM). More than 97% of the alkane solvents can be effectively recovered via simple distillation method. These validate that the use of SAE surfactant-based reverse micelles for dyeing of cotton fabric in alkane non-aqueous medium is potentially applicable for industrial computer-aided color matching with good dyeing properties and color quality comparable to fabrics dyed in conventional water-based system.

Keywords Secondary alcohol ethoxylate · Cotton fabric · Reactive dyes · Non-aqueous dyeing · Computer color matching · Reverse micelle · Alkane solvent

1 Introduction

Color is "generated by interactions of light and matter atoms and molecules," and is defined as "the subjective appearance of light as detected by the eye". When our eyes receive light, in the form of radiating energy or part of the electromagnetic radiation spectrum sensitive to our eyes [1], from the objects in a scene, a perception of the outside world is formed. Color is one of the aspects of that perception [2]. Perceiving colors is one of the earliest abilities of humans in which they learn to recognize different hues and brightness of color when they grow up. From social and artistic points of view, color contributes to the cultural and symbolic growth of human civilizations, signifying status, power and leadership [3].

Color is a valuable property of different kinds of physical objects that needs to be examined in terms of physics and chemistry also. Color comes from interactions between light and matter, or more precisely, the electrons associated with atoms and molecules. This concept was relatively important in the early stage of development of chemistry and chemists have learned that a chemical reaction involves a change of the color of a solution and the amount of the products in that reaction can be indicated by the color intensity [4].

Color is one of the most fundamental and effective tools for communications, not only in science, but also among different sectors in the community, transforming information into meaning as well as transforming imaginative concepts in mind into actual production and sales in market [5, 6]. To achieve this purpose, The International Commission

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on Illumination (CIE) suggested the use of CIELAB and CIELUV color difference formulae in 1976 [7, 8]. More sophisticated color difference formulae, such as CMC, BFD, CIE94 and LCD, were then proposed later, while the CIEDE2000 formula was finally created with the use of all data sets [6, 9]. To date, several color difference formulae, such as CIELAB, Hunter Lab, FMC-2, CMC and CIELUV, are still used commonly in industrial applications [10].

In textile industry, color and esthetic appeal of the fabric are equally important physical properties. The use of different energy level of dyestuff [11], additives [12–14], and dyeing medium [15, 16] in the coloration process contributes different effects to color appearance of the dyed substrates. Matching colors and replicating texture, especially for specific textiles of different fibers and blends, are essential for many apparel applications. It becomes more complicated when colors need to be matched exactly with the desired color outcome. As consumers concern more about color matching of textiles and lifestyle apparel-related products, textile product manufacturers have to create their products with more accurate color matching [17].

To formulate color recipes that match the target colors of textile products, manual color prediction relies on a time consuming and tedious method of trial and error which heavily depends on the expertise of the colorists. To improve the lead-time for color matching without the need of highly skilled colorists, computer-aided colorant formulation was first proposed by Alderson and co-workers. It used algorithms based on the Kubelka–Munk theory proposed by Allen in 1960s and has thus become an alternative choice [18].

Computer-aided color matching (CCM) is a technology that uses computer and colorimetry knowledge to measure color and predict recipes. It can be used to decide how close the computed formula is to the target colors and calculate the metameric indices. Using such a system, the best recipe, which is inexpensive and good quality, can be made from the existing database [19]. Our previous works focused on assessing feasibility of color matching of non-aqueous dyed cotton fabric by polyethylene glycol (PEG) [20], alkyl polyglucoside (APG) [21], and rhamnolipid (RL) [22] surfactants. Recently, Qin and Zhang [23] attempted to develop a new dyeing recipe prediction system based on multiple gradient boosting regression tree models (GBRT), whereas color matching models, developed by the use of least squares support vector machine (LSSVM), have been reported for prediction of dyeing recipe of cotton fabric [24, 25].

Previously, our research group has optimized the parameters for dyeing in non-aqueous reverse micellar system using biodegradable secondary alcohol ethoxylate (SAE) surfactant [26]. However, its applicability in computerized color matching is still lacking. This study aims to investigate the feasibility of integrating use of secondary alcohol ethoxylate (SAE)-based surfactant for dyeing and computerized color matching, in several alkane solvent non-aqueous medium including heptane, octane and nonane and compare the resultant properties with those of fabrics dyed in conventional aqueous water-based medium.

This integrated study involves: (a) to dye and examine the dyeing properties, including color yield, reflectance, color levelness and CIE $L^*a^*b^*$ values, of the standard samples and batch samples in non-aqueous and aqueous dyeing medium; (b) to establish the calibration data sets for both non-aqueous reverse micellar and conventional water-based systems; (c) to conduct computer-aided color matching between standard samples and batch samples dyed in different medium; (d) to assess the tensile strength and colorfastness, including washing and rubbing fastness, of the standard samples and batch samples; and (e) to observe the degree of damage to the surface fiber of the standard and batch samples through scanning electron microscopy (SEM). It is believed that this study can contribute to literature by a thorough evaluation of color matching feasibility when using SAE biodegradable surfactant for dyeing of cotton fabric in several alkane non-aqueous solvent medium.

2 Experiment

2.1 Materials and Reagents

Pure cotton woven fabric, with density of 127 ends per cm (warp and weft) and weight of 139 g/m^2, was first pre-washed and conditioned according to Tang et al. [26]. Non-ionic biodegradable surfactant (Tergitol 15-S-12, TS12) derived from secondary alcohol ethoxylate (SAE) was obtained from Sigma Aldrich with chemical structure, as shown in Fig. 1. Co-surfactant, n-octanol (> 99% purity), and alkane solvents of reagent grade, heptane, octane, and nonane (98 + % purity) were sourced from Alfa Aesar (Table 1). Sodium chloride (NaCl), for conventional water-based dyeing, was procured from VWR, while sodium carbonate (soda ash, Na_2CO_3) was acquired from Sigma Aldrich. Levafix Red CA (RCA), Levafix Blue CA (BCA) and Levafix Yellow CA (YCA) bought from Dystar (Shanghai, China) were used without further

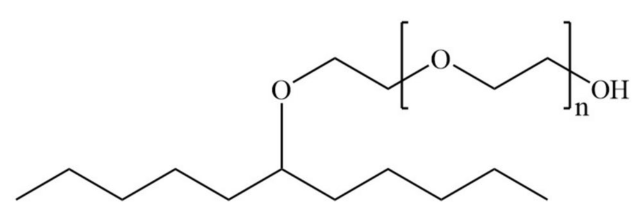

Fig. 1 Chemical structure of SAE-based TS12 non-ionic surfactant ($n = 12$)

Table 1 Alkane solvent dyeing medium

Alkane solvent	Chemical formula
Heptane (C7)	C_7H_{16}
Octane (C8)	C_8H_{18}
Nonane (C9)	C_9H_{20}

purification and were the three primary color reactive dyes used in this study.

2.2 Conventional Calibration Dyeing of Batch Samples with Auxiliaries

Following the recipe recommended by the dye supplier (Table 2), cotton batch samples were water-dyed using liquor ratio of 10:1 with five dye concentrations. They were first submerged in dye liquor prepared with salt and reactive dye and then dyed according to the workflow illustrated in Fig. 2. The dyed batch samples were finally rinsed with 2 g/L detergent solution, drip-dried, and conditioned (20 ± 2 °C; 65 ± 2% relative humidity (RH); 24 h) before measurements.

Table 3 TS12 reverse micellar dye encapsulation recipe

Parameters	
Surfactant to water mole ratio	1:20
Surfactant to co-surfactant mole ratio	1:8
Alkane solvent to cotton ratio (v/w)	10:1
Water-pool volume for dye (mL)	0.5
Water-pool volume for soda ash (mL)	0.3

2.3 Reverse Micellar Calibration Dyeing of Cotton Batch Samples

Table 3 depicts the recipe for dye encapsulation in alkane medium using TS12 surfactant. A solution mixture was first formed by dissolving TS12 surfactant in n-octanol. Reverse micelles were subsequently formed in various alkane solvent medium (heptane, octane, nonane) at normal temperature, by injection. Reactive dye solutions were then introduced dropwise in reverse micelle solutions, to facilitate the dye encapsulation process. The dye liquors, which had dye encapsulated reverse micelles, were stirred until they became well-dispersed. Reverse micellar calibration dyeing of cotton batch samples was conducted (Fig. 3). Prior to further measurements, the reverse micellar-dyed batch samples were finally rinsed

Table 2 Water dyeing recipe for cotton batch samples

Dyeing recipe						
Dye	% o.w.f	0.1	0.5	1.5	2.5	3.5
NaCl	g/L	10	20	42.5	55	65
Na_2CO_3	g/L	5	5	5	5	5
Liquor ratio	mL/g	10:1				
Temperature	°C	70				

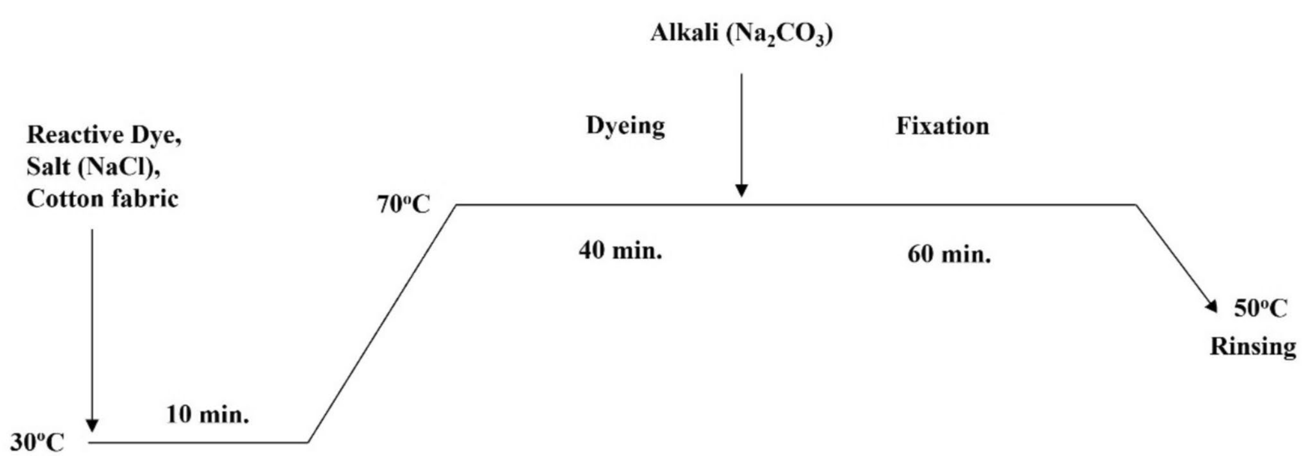

Fig. 2 Workflow of water dyeing of cotton batch samples

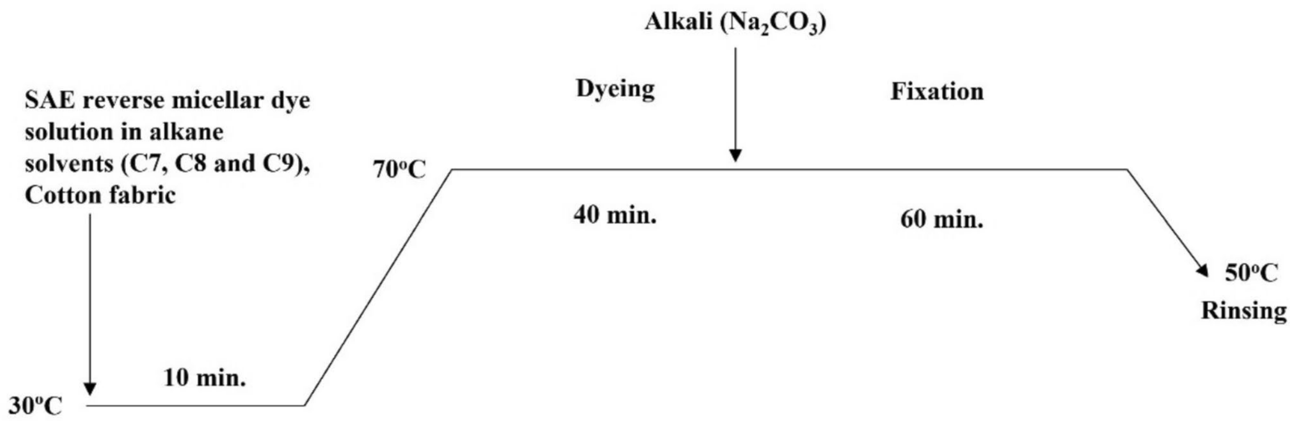

Fig. 3 Workflow of TS12 reverse micellar dyeing of cotton batch samples

Table 4 Dye concentrations (%) of color mixtures

Solvent	Standard sample (%)*	Red (%)	Yellow (%)	Blue (%)
Water	W1 (0.3)	0.1	0.1	0.1
	W2 (1.5)	0.5	0.5	0.5
	W3 (3.0)	1.0	1.0	1.0
Heptane	H1 (0.3)	0.1	0.1	0.1
	H2 (1.5)	0.5	0.5	0.5
	H3 (3.0)	1.0	1.0	1.0
Octane	O1 (0.3)	0.1	0.1	0.1
	O2 (1.5)	0.5	0.5	0.5
	O3 (3.0)	1.0	1.0	1.0
Nonane	N1 (0.3)	0.1	0.1	0.1
	N2 (1.5)	0.5	0.5	0.5
	N3 (3.0)	1.0	1.0	1.0

*W = water; H = heptane; O = octane; N = nonane; 0.3, 1.5 and 3.0 in bracket represent percentage of dye concentration on weight of fabric

with 2 g/L detergent solution, drip-dried and conditioned (20 ± 2 °C; 65 ± 2% RH; 24 h).

2.4 Dyeing of Cotton Standard Samples with Known Concentrations

Table 4 shows concentrations of red, yellow, and blue reactive dyes used to make the color mixture for dyeing the standard samples in conventional water and non-aqueous alkane solvent medium. Samples were dyed for three color depths (0.3%, 1.5%, and 3.0%), following the same dyeing workflows, as shown in Figs. 2 and 3 (Sects. 2.2 and 2.3).

2.5 Color Yield (K/S_{sum} Value)

A Color Eye 7000A Spectrophotometer (X-Rite, USA) was used to measure the color yield of standard cotton and batch samples dyed in conventional water and non-aqueous alkane solvent medium. The device settings were: (a) D65 illuminant; (b) 10° viewing angle; (c) 20 mm medium aperture; (d) 10 nm wavelength gap; and (e) four readings per sample. The K/S_{sum} value was the sum of the K/S values from 400 to 700 nm for each dyed sample. A higher K/S value means a better color yield. The K/S value was computed using the following equation:

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

where K is the absorption coefficient (colorant concentration), S is the scattering coefficient (dyed samples), and R is the reflectance (dyed samples).

2.6 Calibration Plots

Calibration curves of cotton batch samples dyed in conventional water and non-aqueous alkane solvent medium are plotted by K/S_{sum} value versus dye concentration. Linearity of the calibration curves was then calculated by coefficients of determination (R^2).

2.7 Computer Color Matching

The color difference equations, formulated in the Color Eye 7000A Spectrophotometer (X-Rite, USA), were used to match colors of the cotton batch samples and cotton standard samples. Several equations, including CIE $L^*a^*b^*$, CIE $L^*u^*v^*$, ANLAB, Hunter lab, FMC2, JPC 79, CMC 2:1, BFD 2:1, and CIE94 2:1, were used in this study.

2.8 CIE $L^*a^*b^*$ Value

Using instruments and parameters used for measurement of color yield stated in Sect. 2.5 were used for estimating CIE $L^*a^*b^*$ values of the cotton standard and batch samples, dyed in conventional water and non-aqueous alkane solvent medium.

2.9 Relative Unlevelness Indices (RUI)

Relative unlevelness indices (RUI), a technique suggested by Chong et al. [27], was used for measuring color levelness of the standard and batch samples, dyed in conventional water and non-aqueous alkane solvent medium. Four spots were randomly selected on each dyed sample for measurement. Apparatus and parameters mentioned in Sect. 2.5 were used. The RUI values were derived using the following equation:

$$\mathrm{RUI} = \sum_{\lambda=400}^{700} (s_\lambda/\overline{R})V_\lambda \tag{2}$$

where s_λ is the standard deviation of reflectance (specified wavelength); $\overline{R}$ is the reflectance (specific wavelength); and V_λ is the photopic relative luminous efficiency function.

2.10 Scanning Electron Microscopy (SEM)

The surface damage of the cotton batch and standard samples, in conventional water and non-aqueous alkane solvent medium, was assessed using a Hitachi VP-SEM SU1510 scanning electron microscope (Hitachi, Japan).

2.11 Color Fastness Assessments

The washing fastness (color change and staining) and crocking fastness (color staining) of water-dyed and alkane solvent-dyed cotton standard and batch samples were examined by AATCC Test Method 61-2013, Test No. 2A and AATCC Test Method 80-2013, respectively. The light fastness of the dyed fabrics was evaluated following the AATCC Test Method 16-2013 (color change), utilizing a Xenotest 440 light fastness tester (ATLAS, Hamburg, Germany). Test results were rated using the gray scale.

2.12 Tensile Strength

The water-dyed and alkane solvent-dyed cotton batch and standard samples (3.5% dye concentration) were tested for breaking strength and elongation according to the ASTM D5034-21 Grab Test.

2.13 Solvent Recovery

Solvent recovery of heptane, octane, and nonane was conducted via simple distillation method after the reverse micellar dyeing process. The dye solution was first placed into 100 mL round-bottom flask with magnetic stirring for distillation. The round-bottom flask was immersed in an oil bath and connected with a thermometer and a condenser tube via a three-way adapter. The distillation process was controlled at a rate of 1 drop per second. The temperatures measured at the intersection region of the three-way adapter was 98 °C, 125 °C, and 149 °C for heptane, octane, and nonane, respectively. The distillate was completely collected when the temperature starts to drop, and no further distillates were collected after condensation. The collected distillates were then transferred into a separatory funnel for observation [28].

3 Results and Discussion

3.1 Color Yield

Color yield (K/S_{sum} value) of water-dyed and TS12 surfactant-based reverse micellar alkane solvent-dyed batch and standard samples is listed in Table 5. The color yield increases as the dye concentration increases. Alkane solvent-dyed samples, including heptane (C7), octane (C8), and nonane (C9), obtain higher color yield than water-dyed samples owing to the supremacy of reverse micelles for non-aqueous dyeing in alkane solvent medium in which cotton fiber is swollen more effectively on one hand and ionization effect between dye molecules and cotton fiber is reduced on the other hand [29, 30].

Comparison of water-dyed and alkane solvent-dyed with TS12 reverse micelles (Table 5) shows that alkane solvent-dyed batch samples can obtain color yield, which is 9.4–50.9% higher than that of water-dyed batch samples when BCA reactive dye is used. In case of RCA reactive dye, batch samples dyed in alkane solvent medium can acquire 71.4–123.5% higher color yield than batch samples dyed in water medium. This large difference between color yield of water-dyed and alkane solvent-dyed samples in red reactive dye is the result of the optimization done in our previous work [26].

With regard to YCA reactive dye, although the percentage difference in color yield is the lowest among the three reactive dyes, the alkane solvent-dyed samples can still gain a 4.7–22.7% increase in color yield when compared with the water-dyed samples. With respect to the color mixture produced by the three reactive dyes, alkane solvent-dyed samples can attain 73.1–91.8% higher color yield when compared with the water-dyed samples. These statistical findings

Table 5 Color yield of batch and standard samples

Color	Dye conc	K/S_{sum} value						
		Water	C7	%	C8	%	C9	%
BCA	0.1%	6.19	9.34	50.85	8.74	41.24	8.44	36.41
	0.5%	23.57	31.30	32.79	29.50	25.16	30.64	30.00
	1.5%	71.35	86.03	20.58	79.29	11.13	80.14	12.32
	2.5%	121.10	137.83	13.81	132.48	9.40	132.69	9.57
	3.5%	163.17	202.49	24.10	203.50	24.72	192.02	17.68
RCA	0.1%	5.43	11.27	107.57	11.33	108.67	10.85	99.74
	0.5%	19.35	42.78	121.09	43.24	123.47	39.94	106.38
	1.5%	63.43	122.26	92.75	124.22	95.84	120.38	89.78
	2.5%	110.34	198.42	79.82	203.14	84.10	189.18	71.45
	3.5%	143.89	246.68	71.43	270.94	88.30	264.65	83.93
YCA	0.1%	8.25	9.94	20.54	9.90	19.96	8.64	4.67
	0.5%	30.07	36.89	22.67	36.27	20.62	35.37	17.64
	1.5%	88.90	96.86	8.95	100.28	12.80	93.60	5.29
	2.5%	137.97	153.31	11.11	156.72	13.59	156.81	13.66
	3.5%	177.10	206.97	16.86	211.15	19.23	210.38	18.79
Mixture	0.3%	14.19	27.21	91.83	25.49	79.66	26.08	83.81
	1.5%	66.05	108.51	64.29	110.28	66.97	109.60	65.94
	3.0%	126.44	223.53	76.79	225.13	78.06	218.88	73.12

validate the utility of using alkane solvents as medium for non-aqueous dyeing of cotton fabric with TS12 reverse micelles.

Color yield of alkane solvent-dyed cotton batch (samples dyed with three primary colors of BCA, RCA and YCA) and standard samples dyed with mixture of three primary colors (Table 5) is almost the same (± 20) in case of C7-dyed, C8-dyed and C9-dyed samples, except when 3.5% red reactive dye is used for non-aqueous dyeing of cotton fabric in C7 medium. To a large extent, this reflects that the difference between C and H atoms of C7, C8, and C9 does not cause significant variation in color yield of the cotton batch and standard samples.

3.2 Calibration Plots

Table 6 presents the calibration results of water-dyed and alkane solvent-dyed batch samples. With regard to the y-intercept, alkane solvent-dyed batch samples generally have higher y-intercept than water-dyed samples owing to higher *K/S* value of alkane solvent-dyed samples when compared with the water-dyed samples (Fig. 4). In case of alkane solvent-dyed batch samples (C7, C8, and C9), the highest y-intercept is found when RCA reactive dye is used (6.86–7.33), followed by YCA reactive dye (6.27–6.63), while BCA reactive dye exhibits the lowest y-intercept (3.96–4.14). However, water-dyed batch shows different phenomenon in which the highest y-intercept is found when samples are dyed with YCA reactive dye (5.42).

Table 6 Calibration results of water and alkane solvent-dyed cotton batch samples

Solvent	Dye	y-intercept	R^2	λ_{max} (nm)
Water	BCA	3.3822	0.9995	620
	RCA	3.6039	0.9994	540
	YCA	5.4233	0.9953	430
C7	BCA	4.1366	0.9997	620
	RCA	6.8634	0.9926	540
	YCA	6.2691	0.9984	430
C8	BCA	4.0879	0.9978	620
	RCA	7.3331	0.9972	540
	YCA	6.3604	0.9975	430
C9	BCA	3.9606	0.9997	620
	RCA	7.1145	0.9987	540
	YCA	6.6264	0.9998	430

The R^2 value (coefficient of determination) of both water-dyed and alkane solvent-dyed batch samples is 0.99 which is very close to 1 (Table 6). In case of water-dyed batch samples, the R^2 value is within the range of 0.9953 to 0.9995. In case of alkane solvent-dyed samples, the R^2 values of C7, C8 and C9-dyed batch samples are between 0.9926 and 0.9997, 0.9972 and 0.9978, 0.9987 and 0.9998, respectively. This indicates that the calibration curves of both water-dyed and alkane solvent-dyed batch samples are almost linear in structure and thus, acceptable for subsequent computerized color matching with the standard samples.

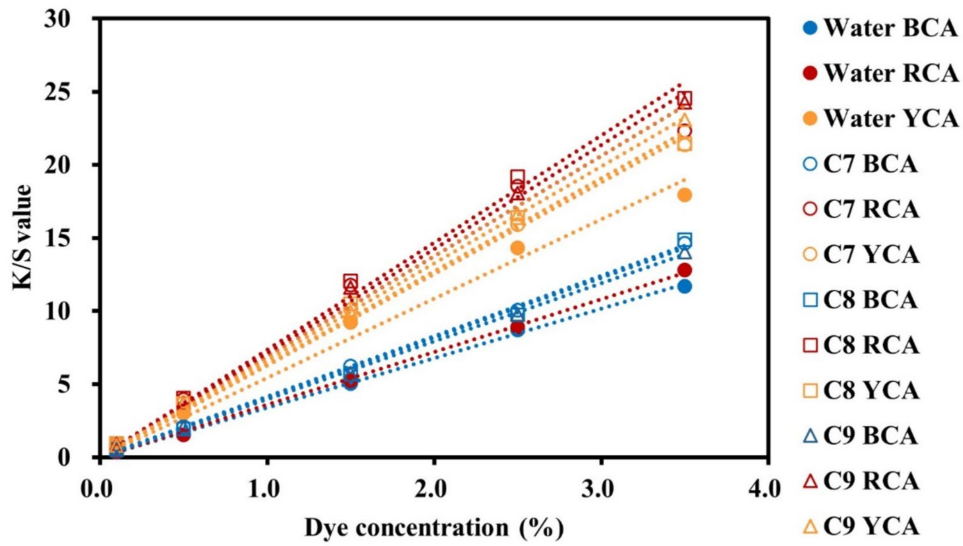

Fig. 4 Calibration plots of three primary colors in water and solvent medium

Maximum wavelength λ_{max} (Table 6) of both water-dyed and alkane solvent-dyed batch samples is the same. λ_{max} of BCA, RCA, and YCA reactive dyed batch samples is 620 nm, 540 nm, and 430 nm, respectively, which confirms the consistency and accuracy of the *K/S* values of these reactive dyes at that specific wavelength.

3.3 Computer-Aided Color Matching (CCM)

3.3.1 Conventional Water-Dyed Samples

Table 7 presents the color matching results and the percentage difference between water-dyed batch samples and standard samples. The actual color yields of calibrated batch samples dyed with the three concentrations (0.3%, 1.5%, and 3.0%) are below the yields of theoretical concentrations which are expected to be given. The actual results are (blue: 0.072; red: 0.081; and yellow: 0.089), (blue: 0.410; red: 0.390; and yellow: 0.486), and (blue: 0.974; red: 0.823; and yellow: 0.963), respectively. The percentage differences between these three concentrations, 0.3%, 1.5%, and 3.0%, are 11–28%, 2.8–22%, and 2.6–17.7%, lower than the theoretical concentrations. It is observed that the percentage difference between actual results and theoretical concentrations decreases with increasing dye concentration. In addition, although different color difference equations are used, the computer-aided color matching results are the same, confirming the consistency and accuracy of the CCM results. The difference between actual results and theoretical concentrations, to a large extent, may be caused by the amount of dye uptake and loss during the dyeing and rinsing process, where it depends largely on: (a) how well the dye molecules interact with the cotton fiber; (b) how evenly the dye molecules spread on the dye site of the fiber; and (c) how strongly the dye molecules covalently bond with the fiber [22].

3.3.2 TS12 Surfactant-Based Reverse Micellar-Dyed Samples

Tables 8 and 9 show the computer-aided color matching results and the percentage difference between TS12 surfactant-based reverse micellar alkane solvent-dyed batch samples and standard samples. In contrast to conventional water-dyed samples, nearly all the alkane solvent-dyed samples achieve better results than the theoretical calculations, except O1 and N1 (Table 8).

For dyeing with 0.3% concentration, actual results of heptane-dyed (H1), octane-dyed (O1), and nonane-dyed (N1) samples are (blue: 0.120; red: 0.105; and yellow: 0.106), (blue: 0.119; red: 0.092; and yellow: 0.096), and (blue: 0.132; red: 0.091; and yellow: 0.089), respectively. At 1.5% concentration, the actual values of samples H2, O2, and N2 are (blue: 0.524; red: 0.512; and yellow: 0.528), (blue: 0.607; red: 0.548; and yellow: 0.542), and (blue: 0.653; red: 0.527; and yellow: 0.518). In case of 3.0% dye concentration, samples H3, O3, and N3 actual values are (blue: 1.094; red: 1.202; and yellow: 1.126), (blue: 1.157; red: 1.192; and yellow: 1.047), and (blue: 1.238; red: 1.139; and yellow: 1.079). However, it is found that only samples dyed with 0.3% concentration (H1, O1, and N1) and dyed by nonane solvent (N1, N2, and N3) can gain a consistent recipe when different equations are used, whereas samples H2, O2, and O3 have slightly different recipes when equations FMC2, JPC79, CMC 2:1, CIE94 2:1 are used (Table 8).

With respect to the percentage difference between actual results and theoretical concentrations (Table 9), the actual results of samples H1, O1, and N1 have a percentage difference ranging from 5% to 20%, −4% to 19%, and −11% to 32%, respectively, when compared with the theoretical concentration (0.3%). The percentage differences between actual results and theoretical concentration (1.5%) for samples H2,

Table 7 CCM results and percentage difference of water-dyed cotton samples

Formulae	Color	Conventional					
		W1	%	W2	%	W3	%
Theoretical	Blue	0.100		0.500		1.000	
	Red	0.100		0.500		1.000	
	Yellow	0.100		0.500		1.000	
CIE $L^*a^*b^*$	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
CIE $L^*u^*v^*$	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
ANLAB	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
Hunter lab	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
FMC2	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
JPC79	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
CMC 2:1	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
BFD 2:1	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70
CIE94 2:1	Blue	0.072	−28.0	0.410	−18.0	0.974	−2.60
	Red	0.081	−19.0	0.390	−22.0	0.823	−17.7
	Yellow	0.089	−11.0	0.486	−2.80	0.963	−3.70

+: above theoretical prediction; –: below theoretical prediction

O2, and N2 are from 2.4% to 5.6%, 8.4% to 21.4%, and 3.6% to 30.6%, respectively, whereas the differences between actual results and theoretical concentration of 3.0% in case of samples H3, O3, and N3 are between 9.4% and 20.2%, 4.7% and 19.2%, and 7.9% and 23.8%, respectively. The difference between actual results and theoretical concentrations may be related to the amount of dye uptake and loss during the dyeing and rinsing process. The factors that affect the results are: (a) how well the dye molecules interact with the cotton fiber; (b) how evenly the dye molecules spread on the dye site of the fiber; and (c) how strongly the dye molecules covalently bond with the fiber [22].

3.4 Reflectance Curves

Figure 5 shows reflectance curves of water-dyed and alkane-dyed cotton batch and standard samples. It is observed that both batch samples (Fig. 5a–i) and standard samples (Fig. 5j) dyed in TS12 surfactant-based reverse micellar alkane medium exhibit lower reflectance than samples conventionally dyed in water medium. This indicates that TS12 reverse micellar alkane-dyed samples generally have darker shades, predictably having higher color yield (K/S_{sum} value) than the water-dyed samples.

Moreover, as presented in Fig. 5a–i, TS12 reverse micellar reactive red-dyed batch samples in alkane (heptane, octane, and nonane) medium generally reveal the most obvious and the largest reflectance percentage difference, followed by alkane reactive blue-dyed batch samples, whereas alkane reactive yellow-dyed batch samples show the lowest reflectance percentage difference when compared with samples dyed in conventional water medium. In addition, both heptane, octane, and nonane-dyed batch and standard samples show similar

Table 8 CCM results of TS12-dyed cotton samples

Formulae	Color	TS12 reverse micelle dyeing								
		(0.3%)			(1.5%)			(3.0%)		
		H1	O1	N1	H2	O2	N2	H3	O3	N3
Theoretical	Blue	0.100			0.500			1.000		
	Red	0.100			0.500			1.000		
	Yellow	0.100			0.500			1.000		
CIE $L^*a^*b^*$	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
CIE $L^*u^*v^*$	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
ANLAB	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
Hunter lab	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
FMC2	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.510	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
JPC79	Blue	0.120	0.119	0.132	0.524	0.613	0.653	1.094	1.166	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.193	1.139
	Yellow	0.106	0.096	0.089	0.528	0.543	0.518	1.126	1.047	1.079
CMC 2:1	Blue	0.120	0.119	0.132	0.524	0.613	0.653	1.094	1.166	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.193	1.139
	Yellow	0.106	0.096	0.089	0.528	0.543	0.518	1.126	1.047	1.079
BFD 2:1	Blue	0.120	0.119	0.132	0.524	0.607	0.653	1.094	1.157	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.192	1.139
	Yellow	0.106	0.096	0.089	0.528	0.542	0.518	1.126	1.047	1.079
CIE94 2:1	Blue	0.120	0.119	0.132	0.524	0.613	0.653	1.094	1.166	1.238
	Red	0.105	0.092	0.091	0.512	0.548	0.527	1.202	1.193	1.139
	Yellow	0.106	0.096	0.089	0.528	0.543	0.518	1.126	1.047	1.079

reflectance percentage (Fig. 5a–j), validating that the difference between C and H atoms in heptane and nonane solvent does not cause significant change in reflectance percentage of the dyed cotton samples.

Furthermore, the reflectance curves of both alkane and water-dyed standard and batch samples dyed with reactive red, blue and yellow reactive dyes simultaneously (color mixture displayed in Fig. 5j) or independently (Fig. 5a–i) are generally identical in shape without peak shift, indicating that the use of alkane solvents (heptane, octane, and nonane) as non-aqueous dyeing medium for dyeing of cotton fabric with TS12 SAE surfactant-based reverse micelles does not cause color alteration to the dyed standard and batch cotton samples.

3.5 Color Evenness

Table 10 shows color evenness of standard and batch samples dyed in conventional water and non-aqueous alkane medium in terms of relative unlevelness indices. Both water-dyed and alkane-dyed cotton standard and batch samples possess good to excellent evenness. Water-dyed samples obtain slightly better RUI values, between 0.03 and 0.29, while alkane (C7, C8, and C9)-dyed samples achieve slightly poor RUI values ranging from 0.04 to 0.47. The color evenness of the alkane-dyed standard and batch samples reveal a decreasing trend in which C7-dyed samples generally have the best RUI values (0.04–0.37), followed by C8-dyed samples (0.04–0.39), whereas

Table 9 Percentage difference of CCM results of TS12-dyed cotton samples

Formulae	Color	CCM percentage difference (%)								
		(0.3%)			(1.5%)			(3.0%)		
		H1	O1	N1	H2	O2	N2	H3	O3	N3
CIE $L^*a^*b^*$	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
CIE $L^*u^*v^*$	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
ANLAB	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
Hunter lab	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
FMC2	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.00	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
JPC79	Blue	+20.0	+19.0	+32.0	+4.80	+22.6	+30.6	+9.40	+16.6	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.3	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.60	+3.60	+12.6	+4.70	+7.90
CMC 2:1	Blue	+20.0	+19.0	+32.0	+4.80	+22.6	+30.6	+9.40	+16.6	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.3	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.60	+3.60	+12.6	+4.70	+7.90
BFD 2:1	Blue	+20.0	+19.0	+32.0	+4.80	+21.4	+30.6	+9.40	+15.7	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.2	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.40	+3.60	+12.6	+4.70	+7.90
CIE94 2:1	Blue	+20.0	+19.0	+32.0	+4.80	+22.6	+30.6	+9.40	+16.6	+23.8
	Red	+5.00	−8.00	−9.00	+2.40	+9.60	+5.40	+20.2	+19.3	+13.9
	Yellow	+6.00	−4.00	−11.0	+5.60	+8.60	+3.60	+12.6	+4.70	+7.90

+: above theoretical prediction; −: below theoretical prediction

C9-dyed samples exhibit the worst RUI values (0.04–0.47) among the three alkane solvents.

Figure 6 presents visual color images of water-dyed and alkane-dyed standard and batch cotton samples. The visual appearance and color evenness of the dyed samples are generally excellent, without any defects and unevenness, while alkane-dyed standard and batch samples show darker shades than water-dyed samples. This supports the findings in terms of color yield and reflectance percentage sections and further verify the supremacy of reverse micellar dyeing of cotton fabric with the use of TS12 SAE surfactant in non-aqueous alkane medium.

3.6 CIE $L^*a^*b^*$ Value

The CIE $L^*a^*b^*$ values of water-dyed and alkane-dyed cotton in reactive blue, red, yellow, and their mixtures are depicted in Table 11. With regard to L^* value, cotton standard and batch samples dyed with blue, red, yellow, and mixed colors in non-aqueous alkane solvent medium, including heptane, octan,e and nonane, generally obtain lower L^* value than samples dyed in conventional water medium. This indicates that alkane solvent-dyed samples have darker shades than water-dyed samples, highlighting the advantages of using TS12 surfactant-based reverse micelle as dye carrier for dyeing of cotton in non-aqueous medium. Among the three alkane solvents, C7- and C8-dyed samples achieve slightly lower L^* values than C9-dyed samples in which C9-dyed samples have slightly smaller values than C7- and C8-dyed samples. This reflects that the increase of chain length of alkane solvent with more C and H atoms may lead to a decrease in L^* value. It may be the result of the increase in bulkiness of the solvent which lowers its flexibility, causing higher steric hindrance [31].

Also, alkane solvent-dyed samples have higher a^* and b^* values than water-dyed samples when reactive blue dye

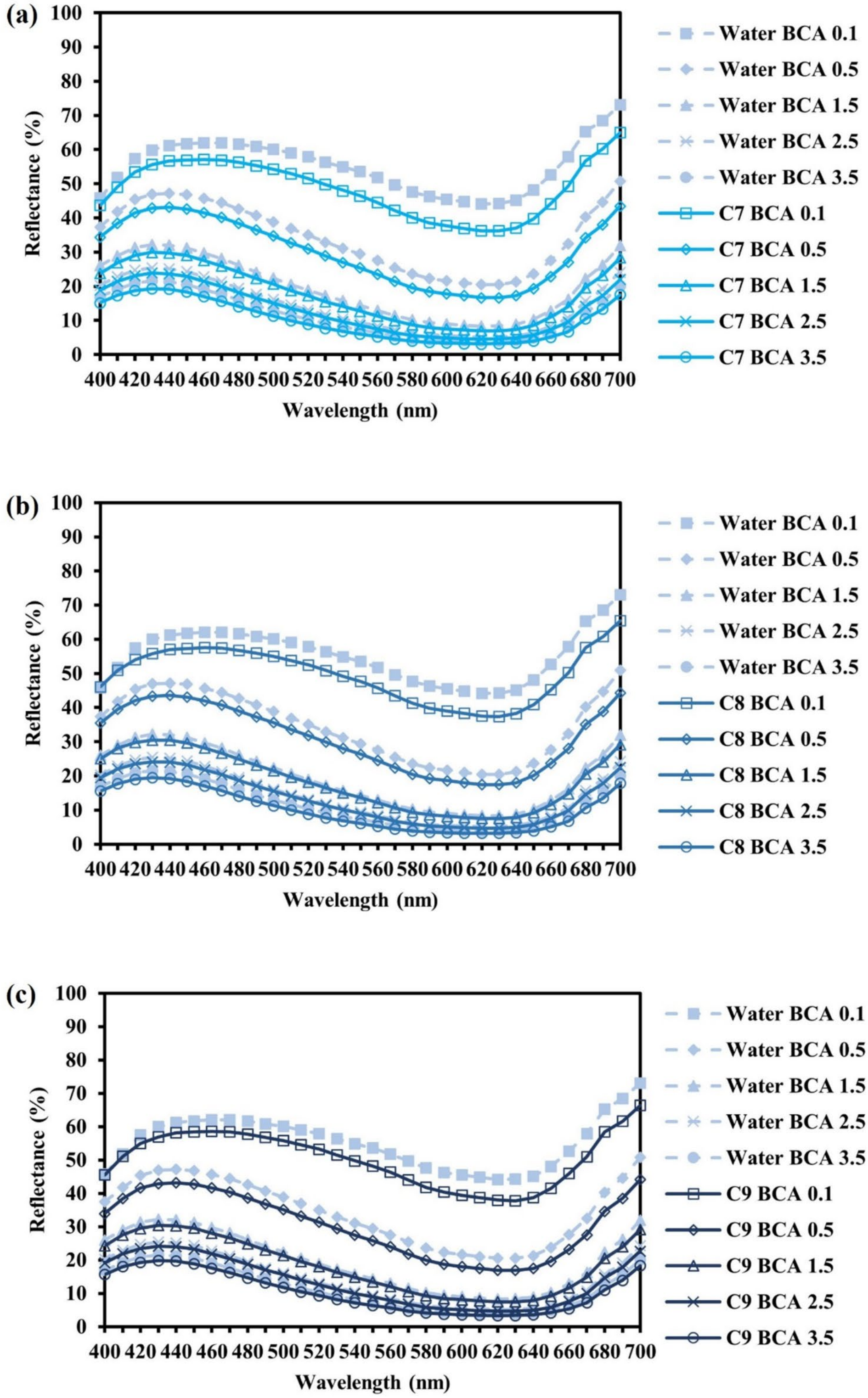

Fig. 5 Reflectance curves: **a** C7 Blue; **b** C8 Blue; **c** C9 Blue; **d** C7 Red; **e** C8 Red; **f** C9 Red; **g** C7 Yellow; **h** C8 Yellow; **i** C9 Yellow; and **j** Color mixture

Fig. 5 (continued)

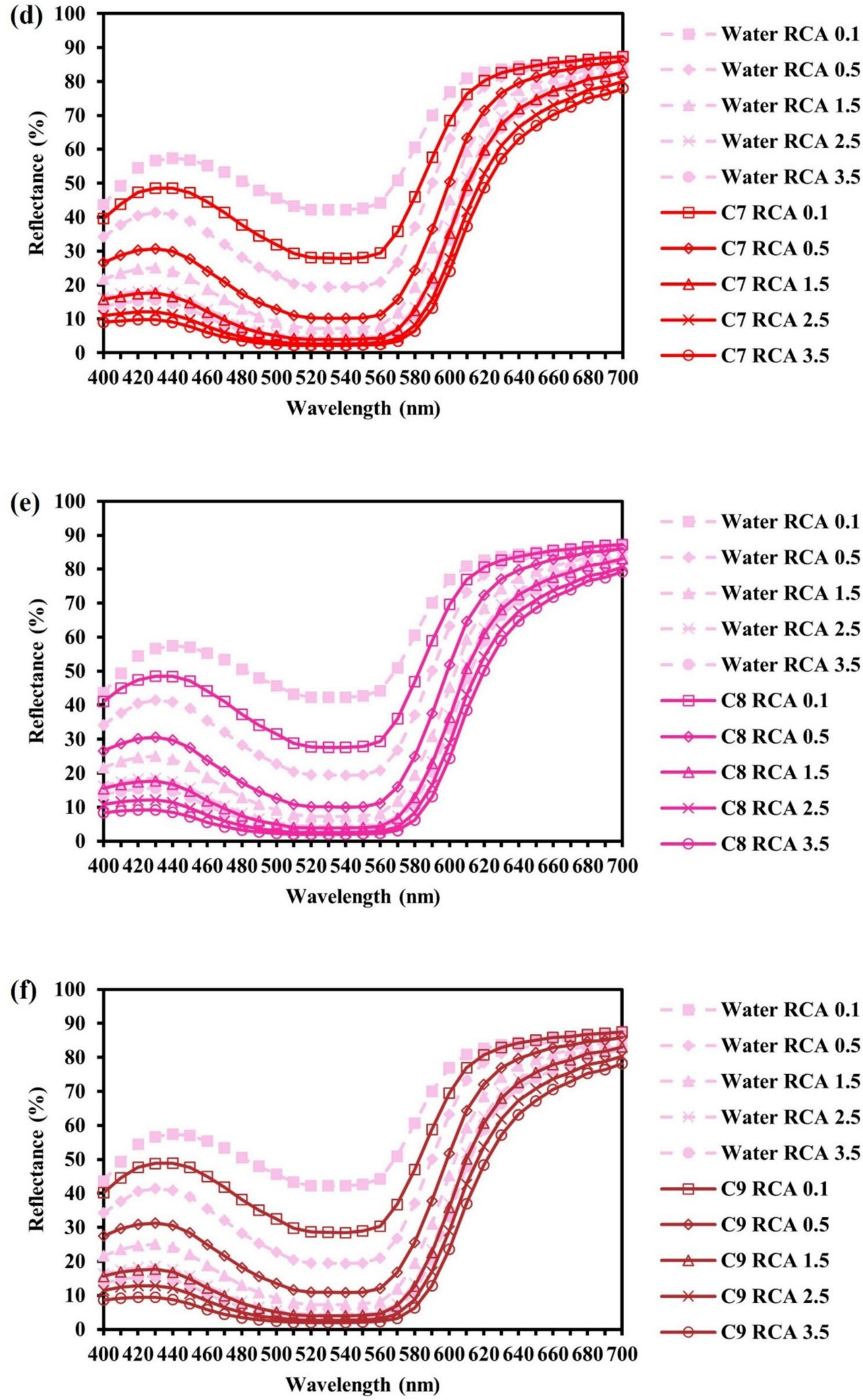

Fig. 5 (continued)

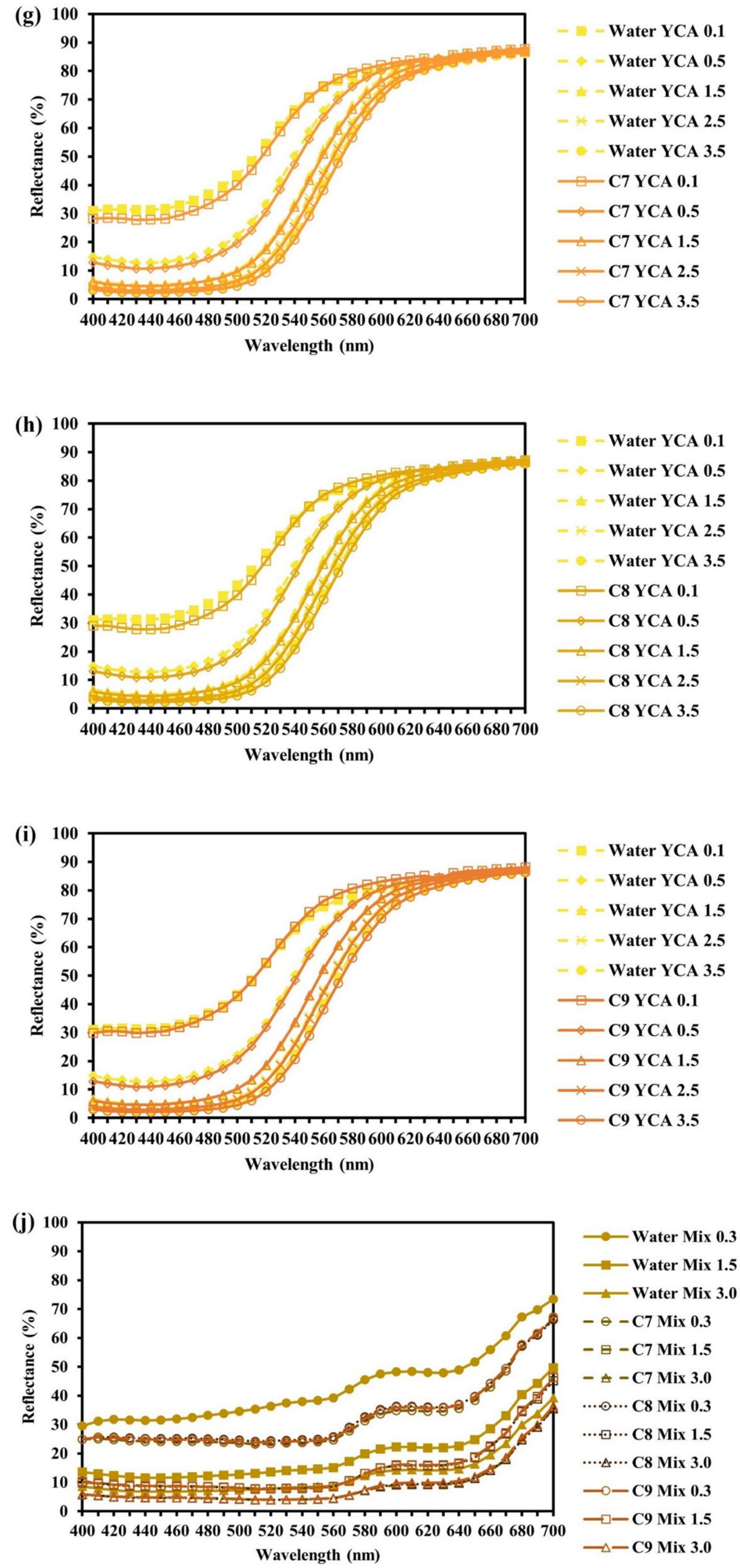

Table 10 Relative unlevelness indices of standard and batch samples

Color evenness									
Color	Dye conc	Water	Visual	C7	Visual	C8	Visual	C9	Visual
BCA	0.1%	0.03	Excellent	0.13	Excellent	0.12	Excellent	0.13	Excellent
	0.5%	0.05	Excellent	0.21	Good	0.08	Excellent	0.14	Excellent
	1.5%	0.13	Excellent	0.25	Good	0.15	Excellent	0.22	Good
	2.5%	0.24	Good	0.27	Good	0.37	Good	0.37	Good
	3.5%	0.15	Excellent	0.26	Good	0.31	Good	0.47	Good
RCA	0.1%	0.06	Excellent	0.11	Excellent	0.20	Good	0.14	Excellent
	0.5%	0.07	Excellent	0.24	Good	0.13	Excellent	0.18	Excellent
	1.5%	0.08	Excellent	0.37	Good	0.36	Good	0.30	Good
	2.5%	0.09	Excellent	0.32	Good	0.34	Good	0.30	Good
	3.5%	0.06	Excellent	0.23	Good	0.24	Good	0.13	Excellent
YCA	0.1%	0.03	Excellent	0.09	Excellent	0.04	Excellent	0.04	Excellent
	0.5%	0.06	Excellent	0.14	Excellent	0.04	Excellent	0.09	Excellent
	1.5%	0.09	Excellent	0.13	Excellent	0.11	Excellent	0.09	Excellent
	2.5%	0.05	Excellent	0.12	Excellent	0.15	Excellent	0.18	Excellent
	3.5%	0.12	Excellent	0.04	Excellent	0.14	Excellent	0.22	Good
Mixture	0.3%	0.08	Excellent	0.18	Excellent	0.10	Excellent	0.22	Good
	1.5%	0.22	Good	0.21	Good	0.39	Good	0.21	Good
	3.0%	0.29	Good	0.08	Excellent	0.35	Good	0.43	Good

< 0.2 = excellent; 0.2–0.49 = good; 0.5–1.0 = poor; > 1.0 = bad evenness [27]

(BCA) is used, indicating that alkane-dyed samples are generally redder and yellower than water-dyed samples. In case of reactive red (RCA), reactive yellow (YCA) and mixed colors produced by combinations of three reactive dyes of primary color, alkane solvent-dyed samples obtain higher a^*, but lower b^* value than water-dyed samples. This reveals that alkane solvent-dyed samples have shades that are normally redder and bluer than water-dyed samples. In addition, it is observed that the CIE $L^*a^*b^*$ values of C7-, C8- and C9-dyed samples are nearly the same. This means that the increase of chain length with more C and H atoms from heptane to nonane level does not cause significant variation in CIE $L^*a^*b^*$ values of the dyed cotton standard and batch samples.

3.7 Scanning Electron Microscopy Images

Figure 7 depicts SEM images showing surface morphology of the dyed standard and batch samples. Both batch samples dyed in water and alkane medium with 3.5% reactive red dye (Fig. 7a–d) have smooth and excellent surface morphologies and there are only a few microfibrils and impurities on the fiber surface. Water-dyed and alkane-dyed standard samples with 3.0% color mixture (Fig. 7e–h) show no significant fiber damage. Only some microfibrils are found on the cotton surface which is similar to the batch samples. This indicates that the use of SAE surfactant-based reverse micelles in alkane solvent medium does not cause any noticeable morphological damage to the surface appearance of the cotton fiber.

3.8 Fastness Properties

3.8.1 Washing Fastness

Washing fastness of water-dyed and alkane-dyed samples dyed in single color and mixtures is shown in Table 12. Both water-dyed and alkane-dyed samples generally obtain excellent ratings against color change (rating 4–5 to 5) after the washing test which means most of the dye molecules are well-bonded with cotton fiber without loss of color. Only a little color staining is found on the wool strip after the washing test in which the ratings are between 4–5 and 5. However, cotton strip has more color staining than wool strip. Most of the ratings of both water-dyed and alkane-dyed samples are between 4 and 4–5, except 3.5% for alkane-dyed red samples (rating 3–4). These ratings are still industrially acceptable, and they indicate that most of the unfixed dye and chemical residues are adequately removed without much color bleeding, guaranteeing the accuracy of dyeing and color matching properties of the dyed cotton samples [32, 33].

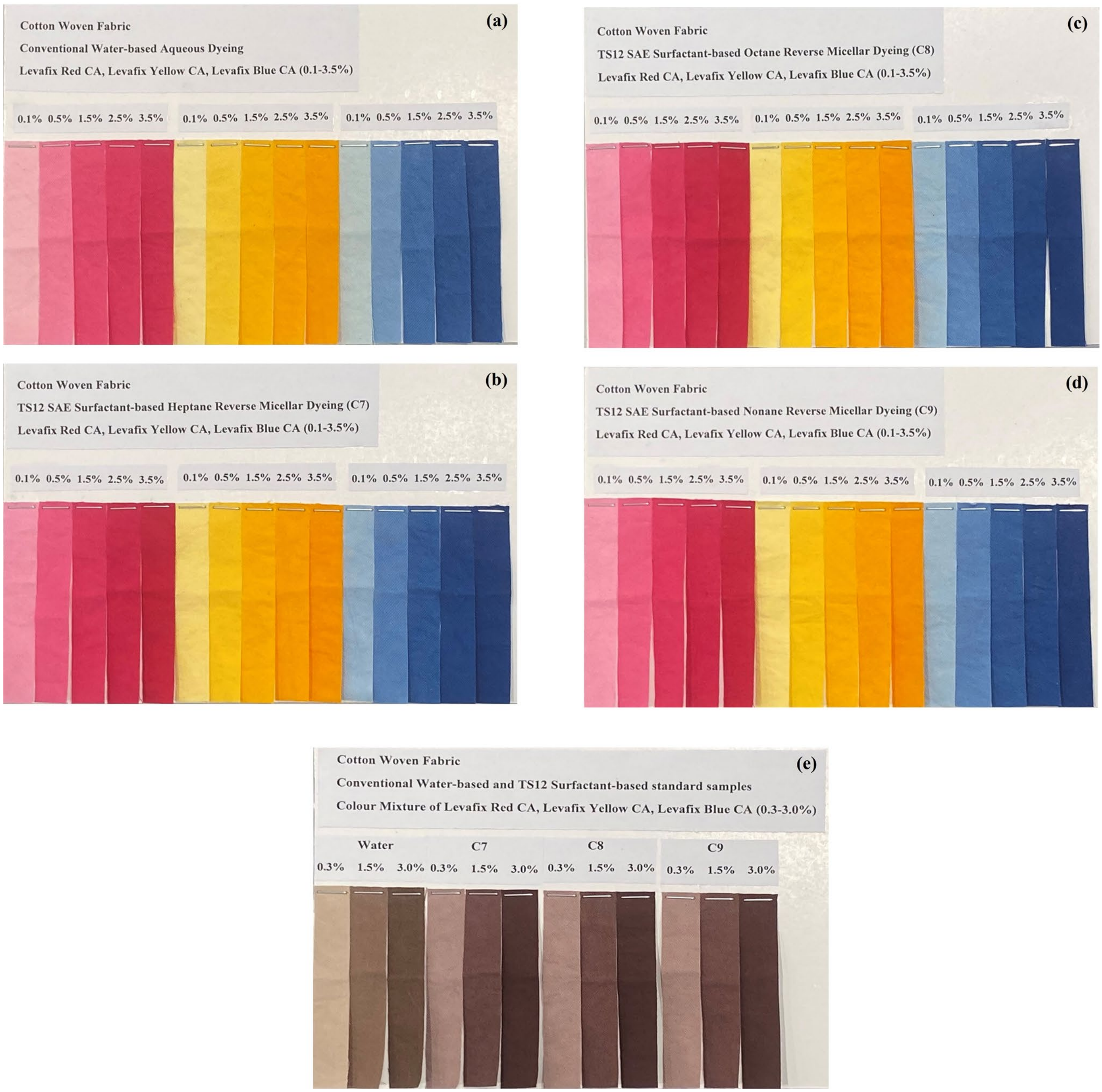

Fig. 6 Visual images of dyed cotton samples: **a** water-dyed batch samples; **b** C7-dyed batch samples; **c** C8-dyed batch samples; **d** C9-dyed batch samples; **e** water-dyed and alkane-dyed standard samples

3.8.2 Crocking Fastness

Table 13 presents the dry and wet crocking fastness of the dyed cotton batch and standard samples. Generally speaking, samples dyed with the primary single color and mixtures of colors gain excellent dry crocking ratings ranging from 4–5 to 5. Both water-dyed and alkane-dyed samples obtained slightly lower ratings against wet crocking (ratings between 4 and 4–5), but these are acceptable. Ratings of 3–4 are found only when 3.5% concentration of reactive red dye is used. These findings validate that both water-dyed and alkane-dyed samples have good resistance against rubbing action without any significant color loss.

3.8.3 Light Fastness

Light fastness of water-dyed and alkane-dyed standard and batch samples is shown in Table 14. Most of the tested

Table 11 CIE $L^*a^*b^*$ value of dyed cotton standard and batch samples

CIE $L^*a^*b^*$													
Sample		Water			C7			C8			C9		
Dye	Dye (%)	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*
BCA	0.1	76.61	−6.87	−9.87	73.57	−7.05	−10.44	74.25	−6.90	−9.68	74.65	−6.90	−10.02
	0.5	59.29	−10.54	−23.18	57.93	−6.30	−21.28	58.77	−6.52	−20.50	58.28	−6.59	−20.84
	1.5	43.05	−12.02	−30.70	43.66	−4.40	−27.33	44.81	−4.88	−26.46	44.64	−4.86	−26.50
	2.5	35.46	−11.47	−32.63	37.00	−2.47	−28.60	37.63	−2.99	−28.23	37.59	−2.99	−28.29
	3.5	31.32	−10.59	−32.73	31.65	−0.33	−29.05	31.64	−0.26	−29.30	32.44	−0.94	−28.84
RCA	0.1	81.19	23.92	4.77	70.60	35.36	−3.46	70.65	35.93	−3.17	71.09	34.94	−3.06
	0.5	69.94	41.61	7.28	56.01	52.89	−2.56	56.19	53.43	−1.89	56.78	52.05	−2.32
	1.5	59.11	53.25	14.71	45.59	59.52	3.83	45.85	60.10	4.49	45.86	59.60	4.10
	2.5	54.44	56.32	19.59	40.91	59.49	8.92	41.22	60.31	9.53	41.49	59.81	8.00
	3.5	52.19	56.95	22.14	38.61	58.62	11.44	38.58	59.75	13.44	38.23	58.99	11.92
YCA	0.1	87.79	10.88	39.00	84.64	8.51	39.79	84.64	8.36	39.85	85.58	7.46	37.99
	0.5	83.79	21.39	65.61	77.86	20.30	62.62	78.02	20.24	62.56	78.36	19.40	62.35
	1.5	78.78	31.73	83.97	71.70	30.95	75.70	71.57	31.36	76.30	72.36	30.08	75.99
	2.5	75.99	35.96	88.84	68.22	36.28	79.58	68.27	36.14	80.14	68.56	35.93	80.52
	3.5	73.98	38.62	90.53	65.76	40.04	81.20	65.69	39.91	81.44	65.56	39.94	81.96
Mixture	0.3	69.78	7.18	11.04	59.23	11.26	5.05	59.27	11.35	5.16	59.90	11.56	5.16
	1.5	47.56	10.57	11.26	38.76	15.18	5.41	38.73	15.01	6.08	38.72	15.73	5.69
	3.0	37.79	11.39	10.49	28.67	14.86	4.81	28.70	15.25	5.13	29.21	15.90	5.60

samples can achieve the ratings between 4 and 5, indicating good-to-excellent light fastness of the samples against light exposure. No significant color change has been found for most of the tested samples.

3.9 Tensile Properties

Tensile strength (*N*) of standard and batch samples dyed in water and alkane medium with mixed colors and single primary colors using reactive dyes is illustrated in Table 15. Generally speaking, both water-dyed and alkane solvent-dyed samples suffer strength loss in warp direction while gaining slight strength in weft direction compared with undyed cotton samples. Alkane solvent-dyed samples do not show significant difference in tensile strength when compared with water-dyed samples. Among the three alkane solvents, heptane-dyed and octane-dyed samples obtain similar tensile strength, whereas nonane-dyed samples possess slightly lower tensile strength. As shown in Table 16, water-dyed samples have nearly the same breaking elongation when compared with undyed samples, while alkane solvent-dyed samples show higher breaking elongation than water-dyed and undyed cotton samples. In addition, it is found that both heptane-dyed, octane-dyed, and nonane-dyed cotton samples have almost the same breaking elongation, without any noticeable difference. These findings verify that cotton samples dyed in alkane solvent medium with SAE surfactant-based reverse micelles can achieve acceptable tensile properties comparable to samples dyed in conventional water medium.

3.10 Solvent Recovery

After distillation, the collected distillate separates into two distinctive layers. A small volume of water settled at the bottom, while the upper layer consisted of the recovered solvent. The solvent recovery percentage was determined by comparing the volume of reclaimed solvent with the theoretical volume estimated prior to dyeing. Experimental results reveal that over 97% (heptane: ~ 98.3%; octane: ~ 98.5%; and nonane: ~ 97.8%) of the alkane solvents can be effectively and efficiently recovered.

4 Conclusions

The effects of dyeing, computer-aided color matching, color fastness, and tensile properties of cotton samples dyed in a non-aqueous medium using alkane solvents—specifically heptane, octane, and nonane—facilitated by reverse micelles with biodegradable secondary alcohol ethoxylate (SAE) surfactants are investigated in an integrated manner in this study. Experimental results show that alkane solvent-dyed batch and standard samples can achieve 4.7–123.5% and

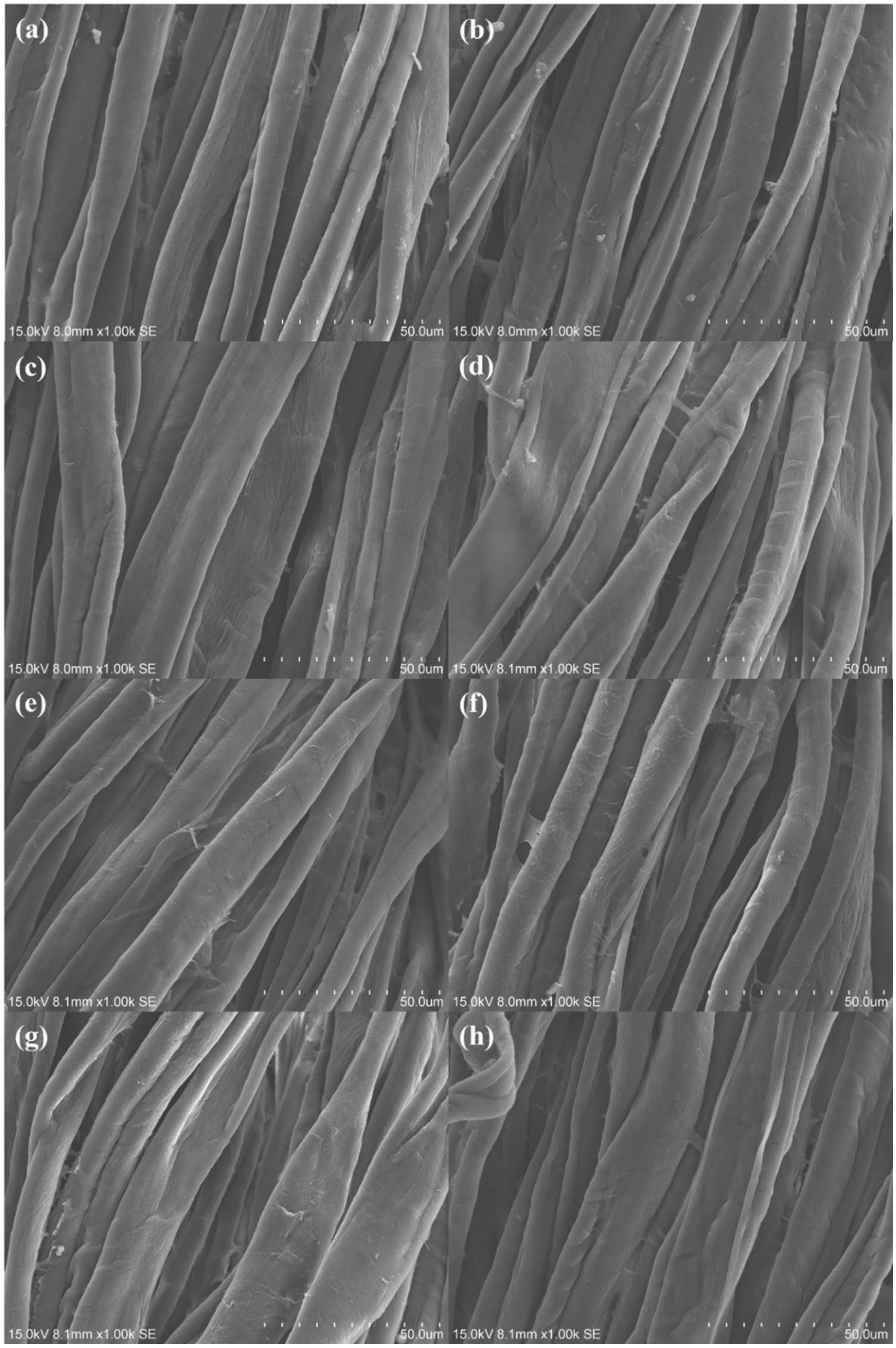

Fig. 7 SEM images of dyed cotton samples (magnification: 1000x): **a** water-dyed batch sample (R3.5); **b** heptane-dyed batch sample (R3.5); **c** octane-dyed batch sample (R3.5); **d** nonane-dyed batch sample (R3.5); **e** water-dyed standard sample (3.0%); **f** heptane-dyed standard sample (3.0%); **g** octane-dyed standard sample (3.0%); and **h** nonane-dyed standard sample (3.0%)

Table 12 Washing fastness

	Dye conc (%)	Color change	Color staining C
BCA	0.1	5/5/5/5*	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4–5/4/4/4
	3.5	4–5/4–5/4–5/4–5	4–5/4/4/4
RCA	0.1	5/5/5/5	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4–5/4/4/4
	3.5	4–5/4–5/4–5/4–5	4/3–4/3–4/3–4
YCA	0.1	5/5/5/5	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	5/5/5/5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
Mixture	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.0	4–5/4–5/4–5/4–5	4–5/4/4/4

Rating 1 (most) to rating 5 (least) color change and staining. C = cotton strip. *Rating sequence: water-dyed sample/heptane-dyed sample/octane-dyed sample/nonane-dyed sample

Table 13 Crocking fastness

	Dye conc (%)	Color staining Dry	Color staining Wet
BCA	0.1	5/5/5/5*	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4–5/4/4/4
	3.5	4–5/4–5/4–5/4–5	4/4/4/4
RCA	0.1	5/5/5/5	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4/4/4/4
	3.5	4–5/4/4/4	3–4/3–4/3–4/3–4
YCA	0.1	5/5/5/5	4–5/4–5/4–5/4–5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	5/5/5/5	4–5/4–5/4–5/4–5
	2.5	5/5/5/5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
Mixture	0.5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.0	4–5/4–5/4–5/4–5	4/4/4/4

Rating 1 (most) to rating 5 (least) color change and staining

*Rating sequence: water-dyed sample/heptane-dyed sample/octane-dyed sample/nonane-dyed sample

Table 14 Light fastness

	Dye conc (%)	Color change
BCA	0.1	5/5/5/5*
	0.5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5
	3.5	4–5/4/4/4
RCA	0.1	5/5/5/5
	0.5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5
	2.5	4–5/4/4/4
	3.5	4–5/4/4/4
YCA	0.1	5/5/5/5
	0.5	5/5/5/5
	1.5	5/5/5/5
	2.5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5
Mixture	0.5	5/4–5/4–5/4–5
	1.5	4–5/4/4/4
	3.0	4–5/4/4/4

Rating 1 (most) to rating 5 (least) color change and staining

*Rating sequence: water-dyed sample/heptane-dyed sample/octane-dyed sample/nonane-dyed sample

73.1–91.8% higher color yield (K/S_{sum} value), respectively, depending on dye concentration, compared with the water-dyed batch and standard samples.

Calibration curves of batch samples dyed with three primary colors are almost linear, with R^2 above 0.99. This is in alignment with a well-established database which is suitable for subsequent computer-aided color matching in which theoretical concentration and the actual CCM results show less than 30% and 33% difference between samples dyed in water and alkane medium, respectively. In addition, this validates that alkane-dyed samples with SAE-based reverse micelle can achieve color matching comparable to water-dyed samples.

Reflectance curves of water-dyed and alkane-dyed batch and standard samples are identical in shape, and both show good to excellent color evenness and distinctive CIE $L^*a^*b^*$ values, guaranteeing the color quality of the dyed samples. The fastness properties of those samples were assessed and both samples dyed in water and alkane medium exhibit good to excellent washing, crocking, and light fastness. Tensile properties and surface morphology of both water-dyed and alkane solvent-dyed samples are evaluated, and it is confirmed that both have good tensile strength and breaking elongation, without severe fiber surface damage. In addition, over 97% of the alkane solvents can be effectively and efficiently recovered via simple

Table 15 Tensile strength (N) of dyed samples

Tensile strength (*N*)	Undyed		Water				Heptane				Octane				Nonane			
Sample	Warp	Weft	Warp	(%)	Weft	(%)	Warp	(%)	Weft	(%)	Warp	(%)	Weft	(%)	Warp	(%)	Weft	(%)
BCA 3.5	415	216	346	−16.64	215	−0.38	355	−14.41	224	3.79	352	−15.13	229	6.10	346	−16.64	233	7.96
RCA 3.5			317	−23.46	211	−2.27	330	−20.44	227	5.18	334	−19.47	222	2.86	319	−23.09	216	0.08
YCA 3.5			337	−18.63	209	−3.31	332	−19.95	228	5.64	342	−17.54	219	1.47	323	−22.12	213	-1.31
Mix 3.0			356	−14.17	223	3.32	353	−17.50	237	9.81	351	−15.37	227	5.18	344	−17.06	224	3.79

Table 16 Breaking extension of dyed samples

Breaking extension	Undyed				Water				Heptane				Octane				Nonane			
	Warp		Weft		Warp		Weft		Warp		Weft		Warp		Weft		Warp		Weft	
Sample	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
BCA 3.5	16.65	22.2	9.42	12.56	16.68	22.24	8.85	11.8	18.83	25.74	9.34	12.28	18.33	25.34	9.54	12.48	17.93	24.12	9.22	12.18
RCA 3.5					16.61	22.15	8.61	11.48	17.23	23.24	9.51	12.65	17.45	23.36	9.32	12.57	17.25	23.27	9.11	12.07
YCA 3.5					16.18	21.57	9.16	12.21	17.35	23.67	10.08	13.47	17.78	23.87	9.76	12.89	17.38	23.71	9.34	12.28
Mix 3.0					16.48	21.96	9.31	12.56	19.21	26.34	10.24	13.73	19.21	26.34	10.34	13.83	19.21	26.34	9.89	13.19

distillation method. All these findings validate that the use of SAE surfactant-based reverse micelles for dyeing of cotton fabric in alkane non-aqueous medium is feasible and potentially applicable for industrial computer-aided color matching with good dyeing properties and color quality comparable to fabrics dyed in conventional water-based system.

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Author Contributions C.K. conceptualized and designed the study. Material preparations, experiments and data collections were performed by A.T., H.L., C.L. and Y.W. All authors engaged in data analysis and investigation. A.T. and C.L. prepared the first draft of the manuscript. C.K. and A.T. reviewed and edited the manuscript. A.T. contributed to the figures and tables of the manuscript. C.K. allocated all the resources and supervised the whole process of the study. All authors have read and agreed to the final version of the manuscript.

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Data Availability All relevant data are included in the manuscript.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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