Cellulose
https://doi.org/10.1007/s10570-025-06757-8

ORIGINAL RESEARCH

Dyeing properties of cotton fabric using artificial seawater dyeing medium as the replacement of fresh water

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Received: 25 February 2025 / Accepted: 22 August 2025

Abstract The feasibility of using artificial seawater (ASW) instead of fresh water as the medium for reactive dyeing of cotton fabric is investigated in this study. A number of dyes of different reactive groups are used. Cotton fabrics are dyed in ASW media with (ASW+) or without (ASW−) further addition of NaCl and their dyeing, colourfastness, surface and physical properties are examined and compared with cotton fabrics dyed in deionised (DI) and distilled (DIS) water media. Although nearly all ASW dyed fabrics obtain lower colour yield (0.7–65.2% lower) than that of DI and DIS dyed fabric, the results of this work reveal that triazine-based reactive dyes disfavour cotton dyeing in DIS and ASW (ASW− and ASW+) media (0.2–65.2% lower) while fluorochloropyrimidine (FCP)-based and dichlorochinoxaline (DCC)-based monofunctional reactive dyes in DIS and ASW dyeing system offer better colour yield (5.8–72.5% higher). The pH value and salinity of the dyebath in those four different dyeing media are measured. The reflectance curves, CIE L*a*b* value, colour evenness, fastness, surface, fastness and tensile properties of the dyed cotton fabrics are evaluated. The findings verify that the use of ASW does not alter the colour properties of the dyed specimens. Both DI, DIS and ASW dyed specimens reflect good to excellent colour levelness (0.01–0.46) and fair to excellent washing, crocking and perspiration fastness properties (rating 3–4 to 5) without any significant fibre damage while both exhibit lower breaking strength and extension after the dyeing process when compared with pristine undyed cotton fabric.

Keywords Seawater dyeing · Cotton · Reactive dyes · Salinity · Colour yield · pH value

Introduction

Cotton is a well-known cellulose-based natural polymeric fibre harvested for manufacturing textile products used by human beings. Its unique properties such as breathability, moisture absorptivity and comfortable handle have made it the fibre of choice for manufacture of textiles (Khanzada et al. 2020).

Cotton is dyeable with various types of commercially available synthetic dyestuffs, such as direct dyes, reactive dyes, vat dyes, sulphur dyes and azoic dyes (Tang and Kan 2020). Among these colorants, reactive dyes are the most common due to the broad range of colours available and good colour fastness (Pruś et al. 2022). It has been reported that over 400,000 tonnes of reactive dyes are used each year (Liu et al. 2019) while 20–60% of dyes are being hydrolysed during conventional dyeing process,

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Published online: 10 September 2025

causing serious environmental problems (Song et al. 2024).

Water is a plentiful natural resource which accounts for 70% of the surface of our Planet Earth. However, 97% of this is seawater and only 3% is fresh water. The change in living standards, social culture and the increasing world population have resulted in a huge demand for fresh water and water scarcity has become a critical issue, arousing the concern of the public (Musie and Gonfa 2023). Meanwhile, the wet processing cycle, including desizing, scouring, bleaching, mercerising, dyeing, finishing and printing, in the textile industry consumes significant amounts of fresh water (Adane et al. 2021). In conventional fresh water-based textile dyeing, specific water consumption varies between 30 and 50 L per 1 kg of cloth, depending upon the type of dyestuff used in the dyeing process (Singha et al. 2021).

To resolve the water shortage problem in the near future, one research stream is exploring recyclable solvents as dyeing medium for non-aqueous dyeing of cotton fabric (Deng et al. 2019; Tang et al. 2023a; Zhao et al. 2018) whereas another research stream is working on examining the use of seawater, the most abundant water source, as the dyeing medium for cotton colouration.

Seawater, generally defined as water with salinity of ~ 35,000 ppm (35 g/L or 35 g/kg), consists of six main saline elements: (a) cations: sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+); and (b) anions: chloride (Cl^-) and sulphate (SO_4^{2-}) (Ludwig 2022). The presence of Na^+ and Cl^- ions in seawater favours cotton dyeing while the existence of Ca^{2+} and Mg^{2+} ions, also known as water hardness, hinder the dyeing process (Tang et al. 2019a).

Most of the recent literature primarily focuses on using seawater collected from the beach or bay for dyeing of cotton fabric. Zerin et al. (2017) and Karim et al. (2021) collected seawater from Cox's Bazar sea beach while Solaiman et al. (2019), Raja et al. (2020), de Souza Ferreira et al. (2021) used seawater obtained from the Bay of Bengal in Bangladesh, Arabian Sea in India and Barreira Dagua beach in Brazil respectively to examine the dyeing and fastness properties of the cotton fabrics. However, the use of artificial seawater as a dyeing medium for reactive dyeing of cotton has not yet been found in the literature. Although artificial seawater is made from fresh water, its usage as dyeing medium allows precise control of ionic compositions for reactive dyeing of cotton. This controlled environment can serve as a benchmark for optimizing the use of real seawater in future sustainable dyeing practices. Therefore, it is worthwhile to study its influence and potential application for cotton dyeing with reactive dyes.

This research aims at contributing knowledge by investigating the feasibility of using artificial (simulated) seawater (ASW), developed according to AATCC method, to replace fresh water, tap or ground water commonly used in dyeing industries, as dyeing media for dyeing of cotton fabrics. The dyeing properties, including: (a) colour yield (K/S_{sum} value); (b) CIE L*a*b* value; (c) colour levelness (relative unlevelness indices); and (d) reflectance percentage, and the colour fastness properties, involving washing, crocking and perspiration fastness, of the cotton fabrics dyed in ASW media are assessed and compared with fabrics dyed in fresh water (deionised water and distilled water) medium. Salinity and pH value of the dye liquor, as well as tensile properties and surface damage of the dyed cotton fibre are also examined.

Experimental

Materials and reagents

Ready for dyeing pure cotton woven fabric (127 ends in warp and weft per cm and 139 g/m^2) was first prewashed and conditioned with parameters similar to our previous work (Tang et al. 2023b). Sodium chloride (NaCl) was procured from Duksan. Sodium carbonate (Na_2CO_3) anhydrous was purchased from Sigma Aldrich. Magnesium chloride ($MgCl_2$) anhydrous was obtained from Alfa Aesar. They were of reagent grade. Eleven reactive dyes, monofunctional and bifunctional, of different reactive groups (Table 1) (Tang et al. 2019b) were purchased from Dystar (Shanghai, China) and used as received.

Preparation of artificial seawater (ASW)

The artificial seawater (ASW) was prepared according to AATCC Test Method for Colorfastness to Water: Sea (AATCC Test Method 106). 30 g/L sodium chloride (NaCl) and 5 g/L magnesium chloride ($MgCl_2$)

Table 1 Reactive groups of eleven reactive dyestuffs (Tang et al. 2019b)

Reactive dyestuff	Reactive group(s)
Black-01	VS-DCT
Blue-01	MFT-VS
Blue-02	FCP-VS
Blue-03	VS–VS
Blue-04	MFT
Navy-01	TFP-VS
Red-01	MFT-TFP
Red-02	FCP
Yellow-01	DCC
Yellow-02	VS
Yellow-03	MCT-VS

MFT monofluorotriazine, *TFP* trifluoropyrimidine, *VS* vinylsulfone, *FCP* fluorochloropyrimidine, *DCC* dichlorochinoxaline, *DCT* dichlorotriazine, *MCT* monochlorotriazine

were dissolved in distilled water to make 1000 ml ASW solution.

Preparation of dye stock solution

Dye stock solutions of 1% concentration were prepared by dissolving the dye powder in deionized water, distilled water and artificial sea water separately.

Dyeing of cotton fabrics in different water medium

Cotton fabric specimens were dyed using liquor-to-goods ratio of 10:1 in deionised water (DI), distilled water (DIS), and artificial seawater (ASW) medium. Five colour depths of reactive dye set for experiments ranged from 0.1 to 3.5% (on weight of fabric, o.w.f.). The dyeing profile is illustrated in Fig. 1. The fabric specimens were initially immersed in dye liquors composed of the corresponding concentration of dye and amount of NaCl as listed in Table 2. The dye liquors were prepared with (ASW+) and without (ASW−) NaCl separately. The as-prepared dye liquors were then placed in the shaking water bath at 30 °C for 10 min, followed by heating to 70 °C for 40 min of dyeing of fabric specimens. Corresponding amount of soda ash was then added to the dyebath

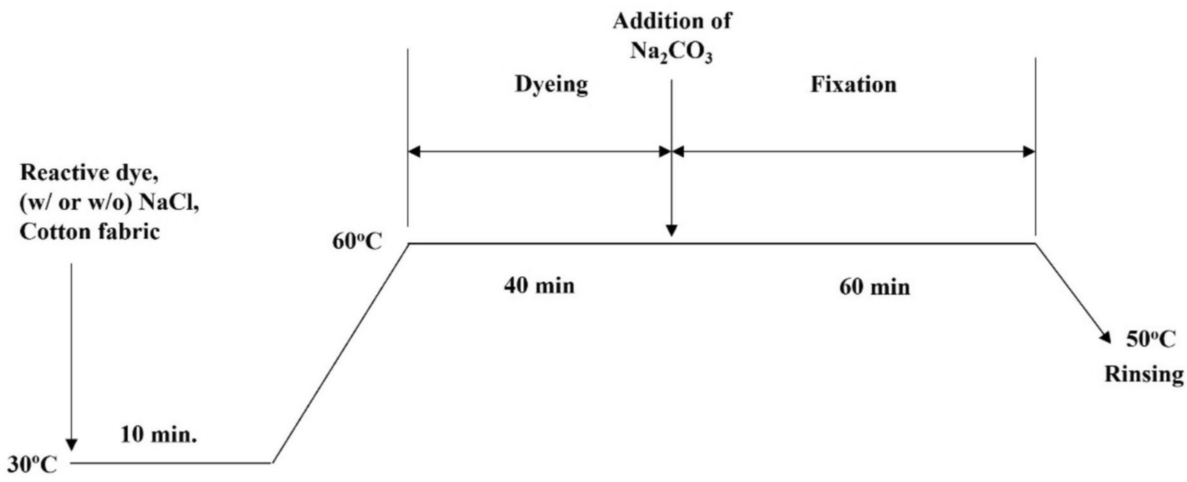


Fig. 1 Reactive dyeing profile of cotton fabrics in different water medium (w/or w/o NaCl)

Table 2 Recipe for dying of cotton fabric

Liquor ratio 10:1, 60 °C						
Reactive dye	% o.w.f	0.1	0.5	1.5	2.5	3.5
Salt (NaCl)	g/L	10/–*[a]	20/–	42.5/–	55/–	65/–
Soda ash (Na_2CO_3)	g/L	5	5	5	5	5

*[a]indication: DI, DIS, ASW+/ASW−

for 60 min of colour fixation at 70 °C. After fixation, the dyed fabric specimens were rinsed at 50 °C for 20 min twice, cold rinsed, air-dried and conditioned before subsequent measurements and tests.

Measurement of salinity and pH value

Salinity and pH value of DI, DIS and ASW dyebaths were measured by Eutech™ Salt 6 + Handheld Meter and Eutech™ CyberScan pH 11 Portable pH/mV Meter (Thermo Fisher Scientific Inc., Singapore) respectively. Salinity and pH values of the dye baths, made of deionized water, distilled water and artificial water were measured in three stages of the dyeing process for evaluation: (a) before the dyeing process; (b) after soda ash addition; and (c) after the dyeing process.

Colour yield (K/S$_{sum}$ value)

Colour yield of DI, DIS and ASW dyed cotton fabric specimens was measured by SF650 Spectrophotometer (DataColor International, USA). The colour property of the dyed specimens was measured using D_{65} illuminant and 10° observer angle within the visible spectrum ranged from 400 to 700 nm at every 10 nm interval. The dyed fabric specimens were folded twice with the face side up and were measured four times each. The K/S value of each specimen was calculated based on the Kubelka–Munk theory using Eq. (1). By summing and averaging the K/S values of four measurements of each specimen, the K/S$_{sum}$ value was finally obtained.

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

where K: absorption coefficient; S: scattering coefficient; and R: reflectance of the dyed sample.

CIE L*a*b* value

CIE L*a*b* values of DI, DIS and ASW dyed cotton fabric specimens were obtained by using similar parameters and instrument for colour yield measurement as mentioned in colour yield section.

Colour levelness

The colour levelness of DI, DIS, and ASW dyed cotton fabric specimens was assessed by using Relative Unlevelness Indices (RUI) proposed by Chong et al. (1992). Four spots of each dyed specimen were randomly chosen. Parameters and instrument for examination were similar to colour yield measurement. Equation (2) was used to calculate the RUI value of each specimen.

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

where s_λ: standard deviation of reflectance value; $\overline{R}$: reflectance value; V_λ: photopic relative luminous efficiency function.

Scanning electron microscopy (SEM)

Undyed and DI, DIS and ASW dyed cotton fabric specimens (3.5% o.w.f. reactive red dye) were first prepared on a round plate using conductive tapes and then gold sputtered. The sputtered specimens were placed in the Hitachi TM3000 tabletop scanning electron microscope (Hitachi, Japan) for morphological examination of the surface to assess the extent of fibre damage.

Colour fastness properties

AATCC Test Method 61, Test No. 2A, AATCC Test Method 8 and ISO 105 E04 were used to evaluate the washing, crocking and perspiration fastness respectively of the DI, DIS, and ASW dyed cotton fabric specimens respectively. The colour change of the dyed specimens and staining of the multifibre fabric and white cotton cloth were ranked by the use of grey scale.

Tensile properties

Tensile strength (N) and breaking extension (mm and %) of pristine, DI, DIS, and ASW dyed fabric specimens were determined along warp and weft direction according to ASTM standard D5034: Grab Test.

Results and discussion

Colour yield

Colour yield (K/S_{sum} value) of the deionised (DI) water-dyed, distilled (DIS) water-dyed, and artificial seawater (ASW− and ASW+) dyed cotton specimens is shown in Table 3. In comparison to the DI-dyed specimens, DIS specimens generally achieve higher colour yields when five reactive dyes (Blue-02, Navy-01, Red-02, Yellow-01 and Yellow-02) are used whereas lower colour yields are found when the other six reactive dyes are used. The percentage difference in colour yields of the DIS specimens fluctuate in the range from 13.4% lower to 26.7% higher than that of the DI specimens and the fluctuation is closely related to the reactive group of the dyestuff. From Table 3, it is observed that reactive groups, involving vinylsulfone (VS), fluorochloropyrimidine (FCP), trifluoropyrimidine (TFP) and dichlorochinoxaline (DCC) perform better when cotton specimens are dyed in distilled water medium than specimens dyed in deionised water medium while triazine-based reactive groups, including dichlorotriazine (DCT), monofluorotriazine (MFT) and monochlorotriazine (MCT) have the same colour yield in both mediums. The possible reason may be the difference in properties of deionised water and distilled water which may affect the reactivity and interaction between reactive group of the dye and cotton fibre during the dyeing process.

Artificial seawater dyed cotton specimens without NaCl addition (ASW−) obtain lower colour yield (− 0.68– − 65.2%) than that of DI specimens when medium to high dye concentrations (0.5–3.5%) are used while they can only attain higher colour yield (10.6–80.6%) when 0.1% dye concentration is used. Higher colour yield of ASW− specimens can be explained by the NaCl content of ASW-based and DI-based dye liquor in which the former comprises of 30 g/L NaCl while the latter contains only 10 g/L NaCl when the specimens are dyed with 0.1% dye concentration. Lower colour yield of ASW− specimens may be the result of insufficient NaCl for neutralisation of negative charge of cotton surface which leads to higher electrostatic repulsion during the dyeing process, hindering the adsorption of dye on cotton fibre (Correia et al. 2020; Grancarić et al. 2021). Another reason for low colour yield of ASW− specimens is water hardness due to the presence of magnesium chloride ($MgCl_2$) which may cause dye precipitation while promoting dye aggregation, leading to the loss of colour depth (Broadbent 2001; Khalil and Sarkar 2014; Tang et al. 2019a). Similarly, colour yields of ASW− specimens are relatively lower when triazine-based reactive dyes are used, owing to properties of ASW which is made of the same distilled water.

Specimen dyed in (ASW+) with NaCl using bi-functional reactive dye Blue-02 (FCP-VS) and mono-functional Red-02 (FCP) had better colour yields, 5.8–50.1% and 6.1–72.5% higher respectively, than DI-dyed specimens at all dye concentrations (0.1–3.5% o.w.f.). This indicates that samples dyed by FCP-based reactive dye are least affected by hardness ($MgCl_2$) in water in the dyeing system. Higher colour yield of ASW+ samples can be explained by higher NaCl content in the dyeing system. Regarding reactive dyes other than FCP-based, addition of NaCl also enhances colour yield of the ASW+ samples in comparison to ASW− samples. However, due to the presence of $MgCl_2$ in the dyeing system, most of the ASW+ samples dyed in 0.5–3.5% dye concentrations still attain lower colour yield (3.5–50.1% lower) while only ASW+ samples dyed with 0.1% dye concentration exhibit higher colour yield (1.7–74.9% higher) compared with DI samples.

The sequence of colour yield (from high to low) of the dyed samples in four different aqueous dyeing media is: DI > DIS > ASW+ > ASW−. Due to the difference in composition of the four aqueous dyeing media and the difference in reactive group(s) of the reactive dyes, the dyeing effectiveness and the resultant colour yield are affected. Triazine-based mono- and bi-functional reactive dyes disfavour cotton dyeing in distilled water and artificial seawater media while FCP-based mono- and bi-functional and DCC-based monofunctional reactive dyes, compared with the others, are more amenable to dyeing of cotton fabric in DIS and ASW (ASW− and ASW+) media.

Lower colour yield of triazine-based reactive dyes is attributed to the sensitivity of the dye reactive group against salt concentration. Triazine-based reactive dyes are generally more sensitive to salt concentration compared to FCP-based reactive dyes. The presence of salt accelerates the hydrolysis of triazine-based dyes, causing larger proportion of dyes being reacted to water or artificial seawater instead of cotton

Table 3 Colour yield of dyed cotton specimens in different water medium

Dyestuff	RG(s)	Conc	DI	DIS		ASW−		ASW+	
		(% o.w.f.)	K/S$_{sum}$	K/S$_{sum}$	(%)	K/S$_{sum}$	(%)	K/S$_{sum}$	(%)
Black-01	VS-DCT	0.1	14.24	12.94	− 9.16	17.29	21.38	21.83	53.29
		0.5	56.71	54.79	− 3.39	47.54	− 16.17	59.17	4.34
		1.5	159.28	160.88	1.00	88.20	− 44.62	115.19	− 27.68
		2.5	267.33	285.01	6.61	111.70	− 58.22	182.15	− 31.86
		3.5	371.87	373.50	0.44	140.98	− 62.09	227.68	− 38.78
Blue-01	MFT-VS	0.1	7.04	6.88	− 2.33	8.24	16.98	8.42	19.59
		0.5	23.27	24.19	3.95	18.90	− 18.78	21.1	− 9.32
		1.5	67.02	66.06	− 1.44	34.90	− 47.93	41.06	− 38.74
		2.5	105.48	105.84	0.34	45.18	− 57.16	59.87	− 43.24
		3.5	153.96	139.46	− 9.42	53.56	− 65.21	70.96	− 53.91
Blue-02	FCP-VS	0.1	15.47	19.38	25.27	21.21	37.08	23.39	51.18
		0.5	67.33	67.50	0.26	63.85	− 5.17	75.87	12.69
		1.5	196.49	210.94	7.35	166.48	− 15.27	217.69	10.79
		2.5	307.70	317.88	3.31	241.32	− 21.57	325.56	5.80
		3.5	374.73	408.48	9.01	290.91	− 22.37	407.35	8.71
Blue-03	VS–VS	0.1	10.36	10.23	− 1.26	13.36	28.95	18.24	76.05
		0.5	43.56	44.37	1.86	43.26	− 0.68	43.65	0.21
		1.5	120.11	101.33	− 15.63	82.90	− 30.98	86.61	− 27.89
		2.5	183.02	162.61	− 11.15	98.62	− 46.12	118.14	− 35.45
		3.5	235.70	251.25	6.59	118.75	− 49.62	149.48	− 36.58
Blue-04	MFT	0.1	4.18	3.62	− 13.36	5.19	24.19	6.52	56.00
		0.5	12.54	12.26	− 2.20	12.59	0.41	14.37	14.59
		1.5	32.40	34.60	6.78	22.95	− 29.16	30.54	− 5.75
		2.5	55.24	59.38	7.49	29.80	− 46.06	44.41	− 19.60
		3.5	75.80	65.58	− 13.49	33.95	− 55.22	57.9	− 23.61
Navy-01	TFP-VS	0.1	8.14	8.54	4.99	7.95	-2.26	10.85	33.36
		0.5	28.13	30.71	9.18	27.87	− 0.91	29.81	5.99
		1.5	75.21	81.97	8.98	52.98	− 29.57	65.52	− 12.89
		2.5	117.44	129.29	10.09	72.96	− 37.87	92.19	− 21.50
		3.5	153.51	170.01	10.75	89.60	− 41.63	117.27	− 23.61
Red-01	MFT-TFP	0.1	5.07	4.89	− 3.65	5.61	10.58	6.23	22.86
		0.5	16.48	16.45	− 0.24	14.41	− 12.57	15.46	− 6.21
		1.5	47.90	44.50	− 7.11	26.64	− 44.39	32.25	− 32.68
		2.5	76.43	76.02	− 0.54	36.61	− 52.10	47.95	− 37.26
		3.5	104.81	107.34	2.41	41.30	− 60.60	63.06	− 39.84
Red-02	FCP	0.1	5.87	6.32	7.66	8.13	38.51	10.13	72.49
		0.5	18.45	19.65	6.54	23.59	27.88	25.82	39.98
		1.5	55.91	61.80	10.53	50.20	− 10.21	65.49	17.13
		2.5	90.91	100.22	10.25	74.34	− 18.22	105.81	16.39
		3.5	128.39	139.80	8.89	87.24	− 32.05	136.18	6.07

Table 3 (continued)

Dyestuff	RG(s)	Conc	DI	DIS		ASW−		ASW+	
		(% o.w.f.)	K/S_{sum}	K/S_{sum}	(%)	K/S_{sum}	(%)	K/S_{sum}	(%)
Yellow-01	DCC	0.1	3.70	4.69	26.72	6.68	80.62	6.47	74.85
		0.5	12.40	15.35	23.76	14.98	20.84	17.52	41.28
		1.5	37.29	44.53	19.40	28.99	−22.26	42.59	14.21
		2.5	63.34	77.22	21.91	36.84	−41.83	60.21	−4.94
		3.5	84.52	107.10	26.71	45.20	−46.52	79.9	−5.47
Yellow-02	VS	0.1	3.78	4.20	11.27	5.26	39.31	6.41	69.67
		0.5	11.45	12.24	6.86	12.19	6.48	14.05	22.69
		1.5	26.48	29.88	12.84	22.57	−14.77	25.56	−3.49
		2.5	42.83	41.38	-3.40	28.27	−33.99	31.84	−25.66
		3.5	51.69	54.79	5.98	31.60	−38.87	35.55	−31.23
Yellow-03	MCT-VS	0.1	7.46	7.75	4.00	7.34	−1.58	7.58	1.68
		0.5	25.70	25.59	−0.44	18.47	−28.13	21.39	−16.79
		1.5	65.22	70.39	7.93	34.32	−47.38	40.85	−37.36
		2.5	98.34	97.91	−0.44	41.14	−58.17	52.59	−46.52
		3.5	125.45	122.68	−2.21	47.18	−62.39	62.58	−50.12

(%) = percentage increase or decrease in colour yield of DIS, ASW− and ASW+ dyed samples when compared to the colour yield of the DI-dyed samples

fibre. This leads to reduced dye uptake and fixation on the cotton fibres, resulting in lower colour yield.

On the contrary, higher colour yield of fluorochloropyrimidine (FCP)-based reactive dyes is probably owing to their higher reactivity, fixation efficiency, salt resistance, and better penetration and interaction with cotton fibre even in challenging artificial seawater medium. The chlorine and fluorine atoms in the pyrimidine ring are highly reactive. These groups can form strong covalent bonds with the hydroxyl groups on the cellulosic structure of cotton fibres via nucleophilic substitution mechanism, assuring better fixation and dye stability on the fibre.

Moreover, the fluorine atoms, which are highly electronegative, in FCP-based dyes create hydrophobic interactions. These interactions help the dye molecules penetrate the cotton fibres more effectively, even in the presence of salts found in artificial seawater. Furthermore, the molecular structure of FCP-based reactive dyes is generally designed to minimize steric hindrance and salt interference, allowing the dye molecules to penetrate deeper into the fibre matrix and contributing better dye-fibre interaction and colour yield.

Reflectance curve

Reflectance curves of cotton specimens dyed in DI, DIS and ASW media with different reactive groups of reactive dyes are depicted in Fig. 2. In comparison to DI-dyed specimens, DIS-dyed specimens dyed with reactive groups of VS (Blue-02, Yellow-02), FCP (Blue-02, Red-02), TFP (Navy-01, Red-01), and DCC (Yellow-01), show lower reflectance percentage while specimens dyed with triazine-based reactive groups of DCT (Black-01), and MFT (Blue-04), exhibit higher reflectance percentage (Fig. 2). This implies that the difference between properties of DI and DIS dyeing medium do affect dyeing performance of certain reactive dyes as discussed in the colour yield section.

Compared with DI-dyed and DIS-dyed specimens, ASW specimens, dyed with 11 different reactive groups, generally obtain the lowest reflectance percentage and thus darker shades at low dye concentration (0.1%), while they have the highest reflectance percentage (paler shade) when dye concentration increases from 0.5 to 3.5% (Fig. 2). Low reflectance of ASW− dyed specimens at low dye concentration may be the result of higher NaCl content whereas

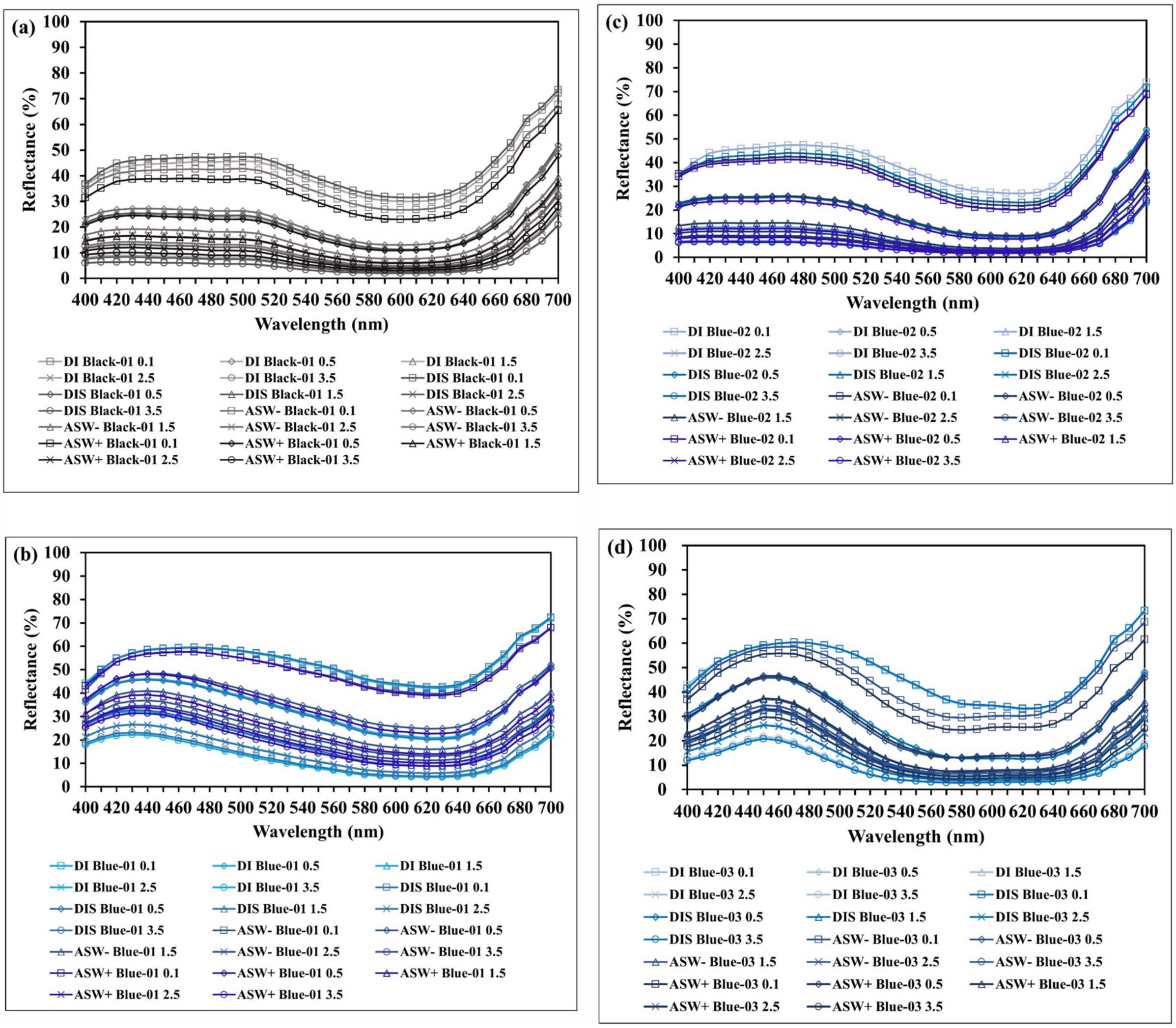


Fig. 2 Reflectance curves of cotton fabric specimens dyed in different aqueous medium with reactive dyes of different reactive groups: **a** Black-01; **b** Blue-01; **c** Blue-02; **d** Blue-03; **e** Blue-04; **f** Navy-01; **g** Red-01; **h** Red-02; **i** Yellow-01; **j** Yellow-02; **k** Yellow-03

high reflectance of ASW− dyed specimens at medium to high dye concentrations can be explained by the presence of water hardness in ASW. Among ASW− and ASW+dyed specimens, ASW+dyed specimens generally have lower reflectance than ASW− dyed specimens since the former dye liquors comprise a higher NaCl content, which reduces the electrostatic repulsion between dye molecules and cotton fibre, compared with the latter dye liquors.

As depicted in Fig. 2, it is clear that reflectance curves of DI-dyed, DIS-dyed and ASW− dyed specimens are generally identical in shape. Each reactive dye exhibits its unique reflectance curve and no peak shift is found for any dyed specimens. This indicates that the use of ASW as dyeing medium for dyeing of cotton fabric only leads to upward or downward shifting of the reflectance curve but it does not alter colour properties of the dyed specimens.

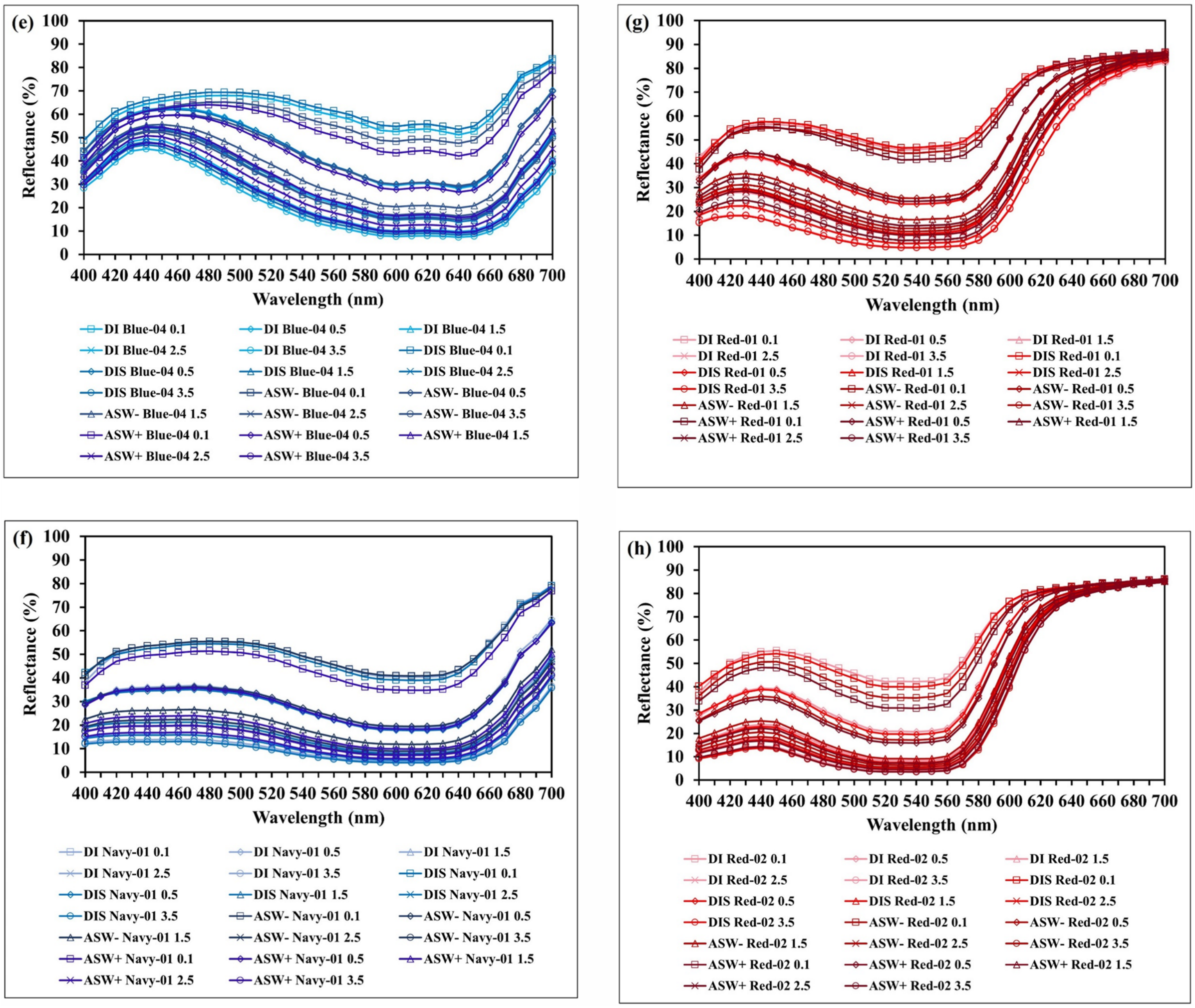


Fig. 2 (continued)

Salinity

Salinity (Parts per trillion, ppt) of dye liquors (five colour depths) before the dyeing process, during the dyeing process after soda ash addition, and after the dyeing process was measured (Table 4). It is apparent that salinity of DI-based, DIS-based and ASW-based dye liquors increases as dye concentration increases. This may be the result of the increase in the NaCl amount at high dye concentrations in order to promote dye exhaustion. In case of ASW−, salinity of the dye liquors slightly decreases and keeps nearly constant with increasing colour depths since no NaCl is added into the dye liquors during the dyeing process.

Before the dyeing process, the least salinity (Table 5) is found in DI-based and DIS-based dye liquors at low to medium colour depths (0.1–0.5%) ranging from 11 to 24 ppt which is lower than that of the ASW− and ASW+ dye liquors with salinity between 44 and 48 ppt at the same colour depth. This verifies that the lower colour yield of DI and DIS dyed specimens at low colour depth in comparison to ASW dyed specimens is possibly owing to lower salinity of the dye liquors, leading to higher electrostatic repulsion during the dyeing process, and thus lower dye exhaustion. ASW+ dye liquors acquire the highest salinity between 56.5 and 94 ppt at medium to high colour depths (1.5–3.5%) since they comprise artificial seawater, which is originally

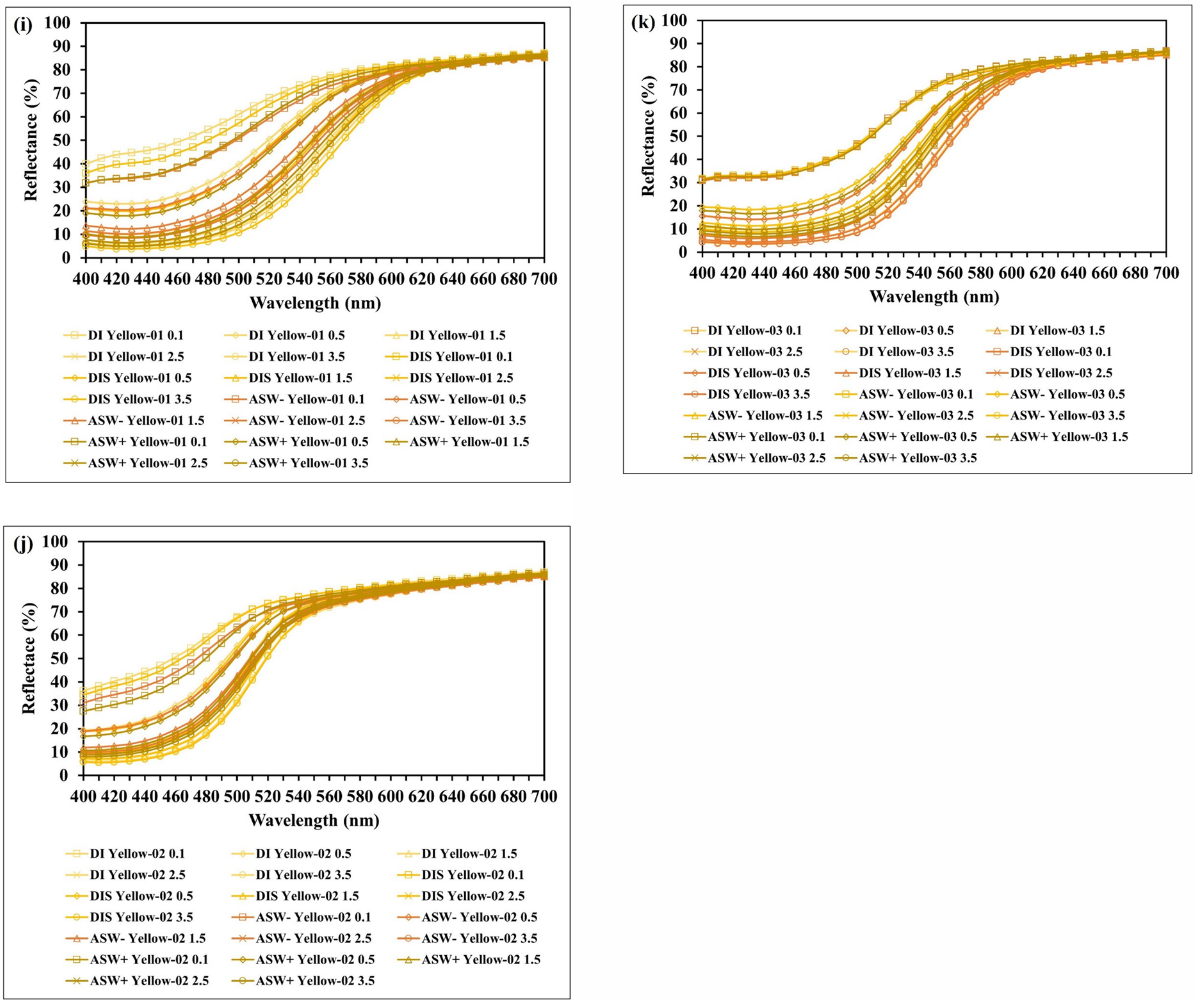


Fig. 2 (continued)

prepared with 30 g/L NaCl, as well as the addition of corresponding amount of NaCl according to the recipe listed in Table 2 previously. DI-based and DIS-based dyebaths have the second and the third highest salinity, between 50 and 58 ppt and between 45 and 57 ppt respectively, at high dye concentrations (2.5% and 3.5%) whereas ASW− have the lowest salinity owing to no NaCl addition during the dyeing process.

Salinity of dye liquors after the addition of soda ash (Table 4) is higher in DI, DIS and ASW dyebaths than in dyebaths before the dyeing process. This validates the notion that addition of soda ash can promote dye exhaustion by increasing the salinity of the dyebaths. In this stage, it can be seen that ASW+ dyebaths possess the highest salinity at all colour depths (42–90 ppt). ASW− dyebaths possess higher salinity at low to medium dye concentrations from 0.1 to 1.5% (47–50 ppt) while having lower salinity at high dye concentrations from 2.5 to 3.5% (44–47 ppt) when compared with that of the DI (17–66 ppt) and DIS (15–66 ppt) dyebaths.

Salinity after the dyeing process (Table 4) is about the same in all dyebaths, including DI, DIS and ASW, as salinity after soda ash addition. ASW+ dyebaths possess the highest salinity (40–96 ppt), followed by DI (17–71 ppt) and DIS (16–66 ppt) dyebaths, whereas salinity of ASW− dyebaths, due to no NaCl addition, is the most stable at all colour depths (42–49 ppt) among the four different kinds of dyebaths, having the highest salinity at low colour

Table 4 Salinity of dye liquors

Salinity	Dye conc (%)	DI (ppt)	DIS (ppt)	ASW− (ppt)	ASW+ (ppt)
Before dyeing	0.1	11.6–13.5	11.1–15.5	44.4–47.5	44.5–47.0
	0.5	22.6–23.4	22.6–24.2	45.5–48.4	46.0–47.3
	1.5	38.6–41.0	34.7–38.2	42.9–46.2	56.5–61.9
	2.5	49.7–53.0	45.2–49.5	40.5–45.7	79.0–81.2
	3.5	51.7–58.0	53.2–56.7	41.4–43.1	86.6–94.1
After adding soda ash	0.1	16.6–17.7	15.4–17.8	46.9–49.7	41.9–43.1
	0.5	30.1–33.1	29.2–32.8	47.9–49.2	46.0–48.4
	1.5	42.3–44.7	38.9–42.1	46.8–48.7	69.8–73.4
	2.5	60.9–63.2	50.9–55.1	45.4–46.4	70.9–85.7
	3.5	62.8–65.9	59.5–66.0	43.5–46.7	79.9–89.4
After dyeing	0.1	16.5–18.3	16.0–17.4	46.4–49.0	39.8–41.0
	0.5	29.8–33.3	29.8–31.8	46.4–49.1	49.6–51.7
	1.5	41.9–42.6	39.7–43.7	46.0–48.8	71.7–74.4
	2.5	53.9–55.2	52.6–55.1	43.6–46.7	86.3–88.0
	3.5	58.9–71.1	59.3–65.9	42.0–46.0	88.9–96.2

Table 5 pH value of the dye liquor

pH value	Dye conc (%)	DI pH	DIS pH	ASW− pH	ASW+ pH
Before dyeing	0.1	5.7–6.6	5.3–6.3	9.1–9.2	9.0–9.2
	0.5	5.4–6.0	5.4–6.1	9.1–9.5	8.8–8.9
	1.5	5.4–6.2	5.8–6.1	8.8–9.3	8.0–8.6
	2.5	5.7–6.1	5.7–6.0	8.6–9.4	6.6–8.4
	3.5	5.2–6.1	5.6–6.0	7.7–9.3	6.2–8.3
After adding soda ash	0.1	11.0–11.3	11.0–11.2	9.7–9.8	9.8–9.9
	0.5	10.6–11.2	10.9–11.1	9.7–9.8	9.8–9.9
	1.5	11.1–11.3	10.7–10.9	9.8–9.9	9.8–9.9
	2.5	11.0–11.3	10.6–10.8	9.8–9.9	9.8–9.9
	3.5	10.8–10.9	10.5–10.8	9.8–9.9	9.8–9.9
After dyeing	0.1	11.2–11.3	10.9–11.1	9.0–9.1	9.1–9.2
	0.5	11.2–11.5	10.8–11.0	9.0–9.2	9.1–9.2
	1.5	10.8–11.0	10.7–10.9	9.0–9.3	9.1–9.2
	2.5	10.9–11.2	10.6–10.8	9.0–9.3	9.0–9.1
	3.5	10.8–10.9	10.5–10.7	9.1–9.4	9.0–9.1

depth while possessing the lowest salinity at high dye concentrations.

These findings reflect that dyebath of high salinity, exemplified by ASW+ dyebaths. Does not eventually contribute to the high colour yield of the dyed fabrics. Adversely, high salinity may cause dye molecules to aggregate, reducing dye solubility and penetrability into the cotton fibres.

The presence of large amount of salt may compete with dye molecules for bonding sites on the cotton fibres. This competition reduces the efficiency of dye fixation, leading to lower colour yield and uneven dye distribution. Meanwhile, dyebaths with optimum salinity, such as DI and DIS dyebaths, can obtain the best dyeing effectiveness as well as the highest colour yield fabric with the best dye uptake.

Last but not least, the artificial seawater prepared in this study is mainly made of sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) according to AATCC Test Method 106. The presence of magnesium ions not only increases water hardness, but also can form complexes with reactive dyes, reducing their solubility and causing them to precipitate out of the solution. In addition, magnesium ions may lead to the formation of dye aggregates and interfere uniform distribution of dye molecules on the cotton fibres, resulting in colour specks, loss of depth, poor colour yield and fastness properties.

pH value

To further examine the dyeing performance of ASW dyeing system and colour yield of the dyed fabric, pH values of ASW dye liquors were measured in three stages: (a) before the start of the dyeing process; (b) after soda ash addition; and (c) after the dyeing process and are compared with that of the DI and DIS dye liquors. The pH values of those dye liquors are as stated in Table 5.

DI and DIS dye liquors generally show similar pH values in all the three stages of the dyeing process. They exhibit slightly acidic pH, ranging from 5.2 to 6.3, before the colouration process. The pH values of the DI and DIS dye liquors then increase sharply from slightly acidic state to alkaline state between 10.5 and 11.5 after addition of alkali while maintaining nearly the same alkaline pH value after the dyeing process.

ASW and ASW+ dye liquors (pH 6.2–9.2) were found to have slightly lower pH value than ASW− dye liquors (pH 7.7–9.5) before the dyeing process. However, both ASW+ and ASW− dyebaths had slightly higher pH values (higher alkalinity) after soda ash addition (pH 9.7–9.9) while their pH values decreased (pH 9.0–9.4) after the dyeing process.

To compare the pH values of ASW− and ASW+ dye liquors with DI and DIS dye liquors, the former two dyebaths (pH 6.2–9.5) generally have higher pH values than the latter two dyebaths (pH 5.2–6.3) before the dyeing process. Nevertheless, when soda ash is added at the intermediate stage of the dyeing process, alkalinity of the DI and DIS dyebaths surpasses that of ASW dyebaths in which DI and DIS dyebaths (pH 10.5–11.5) possess higher pH value than the ASW− and ASW+ dyebaths (pH 9.7–9.9). This indicates that DI and DIS dyebaths are more sensitive to alkali addition and more pH responsive than the ASW dyebaths. It may be the result of absence of water hardness ($MgCl_2$) in DI and DIS dyebaths.

At the exhaustion phase of the dyeing process, maintaining a neutral or slightly acidic pH helps prevent premature hydrolysis of the reactive dyes, reducing the amount of dye available for covalent bonding with cotton fibre. From Table 5, both DI and DIS dye liquors are generally slightly acidic with pH value between 5.2 and 6.6 which reduce the risk of premature dye hydrolysis whereas both ASW− and ASW+ dye liquors reveal slightly alkaline pH from 7.7 to 9.5, having higher chance of premature dye hydrolysis before the fixation phase and thus resulting in poorer colour yields of the dyed specimens compared to the DI and DIS dye liquors.

The optimal alkaline pH for most reactive dyes to achieve dye-fibre fixation is well-known to be around 10.5–11.5. This pH level promotes the formation of cellulosate anions in cotton, which can create strong covalent bonds with the dye molecules. If the dyebath pH is too low, the dye may have less tendency to fix onto the fibre, resulting in poor colour yield. Conversely, if the dyebath pH is too high, excessive hydrolysis may occur, leading to lower depth of shade. As presented in Table 5, both DI and DIS dye liquor can achieve optimal alkaline pH condition after the addition of soda ash (alkali) with dyebath pH ranging from 10.5 to 11.5. However, in case of the ASW liquors, the dyebath pH of both ASW− and ASW+ is below 10. This indicates that the ASW dyebaths possess lower dye-fibre fixation effectiveness and efficiency than that of DI and DIS dyebaths. These findings further validate that the DI and DIS dyed cotton fabrics can achieve better colour yields than that of the ASW dyed specimens.

Table 6 RUI of dyed cotton specimens

Dyestuff	%	DI		DIS		ASW−		ASW+	
		RUI	Visual	RUI	Visual	RUI	Visual	RUI	Visual
Black-01	0.1	0.09	Excellent	0.19	Excellent	0.15	Excellent	0.05	Excellent
	0.5	0.07	Excellent	0.17	Excellent	0.09	Excellent	0.25	Good
	1.5	0.15	Excellent	0.24	Good	0.17	Excellent	0.27	Good
	2.5	0.11	Excellent	0.09	Excellent	0.18	Excellent	0.42	Good
	3.5	0.13	Excellent	0.19	Excellent	0.05	Excellent	0.32	Good
Blue-01	0.1	0.09	Excellent	0.05	Excellent	0.04	Excellent	0.09	Excellent
	0.5	0.04	Excellent	0.05	Excellent	0.12	Excellent	0.10	Excellent
	1.5	0.06	Excellent	0.22	Good	0.03	Excellent	0.06	Excellent
	2.5	0.16	Excellent	0.18	Excellent	0.18	Excellent	0.11	Excellent
	3.5	0.17	Excellent	0.20	Excellent	0.17	Excellent	0.12	Excellent
Blue-02	0.1	0.21	Good	0.07	Excellent	0.07	Excellent	0.16	Excellent
	0.5	0.10	Excellent	0.24	Good	0.18	Excellent	0.15	Excellent
	1.5	0.29	Good	0.23	Good	0.18	Excellent	0.20	Good
	2.5	0.34	Good	0.09	Excellent	0.20	Excellent	0.10	Excellent
	3.5	0.30	Good	0.16	Excellent	0.14	Excellent	0.36	Good
Blue-03	0.1	0.30	Good	0.24	Good	0.10	Excellent	0.17	Excellent
	0.5	0.26	Good	0.34	Good	0.12	Excellent	0.44	Good
	1.5	0.41	Good	0.21	Good	0.13	Excellent	0.30	Good
	2.5	0.19	Excellent	0.34	Good	0.06	Excellent	0.26	Good
	3.5	0.46	Good	0.14	Excellent	0.24	Good	0.14	Excellent
Blue-04	0.1	0.07	Excellent	0.05	Excellent	0.04	Excellent	0.03	Excellent
	0.5	0.10	Excellent	0.05	Excellent	0.07	Excellent	0.15	Excellent
	1.5	0.20	Excellent	0.04	Excellent	0.09	Excellent	0.10	Excellent
	2.5	0.21	Good	0.10	Excellent	0.10	Excellent	0.42	Good
	3.5	0.30	Good	0.08	Excellent	0.12	Excellent	0.08	Excellent
Navy-01	0.1	0.06	Excellent	0.13	Excellent	0.12	Excellent	0.05	Excellent
	0.5	0.24	Good	0.21	Good	0.14	Excellent	0.13	Excellent
	1.5	0.32	Good	0.28	Good	0.17	Excellent	0.11	Excellent
	2.5	0.11	Excellent	0.19	Excellent	0.36	Good	0.21	Good
	3.5	0.20	Excellent	0.20	Good	0.25	Good	0.08	Excellent
Red-01	0.1	0.02	Excellent	0.02	Excellent	0.03	Excellent	0.06	Excellent
	0.5	0.07	Excellent	0.14	Excellent	0.06	Excellent	0.02	Excellent
	1.5	0.22	Good	0.15	Excellent	0.17	Excellent	0.22	Good
	2.5	0.12	Excellent	0.16	Excellent	0.08	Excellent	0.19	Excellent
	3.5	0.24	Good	0.18	Excellent	0.10	Excellent	0.13	Excellent
Red-02	0.1	0.05	Excellent	0.08	Excellent	0.03	Excellent	0.06	Excellent
	0.5	0.08	Excellent	0.06	Excellent	0.08	Excellent	0.18	Excellent
	1.5	0.17	Excellent	0.09	Excellent	0.09	Excellent	0.17	Excellent
	2.5	0.15	Excellent	0.22	Good	0.04	Excellent	0.23	Good
	3.5	0.37	Good	0.13	Excellent	0.15	Excellent	0.14	Excellent
Yellow-01	0.1	0.02	Excellent	0.03	Excellent	0.03	Excellent	0.01	Excellent
	0.5	0.03	Excellent	0.06	Excellent	0.02	Excellent	0.03	Excellent
	1.5	0.11	Excellent	0.07	Excellent	0.05	Excellent	0.02	Excellent
	2.5	0.10	Excellent	0.11	Excellent	0.02	Excellent	0.03	Excellent
	3.5	0.11	Excellent	0.14	Excellent	0.07	Excellent	0.05	Excellent

Table 6 (continued)

Dyestuff	%	DI		DIS		ASW−		ASW+	
		RUI	Visual	RUI	Visual	RUI	Visual	RUI	Visual
Yellow-02	0.1	0.02	Excellent	0.02	Excellent	0.03	Excellent	0.03	Excellent
	0.5	0.03	Excellent	0.01	Excellent	0.03	Excellent	0.01	Excellent
	1.5	0.05	Excellent	0.02	Excellent	0.04	Excellent	0.04	Excellent
	2.5	0.03	Excellent	0.05	Excellent	0.04	Excellent	0.04	Excellent
	3.5	0.02	Excellent	0.04	Excellent	0.03	Excellent	0.03	Excellent
Yellow-03	0.1	0.04	Excellent	0.03	Excellent	0.04	Excellent	0.02	Excellent
	0.5	0.04	Excellent	0.02	Excellent	0.03	Excellent	0.04	Excellent
	1.5	0.05	Excellent	0.30	Good	0.06	Excellent	0.06	Excellent
	2.5	0.08	Excellent	0.04	Excellent	0.04	Excellent	0.03	Excellent
	3.5	0.07	Excellent	0.05	Excellent	0.06	Excellent	0.05	Excellent

<0.2 = Excellent levelness; 0.2–0.49 = Good levelness; 0.5–1.0 = Poor levelness; >1.0 = Bad levelness

Relative unlevelness indices

Tables 6 and 7 present colour levelness values, expressed in terms of relative unlevelness indices (RUI), and visual images of cotton specimens dyed in deionised water, distilled water and artificial seawater. Generally speaking, both DI, DIS and ASW− dyed specimens can achieve good to excellent colour levelness with RUI value below 0.49. Among the specimens dyed in different water medium, DIS-dyed specimens exhibit the best colour levelness with least RUI variations (0.01–0.34), followed by ASW− dyed (RUI values: 0.02–0.36) and ASW+ specimens (RUI values: 0.01 and 0.44) whereas colour levelness of deionised water-dyed specimens is comparatively poorer with higher RUI variations ranging from 0.02 to 0.46. Best colour levelness of distilled water-dyed specimens, to a large extent, may be the result of high purity of distilled water without the presence of any contaminants. The possible reason for ASW− dyed specimens having better colour levelness than DI-dyed and ASW+ specimens is that the former specimens are dyed with lower salt content than the latter two types of specimens. Lower salt content of ASW− dyed specimens reduce the risk of dye aggregation while maintaining dye solubility. This allows for a more controlled and gradual dye uptake, achieving uniform dye-fibre interaction and enhancing colour levelness.

CIE L*a*b* value

In CIE L*a*b* colour values, L* represents perceptual lightness wherein higher L* value means lighter shade whereas a* and b* represent red (+a)–green (− a) and yellow (+b)–blue (− b) respectively. Table 8 presents CIE L*a*b* values of DI, DIS and ASW dyed specimens.

With regard to L* value, it generally decreases with increasing dye concentrations for all specimens. It can be seen that DI and DIS dyed specimens generally achieve lower L* value than ASW+ dyed specimens when black, blue and navy colours of reactive dyes are used whereas ASW+ dyed specimens exhibit poorer L* values than DI and DIS dyed specimens when red and yellow colours of reactive dyes are used. ASW− dyed specimens normally obtain the highest L* values compared with other specimens. This reflects that ASW− dyed specimens have the lightest shades among all the dyed specimens while DI, DIS and ASW+ dyed specimens can be darker, depending upon the colour.

All dyed specimens generally show negative a* values (green zone) when black, blue and navy reactive dyes are used whereas they have positive a* values (red zone) when red and yellow reactive dyes are used. In case of black, blue and navy reactive dyes, DI, DIS and ASW− dyed specimens generally attain lower a* values, and thus are greener than ASW+ dyed specimens. Among DI, DIS and ASW− dyed specimens, ASW− dyed specimens

Table 7 Visual images of dyed cotton specimens

Dyestuff	Dye conc.	DI	DIS	ASW-	ASW+
	% o.w.f.	Image	Image	Image	Image
Black-01	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Blue-01	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Blue-02	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Blue-03	0.1				
	0.5				
	1.5				
	2.5				

obtain the lowest a* value (greenest) when black, navy, blue-02 and blue-03 reactive dyes are used. In case of red and yellow reactive dyes, DI and DIS dyed specimens have higher a* value, and therefore are redder than ASW dyed specimens. Among ASW dyed specimens, ASW+dyed specimens generally

Table 7 (continued)

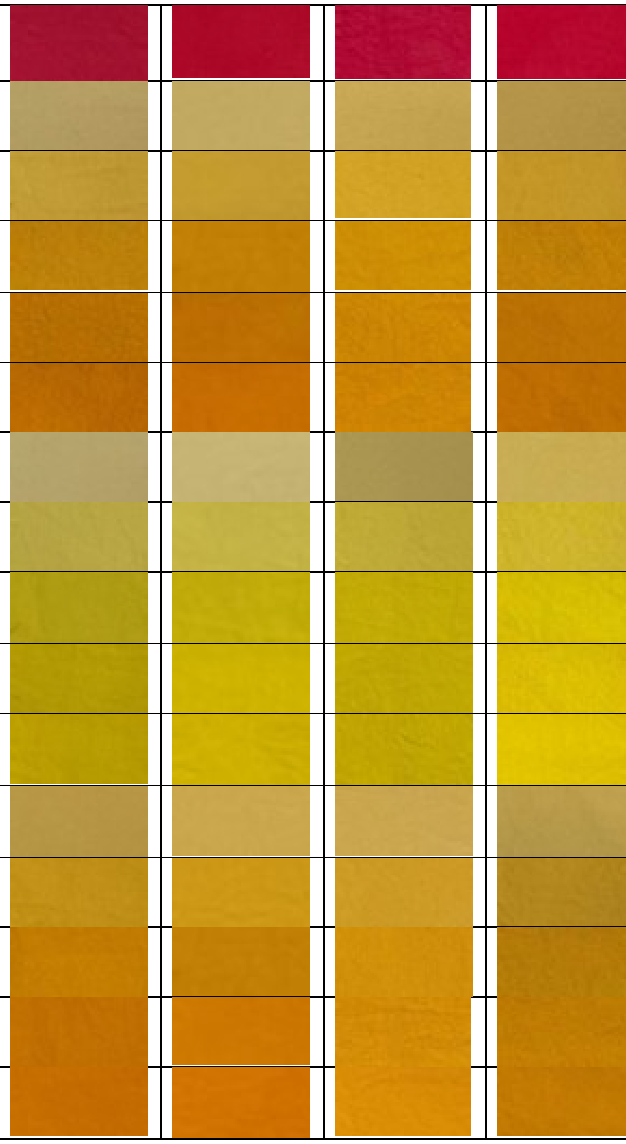
	3.5				
Blue-04	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Navy-01	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Red-01	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Red-02	0.1				
	0.5				
	1.5				
	2.5				

show higher a* values (redder) than ASW− dyed specimens except when red-02 reactive dye is used.

All dyed specimens generally have negative b* values (blue zone) when black, blue and navy reactive dyes are used while they display positive b*

Table 7 (continued)

	3.5				
Yellow-01	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Yellow-02	0.1				
	0.5				
	1.5				
	2.5				
	3.5				
Yellow-03	0.1				
	0.5				
	1.5				
	2.5				
	3.5				



values (yellow zone) when red and yellow reactive dyes are used. In case of black, blue and navy reactive dyes, DI, DIS and ASW− dyed specimens generally attain lower b* values and thus are greener than ASW+dyed specimens. Compared with DI and DIS dyed specimens, ASW− dyed specimens obtain the lowest b* values (bluest) when black, blue-02 and blue-03 reactive dyes are used whereas ASW+dyed specimens reveal the highest b* values, the yellowest among all the dyed specimens. In case of red and yellow reactive dyes, DI and DIS dyed specimens possess higher b* values and therefore are yellower than ASW dyed specimens. Among ASW dyed specimens, ASW− dyed specimens generally show higher b* values (yellower) than ASW+dyed specimens when red reactive dyes are used while ASW+dyed specimens generally exhibit higher b* values (yellower) than ASW− dyed specimens when yellow reactive dyes are used.

SEM images

Figure 3 shows the SEM images of undyed (Fig. 3a), DI dyed, DIS dyed and ASW dyed cotton specimens with 3.5% o.w.f. Red-01 reactive dye. It is clear that DI, DIS and ASW− dyed cotton specimens (Fig. 3b–d)

Table 8 CIE L*a*b* value of dyed specimens

Dyestuff	Conc	DI			DIS			ASW−			ASW+		
	%	L	a	b	L	a	b	L	a	b	L	a	b
Black-01	0.1	66.21	−6.53	−11.15	67.45	−6.48	−11.13	63.46	−6.82	−12.90	61.80	−7.03	−11.40
	0.5	45.92	−8.66	−18.13	46.45	−8.79	−18.20	48.52	−7.83	−17.57	47.14	−6.63	−15.20
	1.5	30.98	−8.30	−19.53	30.87	−8.34	−19.43	39.27	−8.08	−18.97	37.54	−6.60	−16.33
	2.5	24.26	−6.96	−18.35	23.46	−6.53	−17.68	35.85	−8.09	−19.33	31.15	−5.76	−16.03
	3.5	20.26	−5.21	−16.05	20.20	−5.02	−15.71	32.58	−7.89	−19.27	28.13	−5.13	−15.55
Blue-01	0.1	75.39	−7.24	−9.43	75.69	−7.03	−9.13	73.60	−6.94	−10.77	74.64	−6.15	−8.97
	0.5	59.61	−10.51	−21.75	59.03	−10.70	−22.24	62.65	−9.21	−19.42	63.19	−5.72	−18.32
	1.5	44.06	−12.40	−29.43	44.26	−12.38	−29.64	53.73	−10.45	−25.04	53.85	−4.66	−23.19
	2.5	37.53	−12.32	−31.48	37.43	−12.10	−31.51	49.91	−10.62	−26.20	48.44	−4.05	−25.22
	3.5	32.29	−11.64	−32.61	33.56	−11.58	−32.12	47.36	−10.96	−27.51	45.99	−3.71	−25.82
Blue-02	0.1	65.07	−9.58	−14.83	61.88	−10.38	−16.76	60.56	−10.48	−17.21	61.33	−9.74	−14.55
	0.5	43.65	−12.36	−22.96	43.62	−12.49	−23.21	44.37	−12.03	−22.51	44.55	−9.62	−19.11
	1.5	28.61	−10.38	−23.27	27.72	−10.29	−23.18	30.81	−11.05	−23.66	29.87	−7.09	−19.37
	2.5	22.74	−7.70	−20.71	22.40	−7.82	−20.88	25.89	−9.52	−22.61	24.35	−5.11	−17.81
	3.5	20.28	−6.25	−19.23	19.31	−5.88	−18.27	23.49	−8.34	−21.30	21.31	−3.88	−16.25
Blue-03	0.1	70.00	−10.33	−18.64	70.24	−10.30	−18.18	65.81	−6.49	−23.86	64.25	−4.47	−23.68
	0.5	49.51	−11.36	−38.10	49.39	−11.97	−37.93	48.75	−5.69	−38.29	52.52	−1.72	−33.13
	1.5	34.68	−7.62	−44.69	34.89	−8.60	−44.22	39.39	−5.98	−42.82	43.10	1.06	−37.52
	2.5	29.20	−6.94	−44.69	29.48	−6.72	−43.95	37.03	−6.17	−43.45	38.89	2.65	−38.71
	3.5	25.54	−3.85	−42.25	24.73	−3.58	−41.97	34.51	−5.88	−44.64	35.79	3.72	−39.06
Blue-04	0.1	81.10	−6.82	−6.16	82.14	−6.30	−5.72	78.81	−7.32	−7.64	77.92	−8.58	−8.00
	0.5	68.05	−12.84	−24.30	68.22	−12.43	−23.52	67.95	−11.82	−21.93	69.08	−9.16	−19.71
	1.5	55.14	−15.02	−36.90	54.15	−15.03	−37.81	59.76	−13.29	−30.94	59.58	−6.91	−30.05
	2.5	47.53	−15.11	−42.88	46.47	−15.08	−43.21	56.10	−13.82	−34.08	54.60	−5.17	−33.89
	3.5	43.10	−15.01	−45.12	45.11	−15.24	−44.09	54.25	−14.04	−36.11	51.08	−4.00	−36.23
Navy-01	0.1	73.43	−5.61	−8.68	72.62	−5.86	−9.11	73.60	−5.40	−8.46	71.12	−6.70	−8.25
	0.5	56.40	−8.33	−17.34	55.02	−8.41	−17.66	56.59	−7.92	−16.40	57.45	−7.25	−14.42
	1.5	41.63	−8.98	−21.08	40.35	−9.02	−21.23	46.90	−8.43	−19.24	45.76	v6.63	−17.00
	2.5	35.16	−8.55	−21.33	33.81	−8.49	−21.54	42.08	−8.53	v20.39	40.83	−6.48	−17.82
	3.5	31.43	−8.01	−21.08	30.04	−7.77	−21.11	39.03	−8.53	−20.93	37.34	−5.98	−18.07
Red-01	0.1	80.48	19.06	2.63	80.91	18.77	2.49	79.61	19.53	2.68	76.32	20.41	−3.06
	0.5	68.19	34.37	0.65	68.23	34.44	0.29	69.44	31.88	−0.04	65.36	32.96	−7.68
	1.5	56.42	45.34	3.32	57.24	44.81	2.87	62.30	38.40	0.34	55.98	41.42	−8.79
	2.5	51.51	48.61	5.66	51.67	48.76	5.72	58.73	41.47	1.45	51.05	45.31	−8.34
	3.5	48.24	49.86	7.65	48.13	50.23	8.05	57.27	42.28	1.72	47.73	47.25	−7.60
Red-02	0.1	80.98	23.02	5.88	80.34	24.97	6.20	78.22	28.05	6.62	72.67	32.35	−0.37
	0.5	71.33	40.31	9.84	70.80	41.58	10.02	69.02	43.50	11.04	62.69	46.67	0.48
	1.5	61.89	53.02	17.97	61.30	54.17	18.81	62.59	51.92	16.73	53.30	57.01	4.79
	2.5	58.13	56.70	22.72	57.65	57.61	23.93	59.46	55.16	20.41	48.99	60.41	8.40
	3.5	55.55	58.56	26.47	55.00	59.11	27.64	58.11	56.05	22.00	46.90	61.70	10.71

Table 8 (continued)

Dyestuff	Conc	DI			DIS			ASW−			ASW+		
	%	L	a	b	L	a	b	L	a	b	L	a	b
Yellow-01	0.1	90.17	5.87	24.41	89.57	6.75	28.21	87.89	8.51	33.00	86.34	3.76	31.45
	0.5	86.69	13.30	46.44	85.99	14.53	50.64	85.40	14.71	48.75	81.76	10.63	48.85
	1.5	81.78	23.15	66.22	80.94	24.72	69.19	82.53	20.59	60.93	76.24	19.21	62.51
	2.5	78.68	28.54	74.12	77.94	30.15	77.59	81.05	22.85	64.45	73.75	23.48	66.86
	3.5	76.78	31.47	77.75	75.59	33.57	81.12	80.11	24.75	68.04	71.66	26.53	70.09
Yellow-02	0.1	90.82	3.39	24.38	90.69	2.94	26.18	89.76	3.88	29.10	88.43	−2.76	33.51
	0.5	89.66	4.92	45.67	89.53	4.80	47.30	88.93	5.60	46.43	86.71	−2.14	49.07
	1.5	88.24	7.81	62.78	87.98	7.88	65.26	87.59	7.83	58.51	84.87	−0.14	60.73
	2.5	86.77	9.72	71.27	87.02	9.53	71.25	87.01	8.61	62.54	84.07	0.96	64.60
	3.5	86.00	10.95	74.39	86.13	10.96	76.02	86.70	9.12	64.62	83.57	1.72	66.37
Yellow-03	0.1	88.42	9.51	37.50	87.76	9.77	37.10	87.89	9.80	35.99	85.53	5.95	34.31
	0.5	84.06	18.51	61.41	84.02	18.86	61.30	84.93	17.09	54.24	80.46	14.54	52.37
	1.5	80.30	27.36	78.56	79.42	27.98	78.86	82.33	22.73	65.94	76.55	21.36	62.68
	2.5	78.03	31.20	84.19	77.76	31.45	83.78	81.28	24.69	68.75	75.17	24.00	66.75
	3.5	76.73	33.20	87.28	76.47	33.56	86.58	80.51	26.05	70.92	73.98	26.16	69.04

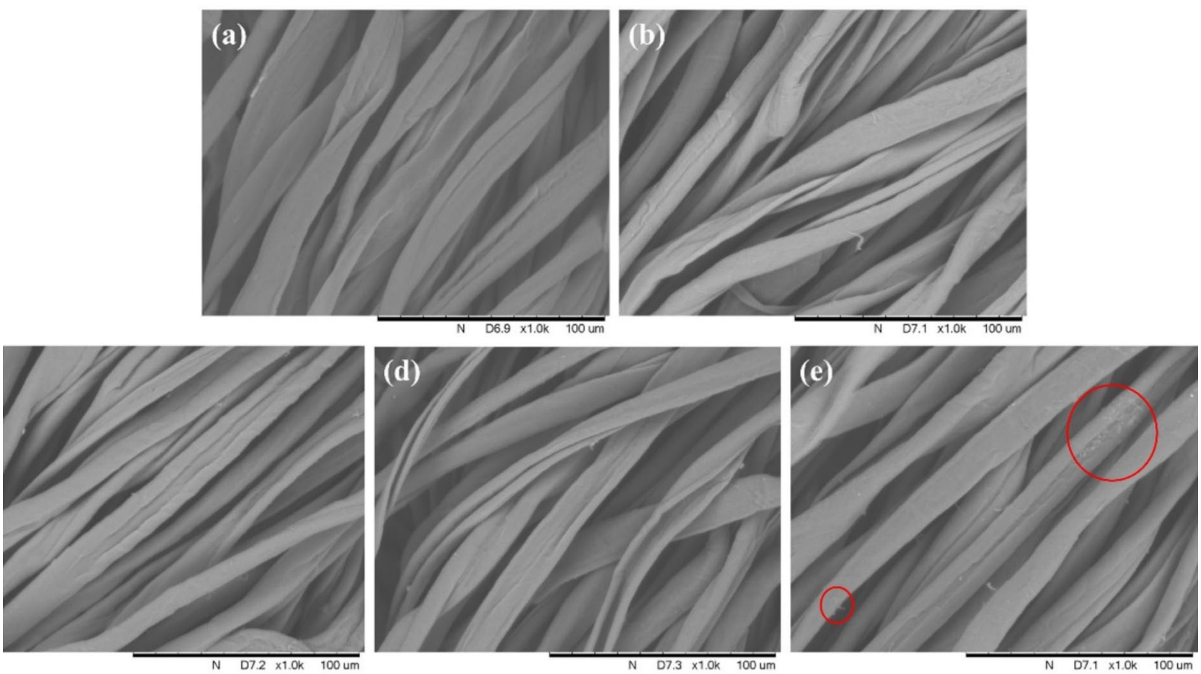


Fig. 3 SEM images of cotton specimens (1000× magnification): **a** undyed; **b** DI dyed; **c** DIS dyed; **d** ASW− dyed; and **e** ASW+ dyed

Table 9 Washing fastness results

Washing fastness of dyed specimens				
Dyes	Conc	Colour change	Colour staining	
	%	Rating	Wool	Cotton
Black-01	0.1	5/5/5/5*	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	5/5/5/5	5/5/5/5	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	5/5/5/5	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4
Blue-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	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	4/4/4/4
Blue-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4
Blue-03	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	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	4/4/4/4
Blue-04	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	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	4/4/4/4
Navy-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	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	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	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4
Red-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	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	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5	4/4/4/4
Red-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	4–5/4–5/4–5/4–5
	1.5	4–5/4–5/4–5/4–5	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	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	4/4/4/4

Table 9 (continued)

Washing fastness of dyed specimens				
Dyes	Conc	Colour change	Colour staining	
	%	Rating	Wool	Cotton
Yellow-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	5/5/5/5	4–5/4–5/4–5/4–5
	2.5	5/5/5/5	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	4–5/4–5/4–5/4–5
Yellow-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	5/5/5/5	5/5/5/5
	2.5	5/5/5/5	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	4–5/4–5/4–5/4–5
Yellow-03	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	4–5/4–5/4–5/4–5	5/5/5/5
	2.5	5/5/5/5	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	4–5/4–5/4–5/4–5

Rating 1: most colour change and staining; Rating 5: least colour change and staining. *Rating indication: DI/DIS/ASW−/ASW+

have generally smooth surfaces without noticeable fibre damage whereas ASW+ dyed cotton specimens have a small fibre damage on the surface and there are some loose and short microfibrils (Fig. 3e) owing to high content of NaCl. Therefore, it can be concluded that DI, DIS and ASW dyeing systems, to a large extent, do not cause significant damage on the surface of the cotton fibre.

Fastness properties

Washing fastness

The colour change and staining results of DI, DIS and ASW (ASW− and ASW+) dyed specimens after washing test are presented in Table 9. Both DI, DIS and ASW dyed specimens show very good to excellent washing fastness against colour change with rating between 4–5 and 5. In case of colour staining, most of the DI, DIS and ASW dyed specimens exhibit good to excellent washing fastness (rating 4–5) against colour staining in case of wool as well as cotton fabric. However, specimens dyed by black, blue-02 and navy-01 reactive dyes have only fair washing fastness (rating 3–4) on cotton since high concentration of reactive dyes has a tendency of higher colour fading when compared with yellow colour of reactive dyes. In short, the washing fastness of both DI, DIS and ASW dyed specimens is commercially acceptable and it validates that the colour measurement of the dyed specimens, to a large extent, is accurate and reliable since the unfixed dye and unwanted chemical auxiliaries are adequately removed after the rinsing process.

Crocking fastness

The colour staining results of DI, DIS and ASW (ASW− and ASW+) dyed specimens after dry and wet crocking are shown in Table 10. Both DI, DIS and ASW dyed specimens have excellent colour fastness (rating 5) against dry crocking. In case of wet crocking, they only obtain fair to excellent colour fastness (rating 3–4 to 5) when black, blue, navy and red reactive dyes are used. Better wet

Table 10 Crocking fastness results

Colour staining of crocked specimens									
Dyes	Conc	DI		DIS		ASW−		ASW+	
	%	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Black-01	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	4/5	5	4/5	5	4–5
	1.5	5	4	5	4	5	4/5	5	4
	2.5	5	3–4	5	3–4	5	4	5	4
	3.5	5	3–4	5	3–4	5	4	5	3–4
Blue-01	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	4–5	5	5	5	5
	1.5	5	4	5	4	5	4/5	5	4–5
	2.5	5	4	5	4	5	4	5	4
	3.5	5	3–4	5	3–4	5	4	5	4
Blue-02	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	4–5	5	4–5	5	4–5
	1.5	5	4	5	4	5	4	5	4
	2.5	5	4	5	4	5	3–4	5	3–4
	3.5	5	3–4	5	3–4	5	3–4	5	3–4
Blue-03	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	4–5	5	5	5	4–5
	1.5	5	4	5	4	5	4	5	4
	2.5	5	3–4	5	3–4	5	3–4	5	4
	3.5	5	3–4	5	3–4	5	3–4	5	3–4
Blue-04	0.1	5	5	5	5	5	5	5	5
	0.5	5	5	5	5	5	5	5	5
	1.5	5	4–5	5	4–5	5	4–5	5	4–5
	2.5	5	4	5	4–5	5	4–5	5	4–5
	3.5	5	4	5	4	5	4–5	5	4–5
Navy-01	0.1	5	5	5	5	5	5	5	5
	0.5	5	5	5	5	5	5	5	5
	1.5	5	4–5	5	4–5	5	4–5	5	4–5
	2.5	5	4–5	5	4	5	4–5	5	4
	3.5	5	4	5	3–4	5	4	5	4
Red-01	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	4–5	5	5	5	5
	1.5	5	4	5	4	5	4–5	5	4–5
	2.5	5	4	5	4	5	4	5	4
	3.5	5	3–4	5	3–4	5	4	5	4
Red-02	0.1	5	5	5	5	5	5	5	5
	0.5	5	5	5	4–5	5	4–5	5	4–5
	1.5	5	4	5	4–5	5	4	5	4
	2.5	5	3–4	5	4	5	3–4	5	3–4
	3.5	5	3–4	5	3–4	5	3–4	5	3–4

Table 10 (continued)

Colour staining of crocked specimens									
Dyes	Conc	DI		DIS		ASW−		ASW+	
	%	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Yellow-01	0.1	5	5	5	5	5	5	5	5
	0.5	5	5	5	5	5	4–5	5	4–5
	1.5	5	4–5	5	4	5	4–5	5	4–5
	2.5	5	4	5	4	5	4	5	4
	3.5	5	4	5	4	5	4	5	4
Yellow-02	0.1	5	5	5	5	5	5	5	5
	0.5	5	5	5	5	5	4–5	5	5
	1.5	5	4–5	5	4–5	5	4–5	5	4–5
	2.5	5	4	5	4–5	5	4–5	5	4–5
	3.5	5	4	5	4–5	5	4–5	5	4–5
Yellow-03	0.1	5	5	5	5	5	5	5	5
	0.5	5	4–5	5	5	5	4–5	5	5
	1.5	5	4–5	5	4–5	5	4–5	5	4–5
	2.5	5	4	5	4	5	4–5	5	4–5
	3.5	5	4	5	4	5	4–5	5	4

Rating 1: most colour staining; Rating 5: least colour staining

crocking results are found when yellow reactive dyes are used in which both reveal good to excellent colour fastness (rating 4–5) against wet crocking. Overall, the crocking fastness of both DI, DIS and ASW dyed specimens is commercially acceptable.

Perspiration fastness

Table 11 shows the perspiration fastness results, including colour change and colour staining against acidic and alkaline perspiration, of DI, DIS, ASW− and ASW+ dyed specimens. Concerning colour change, nearly all the dyed samples in DI, DIS, ASW− and ASW+ medium can achieve excellent fastness results with ratings between 4–5 and 5. Concerning colour staining, most of the DI, DIS, ASW− and ASW+ dyed samples can obtain good to excellent acidic and alkaline perspiration fastness (rating ranged from 4 to 5) while samples dyed with Black-01, Navy-01 and Red-01 receive a fair fastness rating of 3–4, which is commercial acceptable, at high dye concentration of 3.5%. In other words, both DI, DIS, ASW− and ASW+ dyed samples have similar acidic and alkaline perspiration fastness performance while the use of artificial seawater as dyeing medium does not cause adverse effect on the perspiration fastness of the dyed cotton samples.

Tensile properties

Figures 4 and 5 show breaking strength and elongation of undyed, DI dyed, DIS dyed and ASW dyed specimens in warp and weft directions. In warp direction, the dyed specimens (below 400N), including DI, DIS and ASW (ASW− and ASW+), reveal lower breaking strength (N) than undyed specimens (420 N) (Fig. 4a). The reduction of breaking strength is less than 30% (from 15 to 27%), as shown in Fig. 4c. The possible reason is that the dyeing process involves the use of temperature and chemicals which may cause a certain degree of

Table 11 Perspiration fastness results

Perspiration fastness				
Dyes	Conc %	Colour change Rating	Acidic staining Cotton	Alkaline staining Cotton
Black-01	0.1	5/5/5/5*	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	1.5	5/5/5/5	4–5/4–5/4–5/4–5	4/4/4/4
	2.5	4–5/4–5/4–5/4–5	4/4/4/4	3–4/3–4/3–4/3–4
	3.5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4	3–4/3–4/3–4/3–4
Blue-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
Blue-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
Blue-03	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
Blue-04	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
Navy-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4	3–4/3–4/3–4/3–4
Red-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5	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	4–5/4–5/4–5/4–5
	2.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4
	3.5	4–5/4–5/4–5/4–5	3–4/3–4/3–4/3–4	3–4/3–4/3–4/3–4
Red-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	4–5/4–5/4–5/4–5	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	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	4–5/4–5/4–5/4–5
	3.5	4–5/4–5/4–5/4–5	4/4/4/4	4/4/4/4

Table 11 (continued)

Perspiration fastness				
Dyes	Conc	Colour change	Acidic staining	Alkaline staining
	%	Rating	Cotton	Cotton
Yellow-01	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	4–5/4–5/4–5/4–5	4–5/4–5/4–5/4–5
	2.5	5/5/5/5	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	4/4/4/4	4/4/4/4
Yellow-02	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	5/5/5/5	5/5/5/5
	2.5	5/5/5/5	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	4/4/4/4	4/4/4/4
Yellow-03	0.1	5/5/5/5	5/5/5/5	5/5/5/5
	0.5	5/5/5/5	5/5/5/5	5/5/5/5
	1.5	5/5/5/5	5/5/5/5	5/5/5/5
	2.5	5/5/5/5	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	4/4/4/4	4/4/4/4

Rating 1: most colour staining; Rating 5: least colour staining. *Rating indication: DI/DIS/ASW–/ASW+

damage to the fibre, lowering the breaking strength of the fabric (Tang et al. 2023a; Zhang et al. 2021).

In weft direction, both undyed and dyed specimens exhibit lower breaking strength (below 250 N) than in warp direction (Fig. 4b) and the reduction of breaking strength of the dyed specimens is generally lower (less than 7.5%) compared with the undyed specimens (Fig. 4d). Higher breaking strength reduction of the dyed specimens in warp direction may be the result of improper warp yarn tension during processing which may have adversely affected the strength of the dyed cotton specimens (Syed and Jhatial 2013).

Elongation in warp and weft directions (Fig. 5), in both undyed and dyed specimens, is higher in warp (mm and %) than in the weft direction. Overall, dyed specimens display lower elongation (mm and %) than undyed cotton specimens. Warp breaking extension of both undyed and dyed specimens is generally above 15 mm and 20% (Fig. 5a, c) while the weft breaking extension is below 10 mm and 15% (Fig. 5b, d).

ASW+ dyed specimens generally have the lowest breaking strength (N and %) and extension (mm and %) in both warp and weft directions for all types of reactive dyes when compared with DI, DIS and ASW− dyed specimens whereas DI and DIS dyed specimens show the highest breaking strength and extension depending upon the reactive dyes.

Conclusion

The feasibility of using artificial seawater (ASW), prepared according to AATCC Test Method 106, to replace fresh water as the medium for dyeing of cotton fabric with eleven reactive dyes of different reactive groups was investigated in this study. Cotton fabrics were dyed in ASW media with (ASW+) or without (ASW−) addition of NaCl. The dyeing, colourfastness, surface and physical properties of ASW dyed cotton fabrics were examined and compared with those of cotton fabrics dyed in deionised (DI) and distilled (DIS) water media.

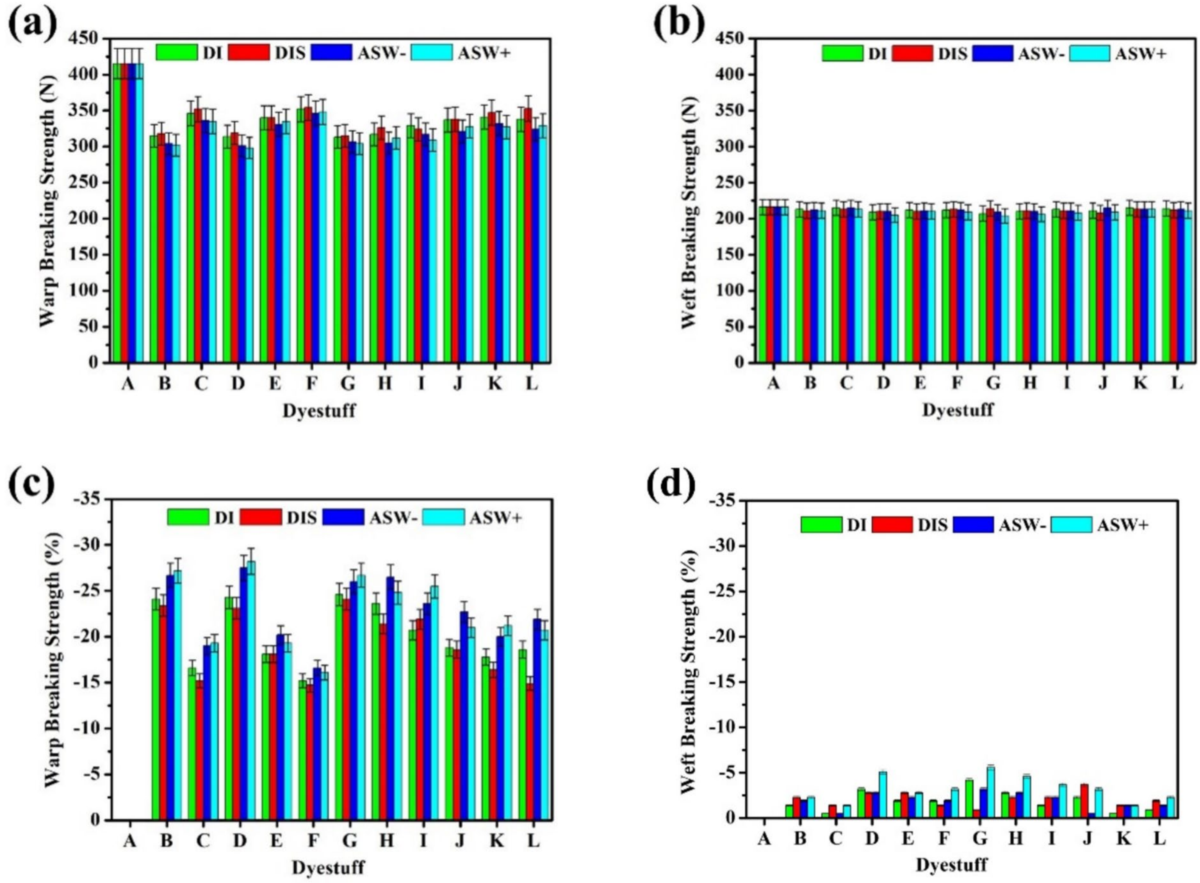


Fig. 4 Breaking strength of the dyed cotton specimens: **a** warp direction (N); **b** weft direction (N); **c** warp direction (%); and **d** warp direction (%). Remark: A = undyed; B = Black-01; C = Blue-01; D = Blue-02; E = Blue-03; F = Blue-04; G = Navy-01; H = Red-01; I = Red-02; J = Yellow-01; K = Yellow-02; and L = Yellow-03. % = percentage decrease in breaking strength of DI, DIS, ASW− and ASW+ dyed samples compared to that of the undyed samples

Although nearly all ASW dyed cotton fabrics obtained lower colour yield than DI and DIS dyed cotton fabric, the findings revealed that triazine-based mono- and bi-functional reactive dyes generally disfavoured cotton dyeing in distilled water and artificial seawater media while FCP-based mono- and bi-functional and DCC-based monofunctional reactive dyes were more favourable to be used for dyeing of cotton fabric in DIS and ASW (ASW− and ASW+) media, resulting in higher colour yield. The pH value and salinity of the dyebath in those four different dyeing media were measured and the findings validated that low colour yield of ASW dyed fabrics may be the result of lower pH value of the dyebath and hard water caused by the presence of magnesium chloride ($MgCl_2$).

Reflectance curves, even though ASW dyed specimens generally had higher reflectance percentage,

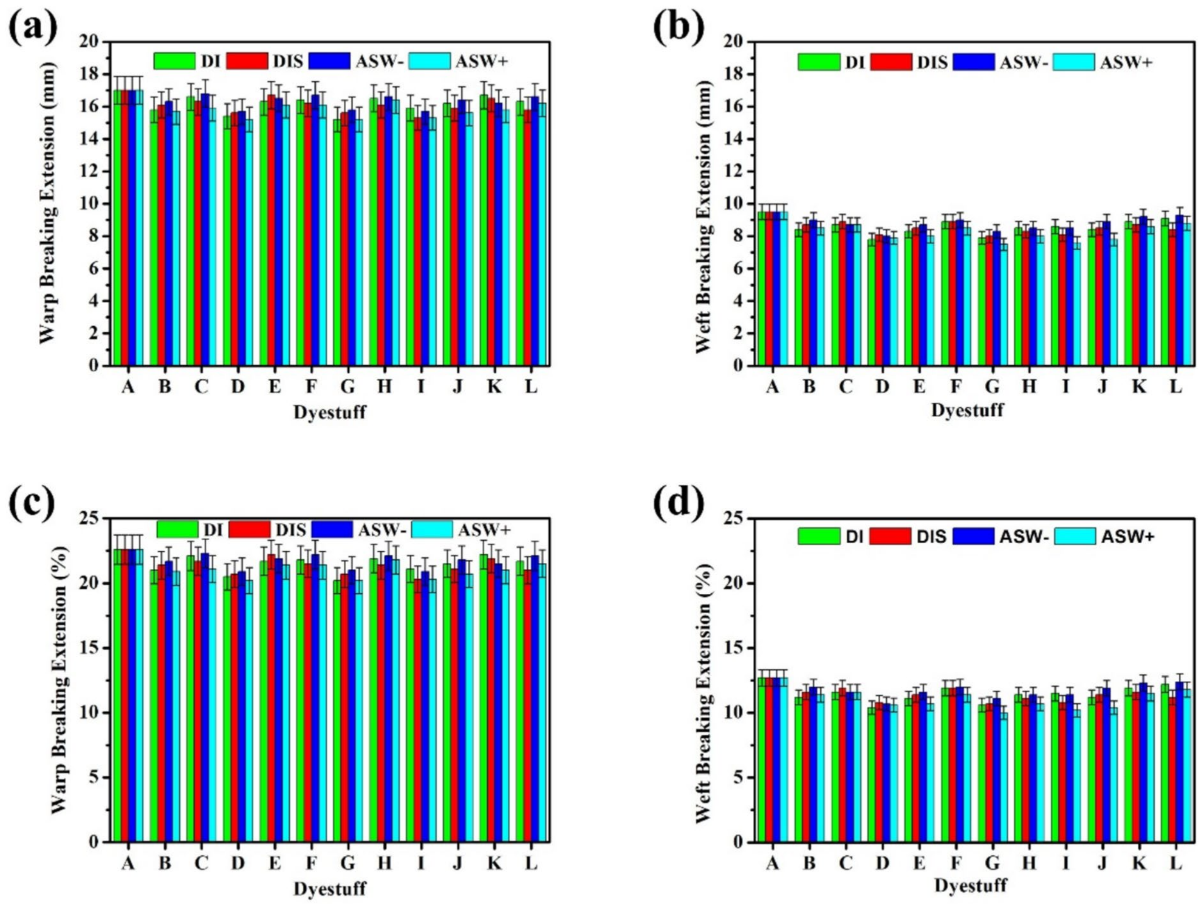


Fig. 5 Breaking extension of the dyed cotton specimens: **a** warp direction (mm); **b** weft direction (mm); **c** warp direction (%); and **d** warp direction (%). Remark: A = undyed; B = Black-01; C = Blue-01; D = Blue-02; E = Blue-03; F = Blue-04; G = Navy-01; H = Red-01; I = Red-02; J = Yellow-01; K = Yellow-02; and L = Yellow-03

were found to be of identical shape, verifying the use of ASW does not alter colour properties of the dyed specimens. Both DI, DIS and ASW dyed specimens reflected good to excellent colour levelness and fair to excellent fastness properties against washing, crocking and perspiration, without any significant fibre damage (SEM images). In addition, those dyed cotton samples exhibited lower breaking strength and extension after the dyeing process when compared with the pristine undyed cotton fabric.

The findings of this work validated that using artificial seawater as medium for dyeing of cotton fabric was feasible. However, hard water owing to the presence of $MgCl_2$, lower alkalinity of the dyebath as well as low salt content for promoting dye exhaustion in salt-free dyeing (ASW−) of cotton fabric were the main obstacles and further studies were needed to address these issues. As industries use significant amount of scarce freshwater, in the form of tap water or ground water containing minerals and impurities of uncertain compositions, for wet processing of textiles, this study provides insight on using alternative medium for cotton dyeing and serves as a benchmark on using real seawater for future sustainable practices.

Acknowledgments This work is funded by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No.: PolyU 15214621) for GRF in 2021/2022 Exercise and from The Hong Kong Polytechnic University (Project code: 1-W19W, R-ZDCC and 1-BBC6).

Author contributions C.W.K.: Conceptualization, Supervision, Resources, Methodology, Validation; Y.L.A.T.: Sample preparation, Investigation, Writing-original draft, Writing-review and editing; C.H.L.: Sample preparation, Investigation, Writing-original draft. All authors have approved the final version of the manuscript.

Funding Open access funding provided by The Hong Kong Polytechnic University.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval This manuscript does not involve human participants or animal studies.

References

Adane T, Adugna AT, Alemayehu E (2021) Textile industry effluent treatment techniques. J Chem 2021:5314404. https://doi.org/10.1155/2021/5314404

Broadbent AD (2001) Water treatment. Basic principles of textile coloration. Society of Dyers and Colorists, Bradford, England, pp 130–151

Chong C, Li S, Yeung K (1992) An objective method for the assessment of levelness of dyed materials. J Soc Dyers Colour 108:528–530. https://doi.org/10.1111/j.1478-4408.1992.tb01405.x

Correia J, Rainert KT, Oliveira FR, de Cássia Siqueira Curto Valle R, Valle JAB (2020) Cationization of cotton fiber: an integrated view of cationic agents, processes variables, properties, market and future prospects. Cellulose 27:8527–8550. https://doi.org/10.1007/s10570-020-03361-w

de Souza Ferreira IL, de Medeiros JI, Steffens F, Oliveira FR (2021) Seawater as an alternative to dye cotton fiber with reactive dyes. Text Res J 91:1184–1193. https://doi.org/10.1177/0040517520972482

Deng Y, Xu M, Zhang Y, Zhou G, Li N, Qiu X (2019) Non-water dyeing process of reactive dyes in two organic solvents with temperature-dependent miscibility. Text Res J 89:3882–3889. https://doi.org/10.1177/0040517518819840

Grancarić AM, Tarbuk A, Sutlović A, Castellano A, Colleoni C, Rosace G, Plutino MR (2021) Enhancement of acid dyestuff salt-free fixation by a cationizing sol-gel based coating for cotton fabric. Colloids Surf A Physicochem Eng Asp 612:125984. https://doi.org/10.1016/j.colsurfa.2020.125984

Karim MR, Islam T, Repon MR, Al Hamim A, Rashid MA, Jalil MA (2021) Exploitation of seawater for cotton and polyester fabrics colouration. Heliyon 7:e07059. https://doi.org/10.1016/j.heliyon.2021.e07059

Khalil E, Sarkar J (2014) Effect of hardness of water on fixation and total wash off percentage of reactive dyes when applied to cellulosic fiber. Int J Sci Res Publ 4:73–76

Khanzada H, Khan MQ, Kayani S (2020) Cotton based clothing. In: Wang H, Memon H (eds) Cotton science and processing technology: gene. Ginning, Garment and Green Recycling, Springer, Singapore, pp 377–391. https://doi.org/10.1007/978-981-15-9169-3_15

Liu L, Mu B, Li W, Yang Y (2019) Semistable emulsion system based on spent cooking oil for pilot-scale reactive dyeing with minimal discharges. ACS Sustain Chem Eng 7:13698–13707. https://doi.org/10.1021/acssuschemeng.9b01003

Ludwig H (2022) Seawater: composition and properties. In: Reverse osmosis seawater desalination volume 1: planning, process design and engineering—a manual for study and practice, Springer International Publishing, Cham, pp 73–203 https://doi.org/10.1007/978-3-030-81931-6_3

Musie W, Gonfa G (2023) Fresh water resource, scarcity, water salinity challenges and possible remedies: a review. Heliyon 9:e18685. https://doi.org/10.1016/j.heliyon.2023.e18685

Pruś S, Kulpiński P, Matyjas-Zgondek E, Wojciechowski K (2022) Eco-friendly dyeing of cationised cotton with reactive dyes: mechanism of bonding reactive dyes with CHPTAC cationised cellulose. Cellulose 29:4167–4182. https://doi.org/10.1007/s10570-022-04521-w

Raja A, Arputharaj A, Senthilkumar T, Saxena S, Patil P (2020) Dyeing of cotton with reactive dyes using pre-treated sea water. Indian J Fibre Text Res 45:319–325

Singha K, Pandit P, Maity S, Sharma SR (2021) Harmful environmental effects for textile chemical dyeing practice. In: Ibrahim N, Hussain CM (eds) Green chemistry for sustainable textiles. Woodhead Publishing, pp 153–164. https://doi.org/10.1016/B978-0-323-85204-3.00005-1

Solaiman M, Surid S, Patwary M, Rahman M, Sinha P, Hossain M, Rahman M (2019) Dyeing of cotton fabric with ground water and sea water: comparison of their fastness properties. J Text Eng Fash Technol 5(276):282. https://doi.org/10.15406/jteft.2019.05.00213

Song Y, Meng Y, Huo K, Wang ZQ, Li Y, Yu M, Zhang B, Li J (2024) Greenly and efficiently dyeing cotton fabric with custom-tailored reactive dyes via electron beam irradiation. ACS Sustain Chem Eng 12:3121–3129. https://doi.org/10.1021/acssuschemeng.3c07075

Syed U, Jhatial RA (2013) Influence of warp yarn tension on cotton greige and dyed woven fabric prosperities. Mehran Univ Res J Eng Technol 32:133–140

Tang AYL, Kan CW (2020) Non-aqueous dyeing of cotton fibre with reactive dyes: a review. Color Technol 136:214–223. https://doi.org/10.1111/cote.12459

Tang AYL, Lee CH, Wang YM, Kan CW (2019a) Reverse micellar dyeing of cotton fiber with reactive dyes: a study of the effect of water pH and hardness. ACS Omega 4:11808–11814. https://doi.org/10.1021/acsomega.9b00597

Tang AYL, Lee CH, Wang YM, Kan CW (2019b) A study of PEG-based reverse micellar dyeing of cotton fabric: reactive dyes with different reactive groups. Cellulose 26:4159–4173. https://doi.org/10.1007/s10570-019-02340-0

Tang YLA, Jin S, Lee CH, Law HS, Yu J, Wang Y, Kan CW (2023a) Reverse micellar dyeing of cotton fabric with reactive dye using biodegradable non-ionic surfactant as nanoscale carrier: an optimisation study by one-factor-at-one-time approach. Polymers 15:4175. https://doi.org/10.3390/polym15204175

Tang YLA, Lee CH, Wang Y, Kan CW (2023b) Effect of solvent dyeing medium on dye encapsulation and non-aqueous dyeing of cotton fabric with rhamnolipid (RL) microbial biosurfactant-based reactive dye encapsulated reverse micelles. Fibers Polym 24:4323–4335. https://doi.org/10.1007/s12221-023-00371-w

Zerin I, Foisal A, Datta E, Rana MS (2017) Dyeing of cotton fabric with ground water and seawater. IOSR J Polym Text Eng 4:32–35. https://doi.org/10.9790/019X-04053235

Zhang M, Zhang Y, Liu Y, Ren X, Huang TS (2021) Simultaneous low-salt dyeing and anti-bacterial finishing of cotton fabric with reactive dye and N-halamine. Color Technol 137:475–483. https://doi.org/10.1111/cote.12542

Zhao J, Agaba A, Sui X, Mao Z, Xu H, Zhong Y, Zhang L, Wang B (2018) A heterogeneous binary solvent system for recyclable reactive dyeing of cotton fabrics. Cellulose 25:7381–7392. https://doi.org/10.1007/s10570-018-2069-8