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Development of High-Performance Non-Foaming Cationic Soap-Washing Agent through the Copolymerization of N-Vinylpyrrolidone with 2-(Dimethyalamino) Ethyl Methacrylate for Wash-off Reactive Dyed Cotton Fabric

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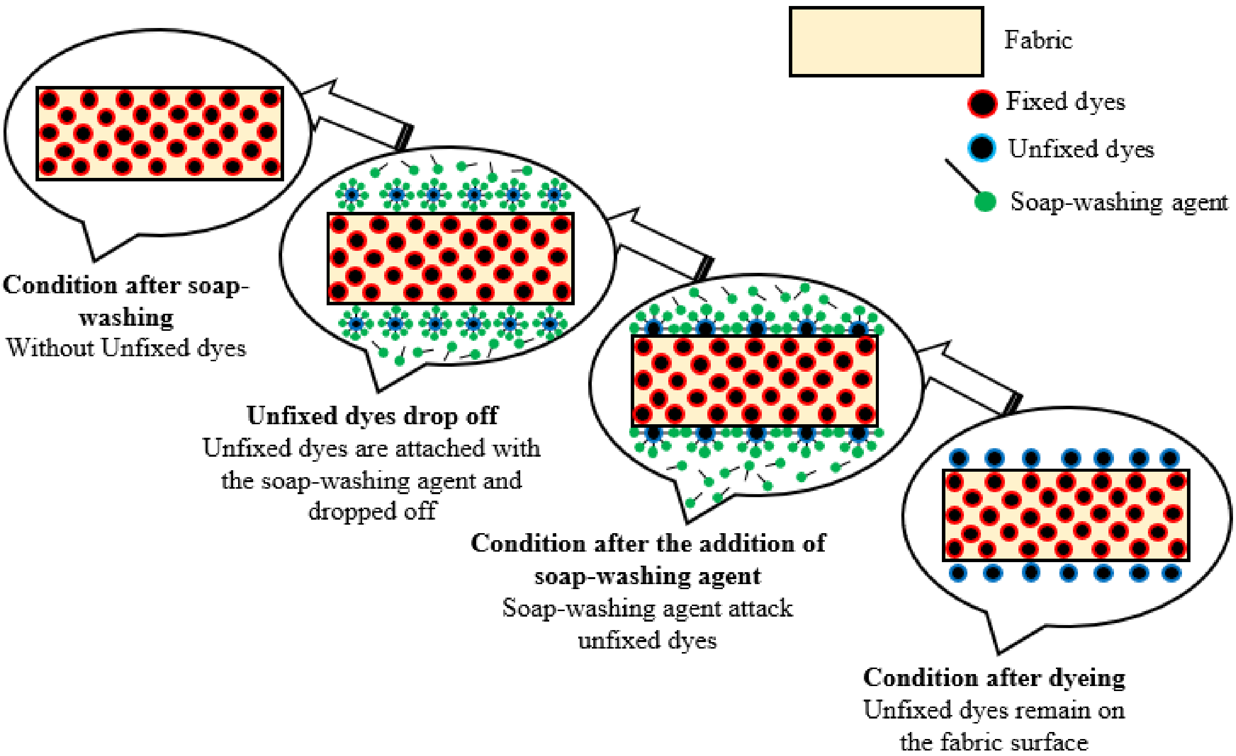
GRAPHICAL ABSTRACT



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ABSTRACT

Reactive dyes are generally used for the coloration of cotton fabric. However, hydrolyzed/unfixed dyes are generated and fail to react with fibers, which are responsible for decreasing the colorfastness and creating undesirable color migration among fabrics during washing. So, after dyeing is finished, an effective wash should be carried out to remove additional and unfixed dyes with an effective soap-washing agent. Thus, the soap-washing agent plays a significant role during wash-off and also can avoid undesirable effects such as colorfastness, shade variation, stains, etc. Hence, in this article, a series of cationic soap-washing agents were prepared by copolymerizing N-vinylpyrrolidone with DMAEMA, and the

working efficiencies were evaluated. All the samples were washed using different soap-washing agents for 30 minutes under 90℃ temperatures. It was found that the pH factor greatly influences the unfixed dye removal efficiencies in washing liquors and the concentration of the soap-washing agent. The best washing result for removing unfixed dyes was obtained for V/D5/SDS2 soap-washing agent for 1g/L at pH 7 in liquors. The soap-washing agent effectively removes unfixed dye and can prevent color migration among fabrics during wash-off. The characteristics were analyzed by Data color650 spectrophotometer, UV-visible spectrophotometer, Dry and wet rubbing fastness, and Fourier Transform Infrared Spectroscopy (FTIR).
Keywords: Reactive dye, Soap-washing agent, Unfixed dye, Color strength(k/s), Residual dye molecules.

I. INTRODUCTION

Nowadays, reactive dyes and cotton fabric have always had a significant place in the textile dyeing and printing industries. In the last few decades, the popularity and demands of reactive dyes have increased rapidly because of their brilliant color, excellent color fastness, facile application, and comparatively low cost [1]. Reactive dyes contain anionic sulfonate ions (SO_3^-) that can be adsorbed by positively charged adsorbents [2] and have the ability to react chemically with fiber to create covalent bond generation between fiber and dye molecules via nucleophilic substations either Michel addition reactions based on the characteristics of the reactive group that are present in dye molecules [3]. The reactive dye molecules continually tend to be hydrolyzed during the reactive dyeing process. After dyeing is completed, the unfixed reactive dye molecules (mainly hydrolyzed and unreacted dye molecules) remain on the inner and exterior surface of the fabric[4]. If those unfixed dyes are not removed properly, it will affect the color and washes fastness and create stains on the fabric, which is not desirable. Hence, after reactive dyeing, an effective soap-washing is badly required to remove unfixed dyes in terms of excellent washing performance [5]. However, for effective washing various chemicals such enzymes, surfactants, cationic fixing agents, anionic, non-ionic detergents, and washing agents are used after reactive dyeing [6–9]. However, the electrolyte effect of the anionic washing agent used to remove unfixed dye molecules is seriously responsible for declining the wet fastness property and is not suitable for washing [10,11]. Conventionally, to obtain excellent colorfastness properties, after dyeing is finished, the unfixed dye substance is neutralized throughout the multiple washing and soaping process for removing those unfixed dyes as much as possible, which is also a time-consuming, energy-consuming, and costly process. Generally, dye-fixing treatment prevents the unfixed dye molecules from attaching to the fabric and avoids undesirable effects [12,13].

In recent years, it is also found that polymers are mostly used for the washing process. The polymer-dye binding formation conducted throughout the interaction between polymer and dye demonstrated many attractive, interesting and significant practical characteristics. Some special factors such as hydrophobic, Coulombic, and steric connections are mainly responsible for thermochemical and dynamic complex formation [14]. Poly(vinylpyrrolidone), PVP is a highly water-soluble non-ionic, non-toxic, chemically stable polymer that can complex hydrophilic and hydrophobic substances. Because of those outstanding characteristics, PVP has an extensive range of applications, such as the removal of hydrolyzed dyes, dye transfer inhibitors, binders, soaps, and detergents in the textile industry [3,15]. 2-(dimethylamino) ethyl methacrylate, DMAEMA is a water-soluble, pH-sensitive, highly cationic monomer that can form complexation through electrostatic interactions as containing amine functional group and is also considered as absorbents for anionic dyes[16]. Sodium dodecyl sulfate (SDS) is an anionic surfactant with solubility in water as it contains a highly polar hydrophilic head group and mostly works as detergents and cleaning substances. It has a high ability to interact with a polymer molecule to create a self-assembled structure due to its attractive force of the hydrophobic affiliation and electrostatic repulsion and also reduces the hydrophobicity of polymer particles which help to stabilize the charge in the suspension [17].

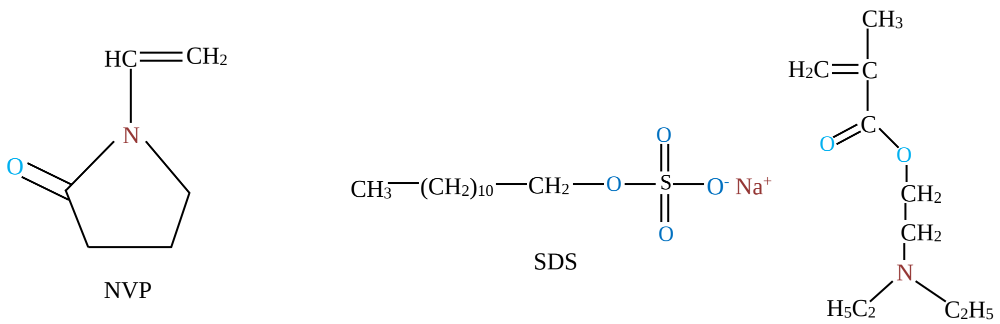

Figure 1: Different Chemicals Structure.

II. EXPERIMENTAL METHODS AND MATERIALS

2.1 Experimental Drugs

In this article, Pure cotton fabric was supplied by Zhejiang Kefeng Silicone Co., Ltd. and applied without any treatment. N-Vinylpyrrolidone (NVP), 2-(Dimethyalamino) Ethyl Methacrylate (DMAEMA), Sodium dodecyl sulfate (SDS), Hydrogen peroxide (25% H_2O_2), 2,2'-Azobis(2-amidinopropane) dihydrochloride (AIBA), Hydrochloric acid (HCL), Sodium Hydroxide (NaOH), Ammonia solution (NH_3. H_2O), the above are all pure analytical chemicals were supplied by Hangzhou Gaojing Fine Chemical Industry Co., Ltd and was used directly without any furthermore purification.

2.2 Method of Reactive dyeing with cotton

Reactive dyes are converted into new compounds through chemical modification and are widely used for cotton fabric dyeing in textile industries. In this article, medium dye concentration (3% owf) was chosen for cotton fabric dyeing with reactive dyes. Generally, two different essential stages are followed for the reactive dyeing process. In the first stage, the dye adsorbs onto the cellulosic substrate through the formation of hydrogen bonding and van der Waals interactions, and in aqueous NaCl or Na_2SO_4 is used as the electrolyte to assist the exhaustion of dyes. In the second stage, alkali is added to the solution to produce many cellulosic anions within the substrate for covalent bond formation between dye and fiber. Thus, the reactive functional group of dye and -OH or -NH_2 functional group of fiber build a strong covalent bond[3]. Fig.2 shows the dyeing mechanism of reactive dye on cotton fabric.

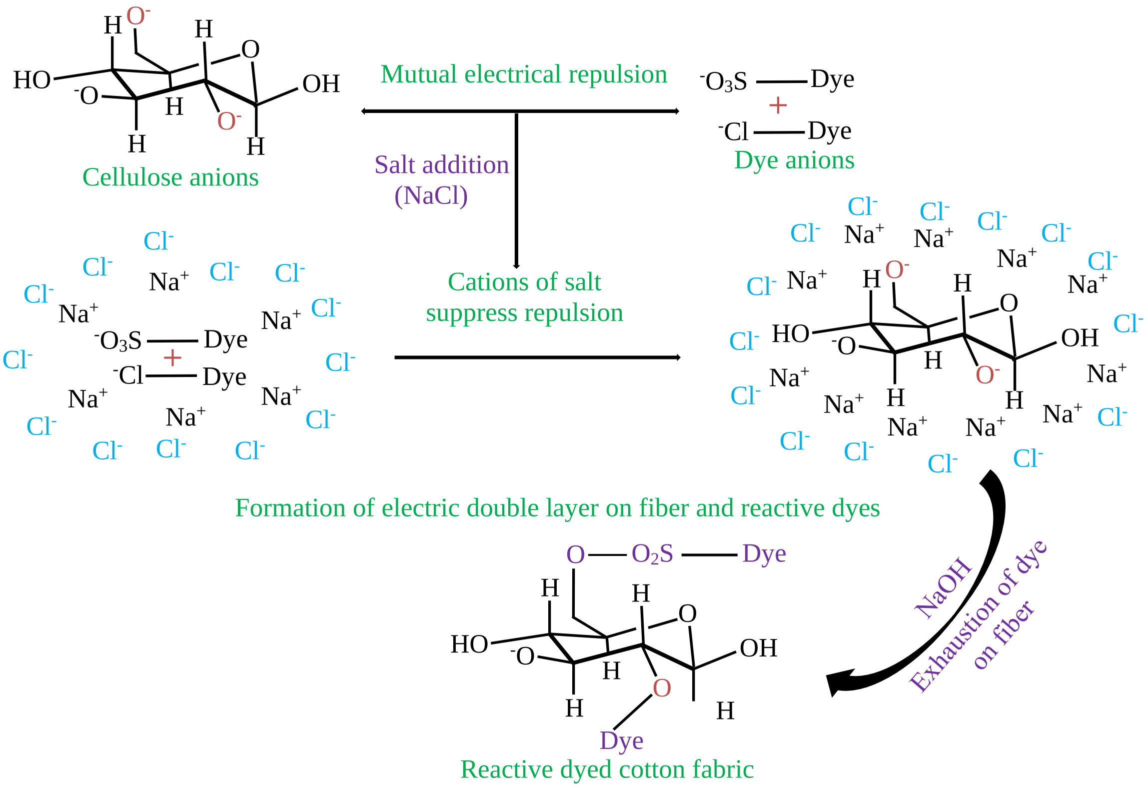

Figure 2 : Reactive dyeing mechanism with cotton fabric.

2.3 Soap-washing agent's preparation

2.3.1 Synthesis of Copolymers P(VP-co-DMAEMA)

The copolymerization of NVP with DMAEMA (VP-co-DMAEMA) was done in an aqueous solution. During the copolymerization process, hydrogen peroxide (H_2O_2), AIBA (V50) were used as initiators, and the weight of H_2O_2 was 1.14g (3% of 38g) for all the soap-washing agents. The H_2O_2 initiator was added to the solution for different soap-washing agents while the temperature was around 72℃. For the V/D10 soap-washing agent, two dosages of the AIBA initiator were used, and the first dosage was added 2 hours later from H_2O_2 added time, and the second dosage was added 3 hours later from the first dosage. The weight of AIBA was about 0.038g (0.1% of 38g) and 0.076g (0.2% of 38g) respectively. For the V/D8, V/D5, and V/D2 soap-washing agents, the weight of the AIBA initiator was 0.038g (0.1% of 38g). To control the positivity of the soap-washing agent, an anionic surfactant SDS was added with V/D5 soap-washing agent, and the weight was measured according to the total weight of the monomer (38g).

2.3.2 Recipes and Reaction conditions for Soap-washing agents

Theoretically, it is known to all that the soap-washing agents should be soluble in water, and the NVP monomer contains a hydrophilic part that is highly soluble in water. As cotton fabric contains anionic charges on its surface and effective unfixed dyes removal efficiency, the efficient soap-washing agents should be cationic. Hence, to develop a cationic soap-washing agent, DMAEMA monomer was selected that is highly cationic and also soluble in water, and to control the positivity of soap-washing agents, an anionic surfactant SDS was added that is not only capable of controlling the positivity but also increase the unfixed dyes removal efficiency as well. That is the reason herein below Table 1 We listed the chemicals.

Table 1: Recipes and Conditions for soap-washing agents

Soap-washing agents	Soap-washing agent's recipes			Reaction conditions		Solid content (%)	Monomer conversion (%)
	VP(g)	DMAEMA(g)	SDS (g)	Temp (°C)	Time (h)		
V/D10	34.2	3.8	-	75˜80	8˜10	36	94
V/D8	34.96	3.04	-	75˜80	8˜10	38	100
V/D5	36.1	1.9	-	75˜80	8˜10	38	100
V/D2	37.24	0.76	-	75˜80	8˜10	37	97
V/D5/SDS1	36.1	1.9	0.38	75˜80	8˜10	38	100
V/D5/SDS2	36.1	1.9	0.76	75˜80	8˜10	38	100
V/D5/SDS3	36.1	1.9	1.14	75˜80	8˜10	37	97
V/D5/SDS5	36.1	1.9	1.9	75˜80	8˜10	36	94

2.3.3 The Appearance of Soap-washing agents and Factors affecting color

The nitrogen atom in the monomer greatly influences the color appearance of soap-washing agents as DMAEMA contains higher nitrogen atoms in its structure. The higher dosages of DMAEMA lead to a darker color. Also, it was found that the higher dosages of ammonia ($NH_3.H_2O$) solution and rapid increase of temperature slightly affect the color of prepared soap-washing agents. It was found that the different colors of soap-washing agents do not significantly influence the removal of unfixed dyes during the wash-off process. So, the different color of soap-washing agents was not a vital issue for removing unfixed dyes. Fig.3 shows the appearances of different soap-washing agents.

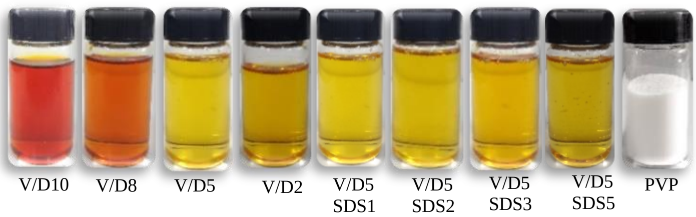

Figure 3: The color appearance of different soap-washing agents.

2.4 Characteristics analysis

2.4.1 Color Migration analysis

The color strength (K/S) of the washed fabric is calculated by using data color650 spectrophotometer from the Kubelka-Munk equation as given below (Eq. I). where the absorption coefficient of the substrate is K, S is determining the scattering coefficient of the substrate, and R is the reflectance of the dyed fabric at λ_{max}. After folding each fabric twice, measurements were taken at three different positions on the fabric surface [18].

$$K/S = \frac{(1-R)^2}{2R} \ldots\ldots\ldots\ldots\ldots (I)$$

2.4.2 Rubbing Fastness analysis

This process examines the amount of color shifted from one surface to another surface during rubbing. Using the AATCC crock meter, the test is performed according to the AATCC testing procedure. The test specimen was graded using a visual greyscale for both dry and wet rubbing fastness, and the grades of rubbing fastness are mentioned as 5, excellent; 4, good; 3, fair; 2, poor; and 1, extremely poor. To investigate the dry and wet rubbing, White samples are cut into (5cm x 5cm) square shape and rubbed approximately 20 times in 10 seconds while the finger of the tester carrying a weight of 2-6 N with the contact of the test sample. A separate sample is used for the dry and weight rubbing test. The wet rubbing test was done by using a wet sample that water content is up to 95% to 105%. All the tests are conducted under the atmospheric conditions of 20 ±1°C and 65± 5% RH [19].

2.4.3 Residual Dye Concentration in washing liquors

After washing is completed, Dye concentration in washing liquors is measured by using a UV-visible spectrophotometer (UV mini-1240) according to the "Beer-Lambert" law shown in equation II, and it is known to all that the absorbance is directly proportional to the concentration of dye in solution [20].

$$A = \varepsilon cl \ldots\ldots\ldots\ldots\ldots \text{(II)}$$

Where A indicates the absorbance, c determines the concentration mol$^{-1,}$ and l is pathlength in cm and molar extinction coefficient.

2.4.4 Fourier-Transform Infrared Spectroscopy (FTIR)

According to the standard method, the Nicolet 5700 Fourier Transform Infrared Spectrometer (American Thermoelectric Company) was used for Fourier Transform Infrared Spectroscopy analysis.

III. RESULTS AND DISCUSSION

3.1 Color migration and Colorfastness analysis (PVP vs Water)

At the end of the dyeing, the unfixed dyes existed mainly inner and on the surface of the cotton fiber via Van Der Waals force between dye and fiber or between dye and dye [1]. In the initial stage, the dyed fabric was washed with PVP for 1g/L and with water to analyze the unfixed dyes removal efficiency, and the results are shown in Fig.4.

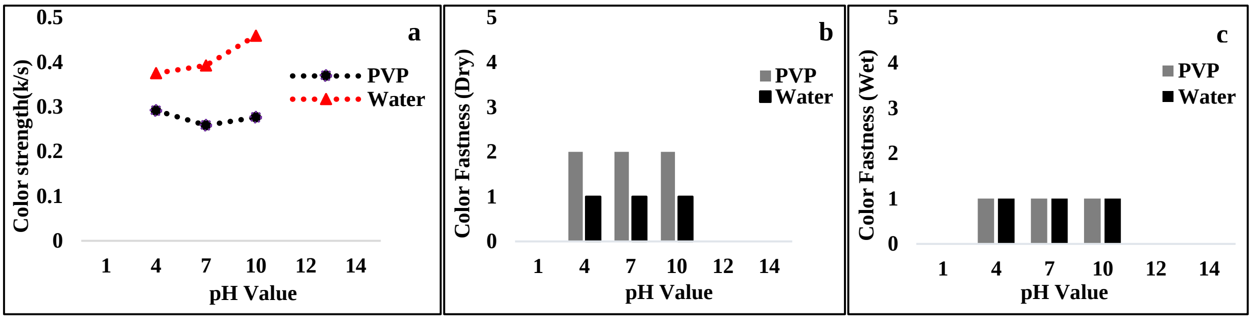

Figure 4: a) Color strength (k/s) of washed fabric (PVP vs Water), b) dry, and c) wet Colorfastness properties of the dyed fabric after washing (PVP vs Water).

From Fig. 4(a), the unfixed dye removal efficiency for PVP was higher than after being washed with water. After washing, both the dry and wet colorfastness were analyzed, and the results are shown in Fig.4(b, c). From the results, It can be seen that both the dry and wet color fastness was much better than water washed. From Fig.4 results, though PVP has higher free dyes removal efficiency than water, the overall results were not satisfactory at all. Because PVP is a non-ionic polymer, it is highly soluble in water and while the cotton fabric contains anionic charge [15]. During wash-off, polymer dye complexation cannot occur through electrostatic attraction because of the non-ionic nature of PVP in washing liquors. As a result, dye molecules have a high affinity to stay in the water and tend to be attached to new fabrics, which creates stains and causes poor colorfastness. Residual dye concentration in washing liquors after washing was also compared and measured by following the standard calibration curve (**Fig.S, Supplementary information**). The results are presented in Fig.S1 (**supplementary information**). It can be seen that higher dye molecules remain in the water after being washed with only water than washed with PVP. So, from the results, it can be said that PVP is not suitable for removing unfixed dyes from reactive dyed cotton fabric.

3.2 A series of NVP/DMAEMA Soap-washing agents

It was found that the copolymers of DMAEMA and N-Vinyl pyrrolidone can bind with anionic dye through electrostatic interaction and the binding capacity is mainly dependent on the hydrophobic binding sites in polymer and also produce a flexible binding environment with ionic and a polar characteristic [21]. Hence, a series of soap-washing agents were prepared through the copolymerization of NVP with DMAEMA and applied for soap-washing both for 0.5g/L and 1g/L. After washing with different soap-washing agents, the results are shown in Fig.5. It was also found that the increase of DMAEMA dosages in soap-washing agents leads to higher color strength (k/s) at low pH also indicates lower unfixed dyes removal. Theoretically, it is known to all the color strength(k/s) of the washed fabrics should be decreased with the increase of unfixed dyes removal [22]. From Fig.5(a, b) results, it can be seen that the pH value in washing liquors greatly influences the unfixed dyes removal efficiency, and the concentration of soap-washing agents does not have any significant influences. Among different ratios of NVP and DMAEMA, the most effective one was V/D5 soap-washing agent that can be seen from Fig.5 according to the color strength(k/s) results. Though the concentration of the soap-washing agent does not have any significant influences, the dry and wet rubbing color fastness V/D5 soap-washing agent was mostly suitable for 1g/L for wash-off reactive dyed cotton fabric. As DMAEMA is highly positive, it is easily affected by the pH in washing liquor. So, the efficiency of the soap-washing process was related to the pH in liquors that greatly influences the removal of unfixed dyes [23]. The reactive dyed cotton fabric can not wash at low pH as the dyeing process is done in alkaline conditions. So, washing the dyed fabric at low pH is expensive because it needs acid in washing liquors. We have shown the results for different pH in liquors to analyze the effect of pH on removing unfixed dyes during washing, and the best result was obtained at pH 10 in washing liquors.

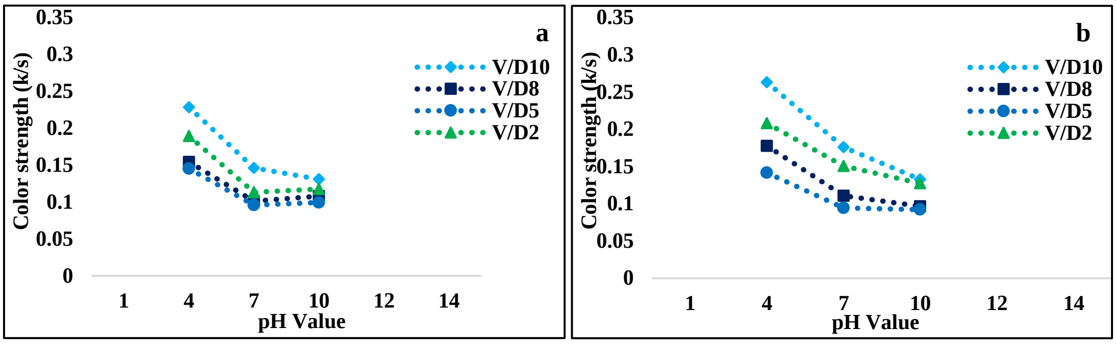

Figure 5: Color strength (k/s) of washed fabric both for a) 0.5g/L and b) 1g/L.

The results attributes may be the synergic effect of carbonyl (C=O), amino ($-NH_2$), and hydroxyl (-OH) functional groups present in the soap-washing agents. Soap-washing agents strongly interact with the released dyes via electrostatic, dipolar, hydrogen bonding, etc. This indicates that the soap-washing agent can form a polyelectrolyte complex with the released dyes and re-stay on the substrate[24]. So, after analyzing the color strength(k/s) and residual dye concentration in washing liquor, it can be said that among different soap-washing agents V/D5 was most effective for the removal of unfixed at pH 10 in washing liquor for 1g/L. From Fig.S2 (**supplementary information**), it can also be seen that during washing with VP/DMAEMA soap-washing agents, dye molecules have a high affinity to stay in the water, which also indicate the high positivity of DMAEMA and if we can control the high positivity of soap-washing agent better result can be achieved in terms of unfixed dyes removal efficiency as well as both the dry and wet colorfastness properties.

3.3 Color migration and Colorfastness analysis (PVP vs V/D5)

It is suggested that the binding strength between dye and polymer mainly depends on two important factors, an increase in the cationic binding sites available for dye-binding due to the protonation of dimethyl aminoethyl residues of the polymer at lower pH and an increase in the hydrophobic domains of the polymer due to the deprotonation of the residues at higher pH in washing liquors. Hydrogen bond and van der Waals binding forces should be almost independent of pH in liquors. At lower pH, the electrostatic force between the cationic center of the polymer and the negatively charged sulfonate group of reactive dye plays a predominant role in the binding. The electrostatic attraction should decrease with the increase of pH and the reduction of electrostatic attraction between the protonated nitrogen atom and the sulfonate ion. The onset of hydrophobic attraction between the hydrophobic moieties of the two binding entities leads to the maximal binding around pH 10 [21]. We also compare the unfixed dyes removal efficiency and dry, wet colorfastness with V/D5 and PVP after washing. According to the color strength (k/s) results from Fig.6(a), it can be seen that V/D5 soap-washing agent was much more effective for removing unfixed dyes through the wash-off and also showed good dry colorfastness after being washed at pH 10 through the wet color fastness is not quite satisfied that can be seen from below Fig.6(b, c). Poor wet colorfastness may be due to the high dye molecules that remain in the water during washing and have the affinity to stay in water because of the high positivity of DMAEMA, which causes poor colorfastness. The residual dye concentration in washing liquors after washing was also measured, and the results are shown in Fig.S3 (**supplementary information**).

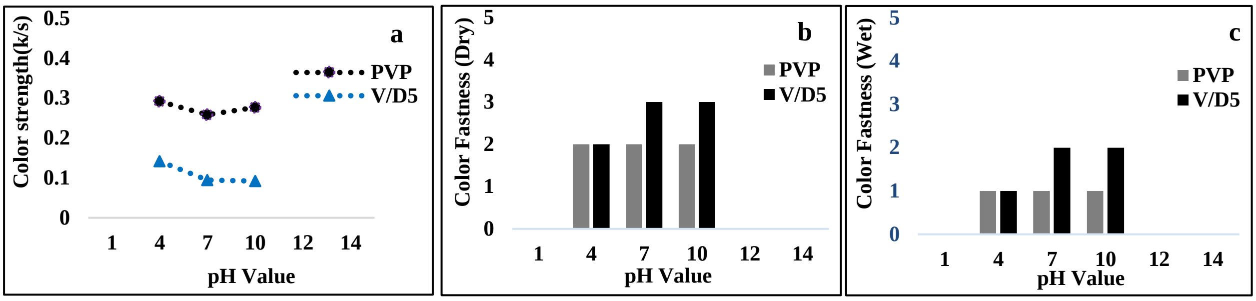

Figure 6: a) Color strength(k/s) of the washed fabric (PVP vs V/D5), b) dry, and c) wet color fastness comparison between PVP vs V/D5.

As it is known to all, DMAEMA is a water-soluble cationic monomer containing both the hydrophobic and hydrophilic function groups and also has a high affinity to water. On the other hand, dye molecules have an affinity both for water and fabric and mostly attract to the water due to the polarity. During washing with DMAEMA containing soap-washing agents, polymer dye complexation occurs between unfixed dyes and soap-washing agents. It has a high affinity to water because of the highly hydrophilic polar head group of DMAEMA. As a result, high dye molecules remain washing liquors and can attach those unfixed dyes to the new fabric, which causes undesirable effects. From Fig.5, it can also be seen that the higher dosages of DMAEMA lead to higher color strength(k/s) and causes poor colorfastness. After the above discussion, it can be said DMAEMA is a highly cationic monomer, and the positivity should be well controlled to get the best-unfixed dyes removal efficiency through wash-off of reactive dyed cotton fabric.

3.4 A series of Soap-washing agents with different SDS concentration

As DMAEMA is a highly cationic monomer, The developed soap-washing agent also has high positivity. Hence, an anionic surfactant SDS has been incorporated with V/D5 soap-washing agent to decrease the positivity of the soap-washing agent. Sodium dodecyl sulfate (SDS) is an anionic surfactant consisting of a tail of 12 carbon atoms attached to a sulfate group (SO_4^{2-}), and its hydrocarbon tail combined with a polar head group provide the amphiphilic compound properties[25]. As a result, the hydrocarbon tail and anionic head group of SDS can create micelles because of its amphiphilic characteristics that can act as a detergent. This is why we incorporated SDS to decrease the positivity. After adding SDS, the unfixed dye removal efficiencies were measured through color strength (k/s) and the results are shown in Fig.7 for 0.5g/L and 1g/L soap-washing agent. It was also found that after SDS of addition increase dyes molecules affinity towards fabric through electrostatic attraction that helps to re-stay on the fabric during wash-off resulting in lower residual dye molecules in liquors (**Fig.S4 supplementary information**).

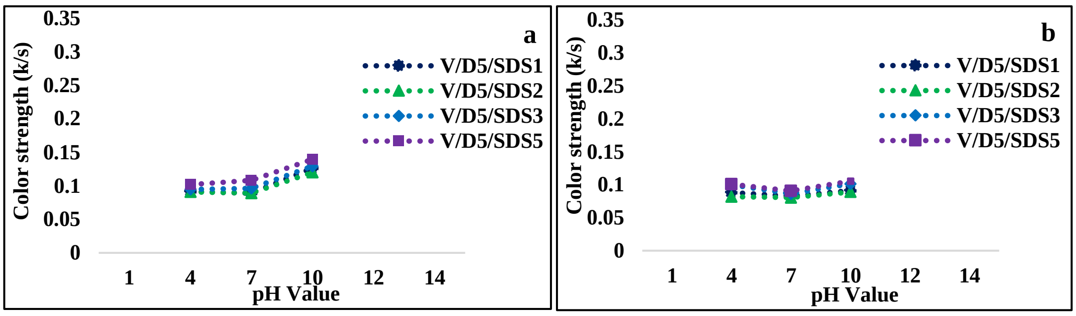

Figure 7: Color strength (k/s) of washed fabric both for a) 0.5g/L and b) 1g/L.

This indicates that the SDS surfactant can control the positivity of soap-washing agents. From Fig.7(a), it can be seen that the pH still influenced unfixed dyes removal efficiency. From Fig.7(b), it can be seen that the free dyes removal capability was relatively dependent on the pH in washing liquors. However, the concentration of soap-washing agents significantly influences the dyes removal efficiency. All most similar results were obtained at pH 7 and 10 in washing liquors for 1g/L for V/D5/SDS2 soap-washing agent. So, the soap-washing process can be performed in a neutral environment in washing liquors to avoid any difficulties. The unfixed dyes removal efficiency is quite satisfactory at pH 7 can be seen from Fig.7(b). It can be concluded from the above discussion that the developed V/D5/SDS2 soap-washing agent unfixed dye removal effectiveness is not only influenced by the concentration but also the carbonyl, amino, and hydroxyl groups enhance the unfixed dyes removal efficiencies. So, for an effective soap-washing agent, the chemical composition should be appropriate depending upon the characteristics of the functional group that presents in the chemical. After finding that the V/D5/SDS2 soap-washing has excellent unfixed dyes removal ability, we also measured residual dye concentration in washing liquors and shown in Fig.S4 (**supplementary information**). It was found that both the dry and wet color fastness was outstanding and quite satisfactory after being washed with V/D5/SDS2 soap-washing agent.

3.5 Color migration and Colorfastness analysis (V/D5 vs V/D5/SDS2)

Commercially, DMAEMA is a cheap cationic monomer with lower production costs. However, the unfixed dyes removal ability was good for V/D5 soap-washing agent but had poor colorfastness, which was not desirable. Nevertheless, after adding anionic surfactant SDS with V/D5, the soap-washing agent shows excellent free dyes removal efficiency and outstanding colorfastness, and the results are shown below Fig.8. From Fig.8(a), according to the color strength(k/s), V/D5/SDS2 soap-washing agent have high ability to remove unfixed dyes than V/D5 and also lower residual dye molecules remain in washing liquors (**Fig.S5 supplementary information**) which decrease the possibility to create stains on among fabrics. From Fig.8(b, c), it can be seen that V/D5/SDS2 soap-washing agent provides excellent dry and wet color fastness of the dyed fabric after being washed. The highest unfixed dyes removal efficiency and colorfastness result was obtained at pH 7 for 1g/L.

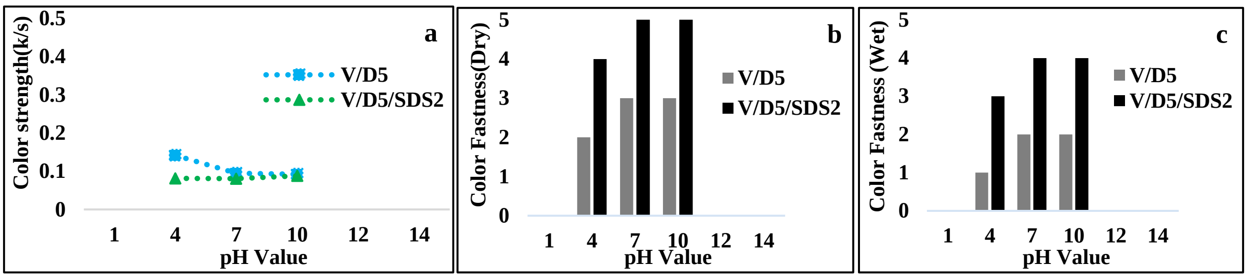

Figure 8: a) Color strength(k/s) of the washed fabric (V/D5 vs V/D5/SDS2), b) dry, and c) wet color fastness comparison between V/D5 vs V/D5/SDS2.

3.6 FTIR analysis

We have successfully synthesized the copolymerization of NVP with DMAEMA, and the FTIR results are shown in Fig.9, both for pure PVP and the copolymers of P(VP-co-DMAEMA). In Fig.9(a, b), the peaks are located at 1652cm^{-1} with the strong intensity corresponding to amide(I) and corresponding to the C=O and C-N groups. The pick shows a broad bending stretch of 3446cm^{-1}, indicating that PVP contains absorbed water (O-H).

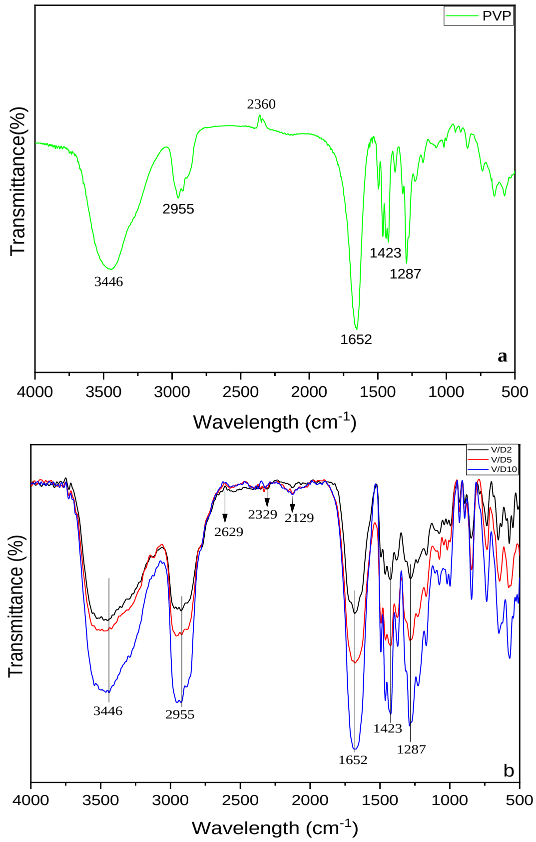

Figure 9: FTIR spectra of a) PVP and b) Copolymers of P(VP-co-DMAEMA).

From the above results and discussion, it is evident that the polymers are highly effective for the washing process and can be documented as the use of polymer plays a significant role in removing unfixed dyes from reactive dyed cotton fabric. After soap-washing treatment, the maximum unfixed dyes removal efficiency was obtained at pH 7 for 1g/L for V/D5/SDS2 soap-washing agent that improve the unfixed dyes removal efficiency as well as increase rubbing fastness properties. It was also found that the concentration of soap-washing agent and the pH value in washing liquors greatly influences unfixed dye removal efficiency, which should be well controlled to get the best soaping results. So, by considering the unfixed dyes removal efficiency, avoiding stains to the new fabric, and the cost of production, the use of developed V/D5/SDS2 soap-washing agent for wash-off of reactive dyed cotton fabric enables a much more effective along with highly economical, which significantly reduces the operation time, water and energy consumption. Finally, it can be concluded that the developed V/D5/SDS2 soap-washing agent is non-foaming, non-toxic, was not skin irritating, comparatively cheap with facile industrial application, and also highly efficient for the removal of unfixed dyes from reactive dyed cotton fabric.

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SUPPLEMENTARY INFORMATION

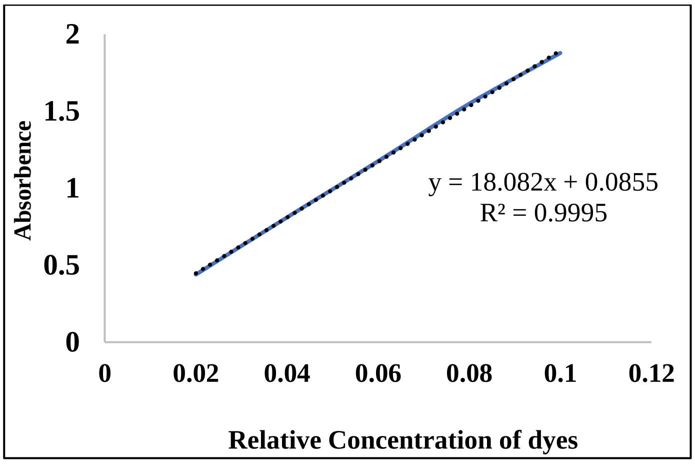

Figure S: Standard calibration curve for measuring residual dye concentration in washing liquors.

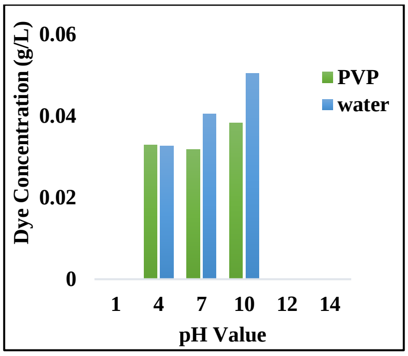

Figure S1: Dye molecules in washing liquors PVP vs water.

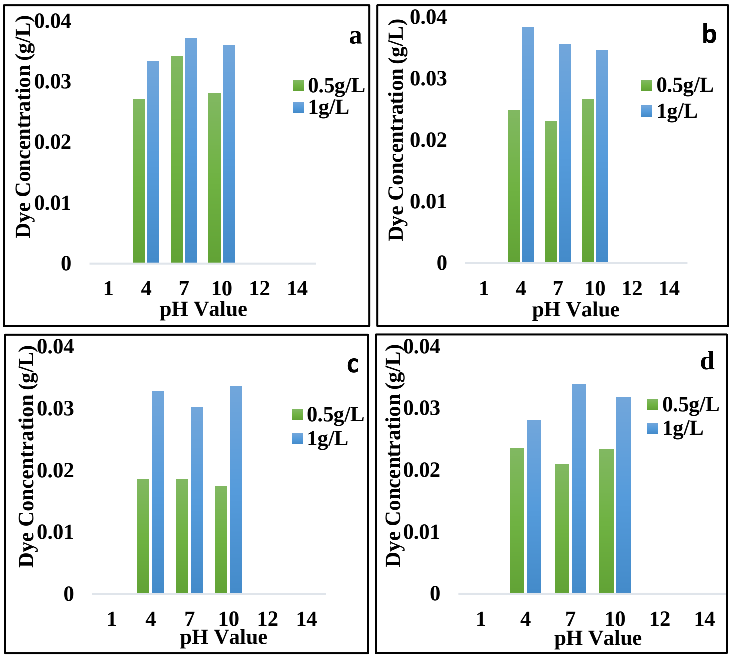

Figure S2: Residual dye concentration in liquors after being washing with a) V/D10, b) V/D8, c) V/D5 and d) V/D2 soap-washing agents.

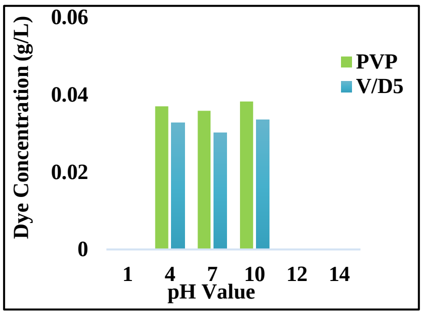

Figure S3: Dye molecules in washing liquors PVP vs V/D5.

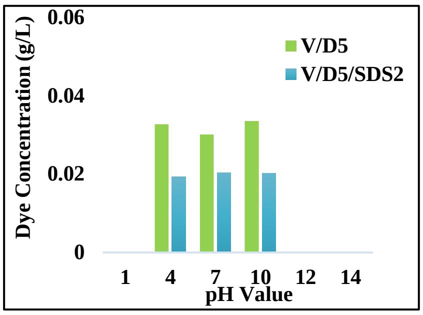

Figure S5: Dye molecules in washing liquors V/D5 vs V/D5/SDS2.

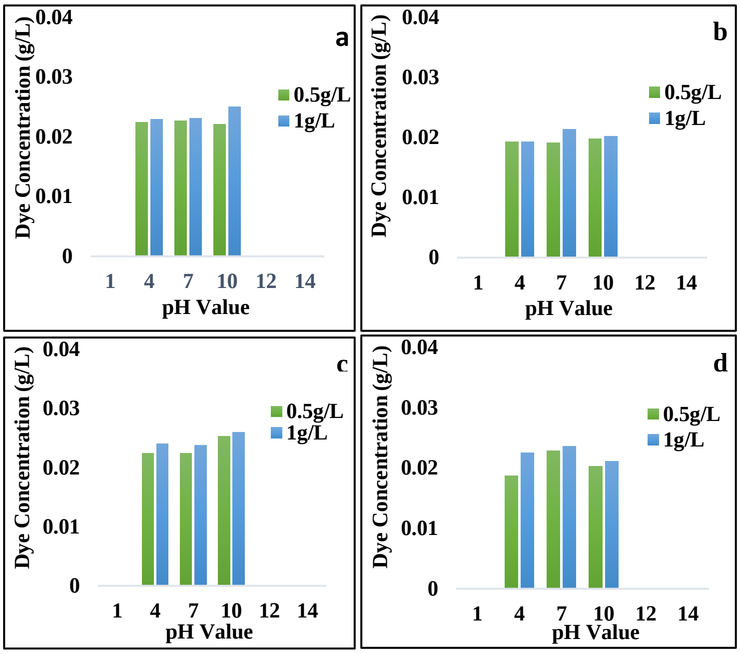

Figure S4: Residual dye concentration in liquors after washing with a) V/D5/SDS1, b) V/D5/SDS2, c) V/D5/SDS3, and d) V/D5/SDS5 soap-washing agents.