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.

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 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 [1, 2].

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 [3]. 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 [4].
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 [5]. 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 liters 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 [6]. 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. [7–9].

Therefore, implementing water-saving processes in reactive dyeing is crucial for reducing the industry's water footprint and promoting sustainable practices [10, 11]. 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 [12, 13]. However, the nonpolar supercritical carbon dioxide cannot effectively swell up highly polar cotton fibers leading to low dye uptake and poor color shade [14]. 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 [15]. 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 [16, 17]. However, achieving zero emissions of organic solvents is difficult. Similarly, Decamethylcyclopentasiloxane (D5)-water system, oil-water system and ethanol-water system have also been tested to achieve the aim of clean cotton dyeing. [18–20]. 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 [21].

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.

**Experimental Section**

**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.

**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.

**Dye Recipe:**

<table>
<thead>
<tr>
<th>Auxiliaries</th>
<th>Trade name</th>
<th>Doses</th>
<th>Brand Name</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild Acid</td>
<td>Citric Acid</td>
<td>0.5 g/l</td>
<td>Trade Asia Int.</td>
<td>Singapore</td>
</tr>
<tr>
<td>Detergent</td>
<td>Rucogen WBL</td>
<td>0.5 g/l</td>
<td>Rudolf Group</td>
<td>Germany</td>
</tr>
<tr>
<td>Anti-creasing Agent</td>
<td>Oxinol A24</td>
<td>1 g/l</td>
<td>Oxford</td>
<td>Australia</td>
</tr>
<tr>
<td>Levelling Agent</td>
<td>Lubrimax TEL</td>
<td>1 g/l</td>
<td>Oxford</td>
<td>Australia</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Salt (Na$_2$SO$_4$)</td>
<td>40 g/l</td>
<td>Lenzing</td>
<td>Indonesia</td>
</tr>
<tr>
<td>Alkali</td>
<td>Soda Ash (Na$_2$CO$_3$)</td>
<td>20 g/l</td>
<td>Nirma</td>
<td>Indonesia</td>
</tr>
<tr>
<td>Alkali</td>
<td>Caustic (NaOH)</td>
<td>2 g/l</td>
<td>Arabian Alkali</td>
<td>KSA</td>
</tr>
<tr>
<td>Shade %</td>
<td>Bezaktive Red S-3B</td>
<td>3%</td>
<td>CHT Switzerland</td>
<td>Germany</td>
</tr>
<tr>
<td>Fixing Agent</td>
<td>Fastasol RD</td>
<td>2 g/l</td>
<td>Oxford</td>
<td>Australia</td>
</tr>
<tr>
<td>Soaping Agent</td>
<td>Winscour RDC</td>
<td>2 g/l</td>
<td>Oxford</td>
<td>Australia</td>
</tr>
<tr>
<td>Softener</td>
<td>Sapamine CWS</td>
<td>3 g/l</td>
<td>Huntsman</td>
<td>Germany</td>
</tr>
</tbody>
</table>

**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 \((8 + 8 = 16 \text{ L/Kg fabric})\) 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:

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\(_2\)CO\(_3\)), hydrogen peroxide (H\(_2\)O\(_2\)). 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\(_2\)SO\(_4\)) 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 unfixed/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.

**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 grey 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.

**Result and discussion**

Water consumption and pollution during the dyeing process in textile industries is a critical issue for all the time which have the detrimental effects on biodiversity and ecosystem. This study focused on the development of a water saving approach for dyeing the cotton fabrics with reactive dyes without hampering the quality of dyed fabrics by avoiding any extra investment.

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 authorities. As a result, significant deviations from the standard values are observed in many cases.

In traditional exhaust dyeing process approximately 120 liters of fresh water are needed to dye 1 Kg of cotton fabric, which is an alarming scale of water usage. By implementing the present approach, one can easily save 16 liters of water per Kg of fabric by simply recycling the water that used for neutralization (8 L) and rinse (8 L) purposes at the 2nd step of the dyeing process. The flowchart of the proposed dyeing process is depicted in the Scheme 1. The stored water collected from the 2nd step was reused without doing any treatment. Therefore, no additional costs are involved in this process. To check the dyeing quality of dyed fabrics, all routine analyses were carried out by standard methods. Results of various tests are presented in Table 1 (Color fastness to light, washing and rubbing), Table 2 (Color fastness to perspiration) and Table 3 (CMC tests):

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color fastness to light, washing and rubbing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard</th>
<th>Sample-1</th>
<th>Sample-2</th>
<th>Sample-3</th>
<th>Sample-4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Light:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4–5</td>
<td>4–5</td>
<td>4–5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Washing:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4–5</td>
<td>4–5</td>
<td>4–5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Rubbing:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dry</strong></td>
<td>5</td>
<td>4–5</td>
<td>4–5</td>
<td>4–5</td>
</tr>
<tr>
<td><strong>Wet</strong></td>
<td>4–5</td>
<td>3</td>
<td>4</td>
<td>3–4</td>
</tr>
</tbody>
</table>
Table 2
Color fastness to perspiration

<table>
<thead>
<tr>
<th>Color Change</th>
<th>Color Staining</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wool</td>
</tr>
<tr>
<td><strong>Acidic Medium:</strong></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>5</td>
</tr>
<tr>
<td>Sample-1</td>
<td>4–5</td>
</tr>
<tr>
<td>Sample-2</td>
<td>4–5</td>
</tr>
<tr>
<td>Sample-3</td>
<td>5</td>
</tr>
<tr>
<td>Sample-4</td>
<td>5</td>
</tr>
<tr>
<td><strong>Alkaline Medium:</strong></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>5</td>
</tr>
<tr>
<td>Sample-1</td>
<td>4–5</td>
</tr>
<tr>
<td>Sample-2</td>
<td>4–5</td>
</tr>
<tr>
<td>Sample-3</td>
<td>5</td>
</tr>
<tr>
<td>Sample-4</td>
<td>5</td>
</tr>
</tbody>
</table>
The above results indicate that the color fastness and color differences under standardized and controlled lighting conditions are highly satisfactory and very much similar to that of the existing conventional dyeing process. No significant differences were observed in the results. Hence, it is possible to save 16 L of fresh water for dyeing for every 1 Kg of fabrics without any extra investment. The findings of this study are highly promising and the process can be used in industries. Implementing this process can not only contribute to water conservation but also reduce the wastewater generation and associated pollution. As a result, the cost related to water treatment plant (WTP) and effluent treatment plant (ETP) will be reduced significantly.

**Conclusion**

The present study addresses a burning issue in the textile industry *i.e.* the excessive use of water in dyeing process and its impact on the environment. Here, a water saving approach is described for dyeing the cotton fabrics with reactive dyes where a substantial amount of water can be saved by maintaining the quality of the dyed fabrics. The process, which does not need any additional investment, definitely
have paramount importance to combat against the scarcity of water resource and environmental pollution.

In the proposed water-saving exhaust dyeing process of cotton fabrics, 16 liters of water are recycled which allows to reduce water uses from 120 liters to 104 liters for dyeing of every 1 Kg fabric. The results indicate that the quality of dyed fabrics is almost similar to the quality that achieved through the existing exhaust dyeing process and most importantly, no additional costs are involved with the proposed process.

Furthermore, the environmental benefits of this process are substantial as it reduces the amount of effluents that can contribute to both water resource preservation and reduced pollution as well as this, in turn, can lead to cost savings related to water treatment and effluent management.

While the issue regarding the environmental sustainability and water conservation is a growing concern, the findings of this study can provide a promising solution for textile industry by minimizing the water uses. By adopting this water-saving approach, textile manufacturers can play a pivotal role in addressing the global challenges associated with water scarcity, pollution, and climate change.

**Declarations**

**Author contribution statement**

Md. Reza-Ul-Hoque: Design the experiments; Performed the experiments; Analyzed the data.

M. Abdul Jalil: Supervision; Analyzed and interpreted the data; Wrote the paper.

Shahin Hossain: Analyzed and interpreted the data; Analyzed tools.

Ayub Nabi Khan: Analyzed and interpreted the data; Reviewing the paper.

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**Financial interests:** The authors declare they have no financial interests.

The authors have no competing interests to declare that are relevant to the content of this article.

**References**


**Scheme 1**

Scheme 1 is available in the Supplementary Files section.

**Figures**

![Figure 1](image)

**Figure 1**

Bezaktive Red S-3B

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalAbstract.png
- Scheme1.png