Water-Saving Dyeing Process: A Sustainable Approach for Exhaust Dyeing of Cotton Fabric

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Abstract

The global demand for water conservation and sustainability in textile manufacturing is imperative in addressing the scarcity of fresh water and environmental pollution. This study introduces an innovative water-saving process for exhaust dyeing of cotton fabrics with reactive dyes, without compromising the dyeing quality or requiring extra investments. Traditional textile dyeing practices consume approximately 120 liters of fresh water per kilogram of cotton fabric, contributing to environmental degradation. In this research, a process modification is proposed that recycles water used for neutralization and rinsing at the second step of the dyeing process. This recycled water is utilized in the fourth step, effectively reducing the total water consumption to 104 liters per kilogram of fabric, thus saving 16 liters per kilogram without any additional investment. The dyed fabrics produced using this water-saving process exhibit excellent colorfastness, matching the quality of conventionally dyed textiles. The color fastness to light, washing, rubbing, and perspiration meets international standards. CMC tests indicate no significant differences compared to the existing dyeing process. Implementing this eco-friendly approach can not only significantly reduce water consumption and wastewater generation but also diminish the need for costly water treatment and effluent management facilities. This research paves the way for cleaner production in the textile industry, promoting water conservation, reducing environmental pollution, and minimizing production costs.

Keywords: *Exhaust Dyeing, Sustainable, Water-saving, Reactive Dye, Cotton fabric*

1. Introduction

Fresh water is considered as a vital resource for all lives on the Earth, playing a crucial role in supporting human well-being, ecosystems, and the overall health of our

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planet. As a finite and increasingly scarce resource, understanding and prioritizing the importance of fresh water has become a burning issue in addressing global challenges such as scarcity of water, pollution, and climate change [Dudgeon *et al.* 2006; Vörösmarty *et al.* 2010].

Freshwater ecosystems, including rivers, lakes, wetlands, and groundwater systems, harbor a remarkable diversity of species and provide numerous ecological services. These ecosystems support fish populations, regulate water flow and quality, recharge groundwater reserves, and provide habitats for various flora and fauna. The degradation and loss of freshwater ecosystems have far-reaching consequences, affecting biodiversity, ecological stability, and the provision of essential ecosystem services. Conservation and sustainable management of freshwater resources are essential for maintaining the health and resilience of ecosystems.

Fresh water is intricately linked to climate change, both as a driver and as a vulnerable component of the Earth's system. Rising global temperatures alter precipitation patterns, leading to increased frequency and intensity of droughts, floods, and extreme weather events [IPCC 2014]. These changes significantly impact water availability, water quality, and ecosystem functioning. Adapting to climate change and mitigating its effects on freshwater resources require proactive measures such as water resource management, conservation, and the development of climate-resilient infrastructure [UN-Water 2020].

The textile industry plays a significant role in the global economy, providing employment opportunities and meeting the growing demand for clothing and other textile products. However, this industry is also known for its intensive water consumption and environmental impact, particularly in the dyeing process [Prakash *et al.* 2019]. Reactive dyes, commonly used for dyeing fabrics due to their excellent color fastness and compatibility with various fiber types. However, conventional textile dyeing practices require substantial amounts of water, energy, and chemicals, leading to water pollution and depletion of freshwater resources. About 120 litters of fresh water are required to dye 1 Kg of cotton fabrics which is huge and alarming. An average-sized textile mill with a capacity of 8 tons/day usually consumes about 1.6 million liters of water per day [Allègre *et al*. 2006]. Apart from that, the effluents produced from reactive dyeing are relatively heavily colored, contain high concentrations of salt, alkali and exhibit high BOD/COD values. [Erswell *et al*. 1988; Cooper 1995; Hachem *et al*. 2001].

Therefore, implementing water-saving processes in reactive dyeing is crucial for reducing the industry's water footprint and promoting sustainable practices [Bhanu Prakash *et al.* 2020; Hossain *et al.* 2022]. To address these challenges and promote sustainability, innovative techniques such as water-saving dyeing processes have emerged as a promising solution.

Researchers are constantly striving to develop greener methods for reactive dyeing of cotton. One of the approaches is to use supercritical carbon dioxide instead of water [Fernandez *et al.* 2005; Wang & Hu 2014]. However, the nonpolar supercritical carbon dioxide cannot effectively swell up highly polar cotton fibers leading to low dye uptake and poor color shade [Fernandez *et al.* 2007]. In addition, the supercritical carbon dioxide dyeing process is expensive because it requires high pressure, which greatly limits its application. Cationic modification of cotton fibers is another method that improves dye absorption and reduces salt consumption [Hauser *et al.* 2001]. However, a large number of cationic auxiliaries is required, which causes additional pollution of the wastewater. Organic solvent dyeing has received considerable attention in recent years. Since a single non-nucleophilic organic solvent cannot effectively swell up cotton fibers, polar - non-polar systems have been developed such as N, N-dimethylacetamide/dimethyl carbonate, ethyl octanoate/dimethyl sulfoxide, etc., Ethyl octanoate (EO)/dimethyl sulfoxide (DMSO) to reduce the hydrolysis of reactive dyes [Chen *et al.* 2015; Zhao *et al.* 2018]. However, achieving zero emissions of organic solvents is difficult. Similarly, Decamethylcyclopen tasiloxane (D5)-water system, oil-water system and ethanol-water system have also been tested to achieve the aim of clean cotton dyeing. [Fu *et al.* 2015; Mu *et al.* 2019; Xia *et al.* 2021]. The dye and D5 can realize salt-free cotton dyeing by ball-milling and reverse micellar. However, cotton dyeing in ball-milling and micellar dyeing systems are not satisfactory because of rapid dyeing where dye fixation is low. Furthermore, D5 is not biodegradable which may cause environmental concerns [Sparham *et al.* 2008].

The present study aims to provide a water-saving process for dyeing the cotton fabric with reactive dyes by exhaust dyeing process. The cotton fabrics dyed through this process exhibited excellent colorfastness and color matching similar to that of the existing dyeing process. This dyeing approach provides substantial reduction in wastewater emission and consumption of freshwater, which has considerable potential for promoting cleaner production in the textile industry. At the same time the process allows no use of citric acid further that is needed for neutralizing the dye bath at the 3rd step. By adopting these water-saving strategies, textile manufacturers can not only contribute to water conservation but also reduce wastewater generation and associated pollution. Simultaneously, it can also reduce the cost by reducing the ETP load.

2. Experimental Section

2.1 Materials

Cotton fabric: A commercially scoured and bleached ready-to-dye organic cotton fabric (100%, Single Jersey, 160 GSM) was used. The fabric was free of fluorescent brightener. It was tested and found to have an absorbency of 1 sec (AATCC 79 – 1995), pH extract of 8.2 and a CIE whiteness index of 78.6.

2.2 Dye Specifications:

Dyes type Reactive (Cold brand, Bi functional); Supplier: CHT Switzerland AG; Origin: Germany. The chemical structure of the dye is presented in **Fig. 1**.

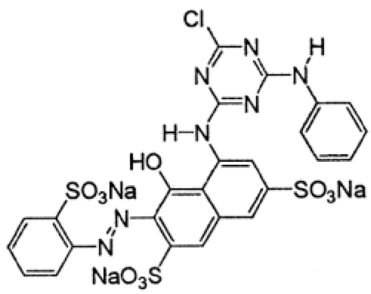

Fig. 1. Bezaktive Red S-3B

2.3 Dye Recipe

Table 1. Recipe for Reactive Dyeing.

Auxiliaries	Trade name	Dosses	Brand Name	Origin
Mild Acid	Citric Acid	0.5 g/l	Trade Asia Int.	Singapore
Detergent	Rucogen WBL	0.5 g/l	Rudolf Group	Germany
Anti-creasing Agent	Oxinol A24	1 g/l	Oxford	Australia
Levelling Agent	Lubrimax TEL	1 g/l	Oxford	Australia
Electrolyte	Salt (Na_2SO_4)	40 g/l	Lenzing	Indonesia
Alkali	Soda Ash (Na_2CO_3)	20 g/l	Nirma	Indonesia

Alkali	Caustic (NaOH)	2 g/l	Arabian Alkali	KSA
Shade %	Bezaktive Red S-3B	3 %	CHT Switzerland	Germany
Fixing Agent	Fastasol RD	2 g/l	Oxford	Australia
Soaping Agent	Winscour RDC	2 g/l	Oxford	Australia
Softener	Sapamine CWS	3 g/l	Huntsman	Germany

2.4 Dyeing process

The dyeing process was carried out experimentally in Hamza Washing and Garment Dyeing Plant (DBL-GROUP), Bangladesh in a small scale (500 gm of cotton in each batch). The dyeing process was same as the existing process. However, here only the amount of water that used for neutralization and rinsing purpose (8 + 8 = 16 L/Kg fabric)) at the 2nd step is stored and reused for neutralization and rinsing purpose at the 4th step.

In the existing exhaust dyeing process, there are 7 steps from scouring to softening. Sequentially these are scouring/bleaching, neutralization, dyeing, neutralization, soaping, fixing and softening. Each of these steps needs 1 or 2 rinse/s and the whole process needs 15 times water use. Each time 8 L water is needed for one kilogram of fabric. So, a total 120 L of water is needed for dyeing one kilogram of fabric. The flowchart of the whole process is depicted in the **Scheme 1.** and the process steps are stated below:

Process Steps	Water (L)	Bath
Scouring/Bleaching	8	Drain
2 Rinse (Hot/Cold)	16	Drain
Neutralization	8	Storing
1 Rinse (Cold)	8	Storing
Dyeing	8	Drain
2 Rinse (Hot/Cold)	16	Drain
Neutralization	0	Reusing
1 Rinse (Cold)	0	Reusing
Soaping	8	Drain
1 Rinse (Hot/Cold)	8	Drain
Fixing	8	Drain
1 Rinse (Hot/Cold)	8	Drain
Softening	8	Drain
Total water required	**104 L**	

Scheme 1. Flowchart of the present reactive dyeing Process

In the 1st step, scouring and bleaching are performed in the same bath. The pH is kept at 12 and the temperature of the bath is maintained at 95°C, where the following chemicals are used: detergent, caustic soda (NaOH), soda Ash (Na_2CO_3), hydrogen peroxide (H_2O_2). Total operational time is 50 minutes. After completing this step, bath water is dropped to drain. Then the fabric is washed with clean hot water at 80°C for 5 minutes and another wash is done at room temperature for 5 minutes. After that the bath water is dropped to drain.

In the 2nd step, citric acid is used to neutralized the pH of the fabric at 40°C for 10 minutes. After that the bath water is dropped to drain. Then a cold wash is done at room temperature for 5 minutes then used water is dropped to drain. However, in the present process, the water that is needed for neutralization and rinse purpose, stored in a separate bath for reusing in the 4th step without draining.

In the 3rd step, the dyeing of fabric is done with auxiliaries. The chemicals used in this step are: leveling agent, anti-creasing agent, salt (Na_2SO_4) as electrolyte, Bezaktive Red S3B as dye stuff of 3%, caustic soda and soda ash to give an alkaline medium at pH 12. Fabric is treated with this recipe for 60 minutes at 60°C. Then the water of dye bath is dropped to drain and successively two washes are done with clean water. One is hot wash at 80°C for 5 minutes and another is cold wash for 5 minutes at room temperature. After completing of each wash, the bath water is dropped to drain.

In the 4th step, the pH of dye bath becomes highly alkaline and needs to minimize the pH level. For this purposed citric acid is used. However, reusing the stored water of the 2nd step can serve this purpose, no need any citric acid for adjusting the pH. The stored water is used for neutralization and rinsing purpose at this step.

In the 5th step, to remove unfix/hydrolyzed dyes the fabric was treated with soaping agent at 50°C temperature for 5 minutes and then one cold wash at room temperature.

In the 6th step, fabric was treated with dye fixing agent at 50°C for 5 minutes and then one cold wash at room temperature.

Finally, softening process is done to the fabric with softener for 5 minutes at room temperature.

In this exhaust dyeing process, total process steps are seven and total rinse steps are eight. For every steps water needed 8 liter per kilogram of fabrics. So total water required for 15 steps was 120 liters. But we used total 104 liters water and 16 liters water were reused within same dyeing batch. So, water saved total 16 liters and also the mild Citric acid was saved.

2.5 Measurements

The color fastness to light (Xenon arc fading lamp test) of dyed fabric was measured according to the ISO 105 B02:2014 by light fastness tester and assessment of the change in color of the specimen was done using grey scale ISO 105-A02. Three exposure cycles were performed under 3 different conditions. 1st cycle: humidity = 40%, BST = 47±3°C, BPT = 45±3°C, blue wool 5 to gray scale 4; 2nd cycle: humidity =15% BST = 62±3°C, BPT = 60±3°C, blue wool 6 to grey scale 3-4; 3rd cycle: humidity = 85%, BST = 42±3°C, BPT = 40±3°C, blue wool 3 to grey scale 4.

The color fastness to washing of dyed fabrics was conducted according to ISO-105-CO1. The sample is treated in a wash wheel with a thermostatically controlled water bath and rating speed of (40±2) RPM for 30 minutes at (40±2) °C with 5gm/l standard soap. The change and staining of color due to washing were assessed by comparing the untreated fabric with the treated fabric samples with respect to the rating of color change and color staining in grey scale (1 – 5).

The color fastness to rubbing was measured according to ISO 105 × 2 L: 2002 by Rubbing Fastness Tester (Crock Master: Macro Rub, Germany). The color staining to rubbing on fabric was assessed by measuring the contrast between the treated and untreated white rubbing cloth with the grey scale and rated 1-5.

The color fastness to perspiration (both in acidic and alkaline media) was measured according to the AATCC15:2013 by perspiration tester. The color change and staining were assessed in gray scale (1 – 5). The CMC tests were performed under standardized and controlled lighting conditions against D65, T83 and T84 light.

3. Results and Discussion

The research focuses on addressing the complex issues of water use and pollution in the textile industry, with a specific emphasis on the dyeing process. Conventional dyeing in the textile sector, particularly with reactive dyes, has long been associated with significant water consumption, environmental impacts and depletion of freshwater resources. The alarming statistics of about 120 liters of fresh water needed to dye 1 kg of cotton fabric highlights the urgency for sustainable alternatives. However, still now the conventional dyeing process is widely employed for dyeing the cotton fabrics with reactive dyes because it is relatively cheaper than the recently developed greener methods. Most of the factory owners are reluctant to invest extra money for adopting the new advanced techniques or they don’t have the ability to do so. Considering the present scenario of the textile industries, this study is focused on exploring a way to reduce the amount of water in dyeing process within the existing machinery setup and by avoiding any further investment.

It is a matter of great concern that many textile factories in South East Asia regions have been discharging the effluents into the rivers or water body without doing proper treatments of the effluents despite the standards are set for major physicochemical parameters of textile effluents by the concerned departments. As a result, significant deviations from the standard values are observed in many cases. This study proposes a water-saving approach through an exhaust dyeing process, which aims to reduce water consumption without compromising the quality of dyed fabrics.

The exhaust dyeing process, conducted in a small-scale experimental setup, has successfully demonstrated a substantial reduction in water consumption. By strategically reusing the water used for neutralization and rinsing purposes in step 4 in step 2, the study achieved a significant reduction from the conventional 120 liters to 104 liters per kilogram of fabric (**Scheme 1)**. This 13% reduction in water consumption per unit of fabric indicates a promising step towards producing cleaner and more sustainable textiles.

The performance of the proposed dyeing process was evaluated through various parameters, including colorfastness to light, washing, rubbing and perspiration. Results of various tests are presented in **Table 2** (Color fastness to light, washing and rubbing), **Table 3** (Color fastness to perspiration) and **Table 4** (CMC tests):

Table 2. Color fastness to light, washing and rubbing

	Standard	Sample-1	Sample-2	Sample-3	Sample-4
Light:					
	5	4-5	4-5	4-5	5
Washing:					
	5	4-5	4-5	4-5	5
Rubbing:					
Dry	5	4-5	4-5	4-5	5
Wet	4-5	3	4	3-4	4

Table 3. Color fastness to perspiration

	Color Change	Color Staining					
		Wool	Acrylic	Polyester	Nylon	Cotton	Di-acetate
Acidic Medium:							
Standard	5	5	5	5	5	5	5
Sample-1	4-5	5	5	5	5	5	5
Sample-2	4-5	5	5	5	5	5	5
Sample-3	5	5	5	5	5	5	5
Sample-4	5	5	5	5	5	5	5
Alkaline Medium:							
Standard	5	5	5	5	5	5	5
Sample-1	4-5	5	5	5	5	5	5
Sample-2	4-5	5	5	5	5	5	5
Sample-3	5	5	5	5	5	5	5
Sample-4	5	5	5	5	5	5	5

Table 4. CMC tests

At D65 Light:

Samples	Decision	DE	DL	Da	Db	Dc	DH	Metamerism
Sample-1	Passed	0.29	-0.27	-0.51	-0.32	-0.53	-0.29	-
Sample-2	Passed	0.30	-0.05	-0.39	-0.52	-0.42	-0.49	-
Sample-3	Passed	0.42	-0.51	-0.82	-0.59	-0.80	-0.41	-
Sample-4	Passed	0.60	-0.59	-1.12	-0.63	-1.16	-0.56	-
At T84 Light:								
Sample-1	Passed	0.37	-0.39	-0.55	-0.47	-0.62	-0.38	0.17
Sample-2	Passed	0.37	-0.13	-0.38	-0.61	-0.46	-0.55	0.11
Sample-3	Passed	0.38	-0.24	-0.62	-0.57	-0.49	-0.43	0.26

Sample-4	Passed	0.52	-0.56	-0.82	-0.60	-0.89	-0.47	0.29
At T83 Light:								
Sample-1	Passed	0.32	-0.35	-0.36	-0.48	-0.50	-0.34	0.18
Sample-2	Passed	0.37	-0.12	-0.34	-0.66	-0.53	-0.52	0.18
Sample-3	Passed	0.45	-0.27	-0.79	-0.87	-0.52	-0.46	0.27
Sample-4	Passed	0.71	-0.79	-1.16	-0.98	-1.41	-0.56	0.23

The dyed cotton fabric exhibits excellent colorfastness under various conditions, confirming the effectiveness of the proposed water-saving dyeing process. Light color fastness was evaluated by xenon arc fading lamp test, which revealed consistent results across three exposure cycles with varying humidity and temperature conditions. Wash coloration, evaluated according to ISO-105-CO1, showed no significant change or staining of the fabric after exposure to washing wheels with standard soaps. Moreover, color fastness measured by ISO 105 × 2 L: 2002, gray scale treated fabric showed minimal color staining with favorable scoring. The results show that the dyed fabrics maintain excellent color fastness under various conditions, comparable to those achieved by conventional dyeing processes. The use of reactive dyes in advanced processes ensures vibrant and durable colors in cotton fabrics. These results highlight the feasibility of achieving sustainable dyeing practices without compromising color stability.

The economic feasibility of the proposed water-saving method is an important factor for its adoption in the textile industry. The results indicate that the improved process not only conserves water but also leads to potential cost savings by reducing the load on Effluent Treatment Plants (ETPs). Water reuse in the dyeing process reduces wastewater generation, leading to the dual benefits of environmental sustainability and economic efficiency.

The proposed water-saving dyeing process addresses the limitations of alternative methods such as supercritical carbon dioxide and organic solvent dyeing. Unlike nonpolar supercritical carbon dioxide, which struggles with dye adsorption on highly polar cotton fibers, the extraction dyeing process exhibits effective dye uptake. Furthermore, the cost-effectiveness of the proposed method, in contrast to the expensive supercritical carbon dioxide process, increases its practicality for widespread application in the textile industry.

Cationic modification and organic solvent dyeing, while offering improved dye absorption, pose additional pollution related challenges and difficulties in achieving zero emissions of organic solvents. In contrast, the extraction dyeing process of the present study stands out as an environmentally friendly alternative, reducing the need for citric acid and reducing wastewater generation. The simplicity and efficiency of the method make it a promising solution for sustainable textile dyeing.

The water-saving dyeing process presented in this study holds significant promise for textile manufacturing practices. By reducing water consumption, reducing waste water production and reducing reliance on chemical additives, textile manufacturers can contribute significantly to environmental conservation. This innovation aligns with the global push towards sustainable and environmentally friendly industrial processes. Further research and industrial adoption of this approach could have huge positive impacts, both ecologically and economically.

The improved water-saving dyeing process provides a practical and sustainable solution for the textile industry, which addresses the pressing issues of water scarcity, pollution and environmental impacts associated with conventional dyeing practices. The promising results of the color fastness test, along with the potential for significant water savings, position this method as a valuable contribution to the ongoing efforts to produce cleaner and greener textiles.

4. Conclusion

In response to the urgent global challenges of water scarcity, pollution and environmental sustainability, this study introduces a water-saving extraction dyeing process for cotton fabrics using reactive dyes. The importance of freshwater resources, intricately linked to climate change and vital to sustaining ecosystems, emphasizes the critical need for innovative and sustainable practices in industries that contribute to water depletion, such as the textile sector.

The developed exhaust dyeing process has demonstrated a significant reduction in water consumption, from the conventional 120 liters to 104 liters per kilogram of fabric. By strategically reusing water during the neutralization and rinsing steps, this method not only conserves freshwater resources but also minimizes wastewater production, contributing to cleaner production and reducing environmental impact.

Color fastness evaluation demonstrated that the dyed cotton fabrics maintained excellent color fastness under various conditions, confirming the effectiveness of the proposed dyeing method. Unlike some existing techniques that face challenges such as high cost, excess pollution and limited environmental compatibility, the extraction dyeing process presented here emerges as a sustainable alternative. The method avoids the problems of non-biodegradable solvents and excessive chemical auxiliaries, providing a practical solution for textile manufacturers aiming to balance economic efficiency with environmental responsibility.

A comparison with other green dyeing methods, including supercritical carbon dioxide and organic solvent systems, highlights the efficiency and cost-effectiveness of the improved process. The simplicity of the proposed method, combined with its positive environmental impact, positions it as a promising candidate for widespread adoption in the textile industry.

The study not only addresses specific challenges posed by water-intensive practices in the textile industry but also aligns with broader global efforts toward sustainable development. By significantly reducing water requirements, minimizing chemical use and maintaining high color fastness, this method represents a real step towards achieving cleaner and more responsible textile production. The potential impact of this innovation extends beyond the laboratory, offering a path for textile manufacturers to contribute meaningfully to the conservation of freshwater resources and the overall well-being of our planet. Further research, industry collaboration and implementation of these approaches could pave the way for a more sustainable future for the textile sector.

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