Environmental Method for Preparation of Higher Color Strength Dyeing Cotton Fabrics with Colored Nanosilica Pigment

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Abstract

Dye wastewater into the water system would cause a severe threat to the natural environment. To reduce the dye discharge, it is highly essential to find a clean and green method to color cotton fabrics. Herein, this work has expediently designed the novel pigment with colored nanoparticles to dye cotton fabrics, which was based on the adsorption of dyes from dyes solution with the synthesis of worm-like hydrophilic porous silica (WHMS) and formed colored particles. It could be found that as-prepared WHMS exhibited with the larger surface area of 968.61 m²/g, the average size of 300 nm and the higher electronegativity on the surface of WHMS materials and could be favorable to capture dye to achieve the capacity above 500 mg/g for different cationic and reduce dyes discharge. The colored WHMS applied in dyeing cotton fabrics show the higher stability and stronger color strength by electrostatic attraction compared with original dyes, in which the mass of WHMS-dyes could be retained by above 80% in thermal decomposition, the color depth of WHMS-dyes dyeing fabrics increased by above 1.2 times and the dye residues in the dyeing process were reduced. The high-quality dyeing fabrics can be obtained and nanospheres uniformly fixed on cotton fabrics through the binder to build a layer film, owing to its hydrophobicity and small sizes. The dyeing cotton fabrics exhibited good wet rubbing, washing fastness and hand feel. These results suggest that the WHMS-dyes can be suitable for cotton dyeing textiles as a sustainable coloring process.

1. Introduction

Cotton fabric as a kind of important natural fibers was widely applied in the different styles of textiles, such as carpets, clothing, wallpapers, and other areas due to its outstanding properties of vast quantities, moisture absorption, pollution-free, comfort and biodegradability (Li et al. 2020). Dyeing is a kind of essential method for the cotton fabric to color using different organic synthetic dyes such as direct dyes, and reactive dyes. During traditional cotton fabric dyeing in water, it is not regarded as an eco-friendly process due to the discharge of wastewater for retaining dyes (Dong et al. 2019).

Organic dyestuffs as colorants are widely employed in current some industries, such as cosmetic, textile, paper industries as well as dyeing (Varjani et al. 2020A; Yun et al. 2020). Dyes have a greater solubilizing performance in water, bright-color and rarely changed fabrics softness for the textile industry. Dyeing as an important part of the textile industry generated large amounts of effluents into the water system every year, which is neither readily amenable to treatment and nor easy to be cleaned and biodegraded naturally (Kan et al. 2016; Payan et al. 2018). Currently, textiles printing is one of the most significant coloration manners. All over the world, the printed textiles account for over 30%-40% of textiles produced (Lili et al. 2018). However, the traditional dye printing procedure consumed a large amount of water to eliminate unfixed dyes, residuary thickeners and auxiliaries, leading to high water consumption and pollutants discharge into environment.

Pigment dyeing presented superior advantages compared with dyes dyeing, such as simple procedures, relatively clean and friendly environment, and applicability to all textile fabrics (Damasceno et al. 2020;

Fang et al. 2017; Hakeim et al. 2020; Liang et al. 2016). Nevertheless, pigments have some drawbacks such as particle size distribution, poor color yield, and crocking fastness (Kan and Man, 2017; Steiert and Landfester, 2010). Moreover, the absence of affinity for fabrics required binder to fix pigment particles on the fabric's surface, resulting in poorer rubbing fastness and stiff hand feel for fabrics (Numan et al., 2018; Hakeim et al. 2020; Min et al. 2017). In recent years, various efforts have been developed, with which modified pigment has been concerned. For example, lbahim et al. prepared pigment with UV protection properties by modifying solvent-free pigment printing formulations (Ibrahim et al. 2013). Wang et al. fabricated ultrafine Spherical Pr-ZrSiO₄ pigment and shows bright lemon yellow (Wang et al. 2020). Correspondingly, compared with printing, pigments dyeing exhibits less usage of binder agent, but it required small particle size pigments.

In view of the trait of ultrafine pigments and dyes, choosing a kind of materials to load dyes forming new pigment in the textile industry. Inorganic loaded materials exhibited good durability and mechanical strength (Geng et al. 2016). Porous silica materials have been focused in the area of dye adsorption, because of their large space, porous structure, high surface area and low refractive coefficient (Liang et al. 2017; Nagappan et al. 2019), which it can promote pigment color strength and chemical stability. Moreover, porous silica materials have some superiority in its harmlessness for humans, and good control, recycled and economical property (Geng et al. 2016). Yin et al. synthesized modified silica coatings (OMSC) by sol-gel manner to apply in knitted cellulose fabric (Yin and Wang, 2012). The color fastness of knitted fabrics treated with the OMSS was enhanced to some extent. Zhang et al. employed thermochromic silica nanocapsules (TLD@SiO₂) in dyeing. For dyeing textiles with TLD@SiO₂, they exhibited good fastness for the finishing polyester fabrics (Zhang et al. 2017). It is likely to capture and recycle the dye-nanoparticles through the separation system. The strategy that utilizes the silica dye-nanoparticles for the wastewater-free, clean and environmental dyeing process has been seldom reported so far.

In this work, cotton fiber was dyed by colored WHMS particles after adsorption from the dye's aqueous solution to achieve dye removal. The property of WHMS and WHMS-dyes was characterized, and during the adsorption of dyes process, the performance was investigated to complete the best adsorption. Color yield, rubbing fastness and hand feel were measured and evaluated for the application in cotton fabrics, which exhibited excellent performance, such as good fastness, hand feel, and high color strength. Besides, pigment can be collected to be recycled. This kind of dyeing method with WHMS-dyes pigment offers the prospect for sustainable and clean development in terms of the textile industry.

2. Materials And Methods

2.1. Materials

Methylene blue (MB), rhodamine B (RB), tetraethyl orthosilicate (TEOS), and cetyltrimethylammonium bromide (CTAB) were of chemical grade acquired from Sinopharm Chemical Reagent Co. Ltd. (Shanghai, China). Triethylamine (TEA) was offered by Shanghai Ling Feng chemical reagents Co. Ltd, China.

Anhydrous alcohol was offered from Shanghai Yishi Chemical Co. Ltd, China. Cotton fabric (100 wt%, 40*40/133*100) was attained from Jiangsu Dayao Textile Co. Ltd, China. Thickener was supplied by Guangzhou zhongwan new materials Co. Ltd, China. Waterborne polyurethane resin was acquired by Zhejiang Gaodebao new materials Co. Ltd, China. Distilled water was applied in whole the experiment processes.

2.2. Preparation of WHMS

Cetyltrimethylammonium bromide (2 mmol) was added into water and stirred for 20 min. Triethylamine and anhydrous alcohol were mixed with the transparent solution, and the reaction was performed at 65°C for 1.5 h. Then tetraethyl- orthosilicate was dropped into the above mixed solution under rapid stirring condition. Finally, the precipitates were obtained after centrifugation and calcination at 520°C for 5 h in air.

2.3. Fabrication of WHMS-dyes

Adsorption was conducted by batch adsorption experiments with the variation of pH = 5, initial dye concentration (450 mg/L), temperature (20°C), and contact time (100 min). The adsorbent dosage and dye solution were mixed and stirred at 220 rpm until adsorption equilibrium. Then, the WHMS-dye was acquired by centrifugation. The dye absorption capacity q_e (mg/g) on nanospheres was calculated using

Eq. 1.
$$q_e = (c_0 - c_e)V/m \quad (1)$$

where q_e (mg/g) is the adsorption capacity at equilibrium for dyes, m (g) refers to the mass of the adsorbent. c_0 and c_e signify the concentration of dye at initial and equilibrium conditions, respectively, V (L) represents the solution volume.

2.4. Dyeing procedure with WHMS-dye

Cotton fabrics were dyed with pigment in the pad dyeing manner by horizontal resin pressing and dyeing machine (rolling mill) (P-B1) and heat setting machine (MINITENTER). The cotton fabrics were respectively dipped into pure dye paste and WHMS-dyes paste for 3 min and then passed through the rolling mill two times. The wet pick-up was 70% after milling. Then, the fabrics were dried at 90°C for 4 min and cured at 120°C for 3 min.

2.5. Characterization

The surface morphologies of the cotton fabrics and WHMS were evaluated by field emission scanning electron microscopy (FESEM, S-4800, Japan) at room temperature. The thermal stability of WHMS was carried out by thermogravimetric analysis (TGA) from 50°C to 800°C at the heating rate of 10°C/min. The particle diameter was performed by Malvern nanometer particle size analyzer (Nano ZS, UK). Contact

angle (CA) was examined by contact angle meter (DSA30). Brunauer-Emmett-Teller (BET, TriStar[®]3020M) was used to determine surface area and pore volume by N₂ adsorption-desorption. The powder X-ray diffraction (XRD, D/max-2550VB+/PC, Japan) and Fourier transform infrared (FT-IR, Spectrum Two, USA) were employed to analyze sample crystal structure and chemical groups. The UV-vis spectra of the WHMS-dyes were tested by a UV-visible Spectrophotometer (U-3310). The morphologies of the fibers before and after dyeing were photographed through the ultra-depth 3D microscope (VHX-6000). The viscosity of the paste was performed by a viscometer (Bookfield viscometer DV2TLV, USA).

The rubbing fastness of the fabrics was evaluated according to GB/T 3920 – 2008. The samples of fabrics were carried out to rub separately continuing 10 times containing dry condition and wet condition with the moisture of 95% water by fastness tester (Y571B). The washing fastness of the fabrics was tested according to GB/T 3920 – 2008. The samples were washed under 2 g/L soap solution condition by water bath shaker (DLS-1000A, Daelim Starlet Co., Ltd). The K/S value and L*, a*, b* values were carried out by color gameter (DATACOLOR 650) to estimate the apparent color depth of cotton fabrics, the hand feel of fabrics was tested by PhabrOmeter (PHABROMETER MODEL 3).

3. Results And Discussion

3.1. Characteristics of WHMS

It was greatly clear that WHMS was relatively spherical and rough spheres morphology in Fig. 3(a), in which the size of the particles was observed with the mean value of about 300 nm. As the WHMS existed a hydrolysis layer in water solution, the particle size was larger than that of TEM and SEM in Fig. 3(c) (Kobler et al. 2008). The WHMS has a higher BET surface area (968.60 m²/g) and a bigger pore volume (0.84 cm³/g,) in Fig. 3(b). Then, the contact angle of WHMS materials was characterized in Fig. 3(d) to explain the hydrophilicity. It indicated WHMS with the water contact angle of 50° possessed higher hydrophilicity owing to a large amount of hydroxy groups (Marjani et al. 2020), suggesting the WHMS could be favor of combination with hydrotropic substance. The thermal stability as an essential property to nanosize WHMS materials application was estimated from 50 to 800 °C as presented in Fig. 3e. The result found that WHMS only had one degradation stage occurring at about 200°C and approximately weight loss reached 2.8%, which was ascribed to the lack of chemically contained water and a part of hydroxy groups (Polshettiwar et al. 2010), proving that WHMS had higher thermal stability. More importantly, the particle structure could affect the adsorption and dye aggregation property. It can be concluded from Fig. 3f that the diffraction peak of the WHMS occurred at approximately $2\theta = 2.4^\circ$ which well-matched with the (100) crystal plane, and this index could explain the formation of the worm-like structure (Zhang et al. 2013).

3.2. Characteristics of WHMS-dyes

3.2.1. The effect of loading conditions on WHMS-dyes

As the important factors to dyes content on the nanospheres. The effect of pH values, temperature and time for adsorption capacity were investigated to affect the color property. In Fig. 4a, the color of powders evidently transferred from white to blue and red after adsorption using nano WHMS and colored powders could display bright color, confirming that the WHMS possessed superior capturing and gathering ability to dyes and was beneficial to dye cotton fabrics. The adsorption performance of WHMS for MB and RB both shows a decrease with increasing temperature until saturation adsorption (Fig. 4b and c). Figure 4d showed the adsorption capacity gradually increased and not changed as time extended. In Fig. 4e, when the pH value increases, the adsorption performance of WHMS for MB displayed the gradually increased tendency, while the adsorption capacity of WHMS for RB gradually increased with pH value increasing from 3 to 5, and then appeared decreasing tendency with further pH value increasing, which manifested that WHMS materials can completely remove dyes at appropriate conditions. The adsorption mechanism on WHMS was explained in Fig. 4f, the novel pigments can acquire bright color under adsorption equilibrium. The WHMS can not only capture cationic dyes due to its dyes due to their electronegative surface but also largely gather dyes due to its porous structure to enhance the color strength of dyes, which could fulfill the clean production process and reduce the dye discharge.

3.2.2. Property of WHMS-dyes

The WHMS-dyes pigment was prepared as illustrated in Fig. 1. The WHMS was prepared for the hydrolysis of TEOS by a simple sol-gel method, and the as-prepared WHMS loaded dyes to form the WHMS-dyes pigment. Finally, the WHMS-dye was collected as a pigment. The FTIR spectra of the WHMS, MB and RB before and after dyes adsorption were analyzed in Fig. 4a and b. The peaks of 1080 cm^{-1} were caused by the Si-O-Si of stretching vibrations, and the appearing peaks around 3320 cm^{-1} and 960 cm^{-1} were corresponding to the stretching vibrations of Si-OH (Huang et al. 2017). It can be observed that the obvious characteristic peak of 578 cm^{-1} stands for frame vibration of C-S-C, and 1400 cm^{-1} and 1590 cm^{-1} refer to the aromatic ring (Xiao and Man, 2007), which reflected that MB was distributed uniformly on the WHMS. Additionally, the characteristic peak of C-H stretching groups for WHMS/RB appeared at 2920 cm^{-1} (Ghorai et al. 2014). This manifests that RB and MB have been successfully covered in the surface of WHMS.

The acquired XPS spectra are shown in Fig. 5c-e. The peaks intensity of WHMS-MB and WHMS-RB become weakened in terms of O1s and Si2p, because the coverage of dyes molecules cover the transmittance, confirming RB and MB dyes molecules are introduced on WHMS materials. The N1s region was fitted with peaks at 399.4, 399.6, and 402.3 eV in Fig. 5d and e. The peaks at 399.4 and 399.6 eV could be assigned to imino groups (= N-R) of MB and RB (Yan et al. 2018; Zangmeister et al. 2013). Meanwhile, the peak locating at 402.3 eV could be ascribed to substituted amines (N-R) (Yan et al. 2018). After adsorbing MB and RB, the binding energy of = N-R and N-R increases. The results are likely to exist hydrogen bonding and electrostatic interaction between WHMS and N^+ and N-R of MB and RB (Feng et al. 2021; Wang et al. 2018). These correlative peaks verify the existence of RB and MB and the connection

between dyes and WHMS materials through electronic interaction. The particles sizes increased after adsorption dyes from Fig. 5f., which was related to loaded dyes on the WHMS.

For colored nanospheres, thermal stability as an important property was analyzed to evaluate the stability between dyes and nanospheres and apply a practical process. TG and DTG curves of various nanoparticle powders were shown in Fig. 6a-d, and some important endothermic reactions existed and occurred at 200°C, and 250°C.

Figure 6a and c exhibited that appeared multiple endothermic reactions, and the first stage suggested a weight loss of 2.5% occurred at 100–200°C, which could be caused by the loss of water. Cationic RB and MB powders, there are some obvious weight loss peaks corresponding to about 230–600°C due to the thermal decomposition of dye structure. The 25% weight loss occurred at 230–350°C, which was assigned to the degradation of azo groups ($N=N$) in the RB and MB structure (Kang et al. 1994). About 35.0% weight loss at the stage of 350–600°C occurred, originating from the degradation of aromatic rings (Yavuz et al. 2018). Comparatively, in terms of WHMS-RB and WHMS-MB powders, it is found that the WHMS nanospheres and the colored ones have similar thermal degradation trends. The residue mass was higher than dyes. This can be explained as the existence of strong interaction between dye molecules and nanospheres, which formed a new structure that hindered the decomposition of the dyes during the heating process.

3.3. Dyeing properties of WHMS-dyes

3.3.1. Preparation and characteristics of dyeing cotton fabrics

The dyeing cotton fabrics process and mechanism with colored nanosphere particles were exhibited in Fig. 2. It was found that cotton fabrics were dipped into dyeing paste and cured to form dyeing fabrics with higher and deeper color from Fig. 2a. Figure 2b illustrated that the combination between pigment and fabrics by the binders. After the cotton fabrics with color paste were cured, the surface of the cotton fibers formed layer films to fixed pigment, resulting in pigment can attach to the surface of the fabrics. This increased dye utilization on cotton fabric can reduce treatment.

For further analyzing the WHMS effect for dyes color, as shown in Fig. 7a, the UV-vis spectra of the WHMS, WHMS-dyes, and dyes were investigated. The characteristic peaks of MB and RB in the WHMS-MB and WHMS-RB spectra emerged the blue-shift phenomenon in comparison to the pure MB and RB. This was originated from the interaction between WHMS and dyes (Fu et al. 2016). Moreover, MB appeared obvious blue-shift in contrast to RB, which was related to dyes structure. The property of WHMS-dyes pigment is important to apply in dyeing textiles. To investigate the effect of WHMS in the paste system, the rheology of paste was conducted. In Fig. 7b, the viscosity of paste gradually decreased with increasing shear rate for both pure paste and WHMS-paste. The viscosity of the pure paste was higher than WHMS-paste while adding WHMS had a slight difference in viscosity. Thus, the result proved

that WHMS has rarely an effect on the paste system. The SEM micrographs of cotton fabrics dyed were shown in Fig. 7c and d. The films and nanoparticles can be found to appear on the surface of the dyed fibers owing to the fixed WHMS-dyes pigment by binders on fibers, causing a rough surface for dyed fibers. This further explained the fixation of WHMS-dyes on cotton fabrics.

3.3.2. Colour property of dyeing cotton fabrics with WHMS-dyes

Figure 8 shows the color strength and depth of the cotton fabrics samples dyed. In addition, the color parameters of the acquired colored fabrics including the color strength (K/S value) as well as the CIE1931 chromaticity diagrams are evaluated in Fig. 8a-e. The K/S values are defined according to the ratio of the scattering coefficient to absorption and are usually employed in evaluating the dyeing effect and color depth, which the higher the values are, the color strength is greater (Lee and Kim, 2004). Besides, the CIE 1931 chromaticity diagram can directly give visualized color property according to the color values of X and Y (Chen et al. 2020). The different recipes are used to investigate the influence of WHMS on the colorimetric performances for the dyed cotton fabrics. In Fig. 8a and b, it can be concluded that the K/S value of dyed fabrics with contained WHMS-dyes is higher than pure dyes in the dye bath. The K/S values of WHMS-MB are 1.2 times of MB dyes dyed cotton fabrics, respectively. At the same time, the K/S values also increase from 0.48 to 0.8 when the colorant changes from RB to WHMS-RB. To elucidate the color change after containing WHMS, samples were explained through the location of CIE 1931 chromaticity diagrams (Fig. 8c). The results indicated that color changes for cotton just by tuning the variety of WHMS-dyes pigment.

Furthermore, in order to deeply clarify the color property after dyeing with dyes and containing WHMS-dyes, the color parameters such as L^* value, a^* value and b^* value were investigated. The chromatic parameters of L^* , a^* and b^* are expressed for color, which illuminated the color lightness, red-green color properties, yellow-blue color properties, respectively (Chen et al. 2019). As shown in Fig. 8d, it clearly reveals the color of dyed fabrics containing WHMS-MB become higher green and blue and possesses low-lightness compared with fabrics with dyes. It also existed a similar trend in Fig. 8e that the color of dyed fabrics containing WHMS-RB become more red and blue and has low-lightness compared with fabrics with dyes. It could be further proved containing WHMS-dyes dyed fabrics have better color strength in Fig. 8f and g.

The silica nanoparticles have not an affinity with the cotton fabrics but could be stably concentrated on the surface of the cotton fabrics mainly via the binders to form films and fix particles on the surface of the fabric. To observe the performance of WHMS-dyes dyed fabrics to cotton fabrics such as hand feel, uniformity, rubbing fastness and washing fastness, dyed cotton fabrics performance was evaluated in Fig. 9 and Table 1. In Fig. 9a and b, it could be found that the stretch, wrinkle and drape of dyed fabrics have not decreased obviously in comparison to pristine cotton, indicating the containing WHMS fabrics have better hand feel and stretch, which did not completely change cotton property. From Fig. 9c and d, the novel WHMS-dyes pigment distributed uniformly on the surface of fabrics and had excellent color

strength, which is likely due to the property of nano-WHMS particles. These results illuminate WHMS particles would be potentially employed in pigment dyeing of fabrics. The color various fastness of the dyed cotton fabrics colored was illustrated in Table 1. The dyed cotton fabrics exhibited outstanding rubbing and washing fastness with at least 3–4 grades. The colorfastness level is relevant to the strong connection force between the binder (Li et al. 2018), colorant and cotton fibers and the state of particles.

Table 1
Color fastnesses of the dyeing cotton fabrics.

Fabrics	Washing fastness (grades)		Rubbing fastness (grades)	
	Discoloring	Staining	Wet	Dry
RB fabrics	3–4	4	4	4
MB fabrics	3–4	4	4	4
WHMS-RB fabrics	3–4	3–4	4	4
WHMS-MB fabrics	3–4	3–4	4	4

3.3.3. Recycled colored properties on cotton with WHMS-dyes

A novel dyeing particle based on the colored WHMS nanoparticles was designed to avoid overuse of water resources and pollution discharge of the dyes. The benefit of this study is that WHMS in the residual solution can be collected through centrifugation to recycled usage, achieving a green dyeing process. The recycled WHMS-dyes residue is employed to color pristine cotton fabrics based on the previous dyeing steps with few numbers of WHMS-dyes to verify the dyed effect of the recycled WHMS-dyes. Dyeing recycled processes are carried out in Fig. 10. Fabrics had a greatly limited variation of K/S values in samples before and after recycling is observed, indicating that the color strength from the acquired cotton fabrics was not hugely affected by using the recycled pigment to color. The color repeatability of the obtained cotton demonstrated that the feasibility of the recycled pigment to employ, providing a versatile to realize clean pollutant discharge in the textile industry.

4. Conclusions

The colored nanospheres were successfully prepared through WHMS capturing efficient dyes from water solution. Then, color nanospheres were employed in dyeing cotton fabrics to fulfill the green and clean coloring process. The results show the average diameter, the monology, and surface area was 200–300 nm, sphere and 968.60 m²/g, respectively. The higher color strength, better fastness and hand feel for cotton fabrics were triumphantly produced with WHMS-dyes. The molecular structures of WHMS and its captured dyes are confirmed by different characterizations. The adsorption of WHMS for dyes exhibited great capacity by the interaction between the negative charges sites on the WHMS and the cationic amino sites on dyes. The adsorption capacity of loaded dyes had the effect on color property, in which

the cotton samples dyed with WHMS-dyes showed a notable increase in color depth. Satisfactory results in various fastness properties were obtained, which the washing and rubbing fastnesses were all above 3–4 grades. Besides, the WHMS could be collected in the residue after the dyeing route. It could be believed that this novel recycled WHMS pigment dyeing method can decrease the waste of dyes and wastewater pollution from the textile color industry to form a green environment system.

5. Declarations

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Authors' contributions

JZ: Methodology, Investigation, Visualization, Resources, Writing-original draft. YL: Visualization. PD: Methodology, Visualization. ZG: Methodology, Investigation. ZC: Resources, Formal analysis. FG: Funding acquisition, Supervision.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

This study does not involve any animal and human sample.

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Figures

Figure 3

(a) SEM images of WHMS (inset is TEM images), (b) N₂ adsorption-desorption isotherms curves (inset presents BJH pore size distribution), (c) the size distributions of WHMS in water, (d) the water contact angle of WHMS, (e) TGA analysis of WHMS, (f) the low-angle XRD of WHMS.

Figure 4

(a) The image of powders before and after dye adsorption using WHMSN, the effect of adsorption temperature on dye adsorption capacity (b) MB and (c) RB, (d) the effect of contact time on dye adsorption capacity (dye concentration = 200 mg/L) (e) the effect of pH on dye adsorption capacity (dye concentration = 200 mg/L), (f) the adsorption of dye mechanism on WHMS.

Figure 5

(a) The FTIR spectra of WHMS and MB before and after dyes adsorption; (b) the FTIR spectra of WHMS and RB before and after dyes adsorption; (c) XPS full-range spectra of WHMS before and after dyes adsorption (d) and (e) N1s spectra of WHMS-MB and WHMS-RB, respectively, (f) the size distributions of WHMS loaded dye in water.

Figure 6

Thermostability characteristics of the WHMS-dyes nanosphere. (a), (b), (c) and (d) show the TGA and DTG spectra of RB and MB powders, WHMS nanosphere powders, and WHMS-dyes nanosphere powders.

Figure 7

(a) The UV-vis spectra of WHMS and WHMS-dyes (inset is the photo image of WHMS) (b) The rheology curve of pure paste and WHMS-paste; SEM images of (c) pristine cotton fabrics and (d) dyed cotton fabrics with WHMS-dyes.

Figure 8

The K/S curves for cotton of (a) MB and WHMS-MB dyed fabrics and (b) RB and WHMS-RB dyed fabrics; (c) CIE 1931 chromaticity diagrams of the obtained color fabrics, chromatic parameters of (d) MB fabrics and WHMS-MB fabrics, (e) RB fabrics and WHMS-RB fabrics, and (f and g) morphologies of the WHMS-dyes and dyes cotton fabrics.

Figure 9

The fabrics performance of (a) fabrics, MB and WHMS-MB dyed fabrics, (b) fabrics, RB and WHMS-RB dyed fabrics; the photographic images of fabrics of (c) pure cotton fabrics, MB dyed fabrics and WHMS-MB fabrics, and (d) pure cotton fabrics, RB dyed fabrics and WHMS-RB fabrics.

Figure 10

The K/S curves for cotton of the recycle dyeing processes: (a) WHMS-RB dyed fabrics; (b) WHMS-MB dyed fabrics.