



Revolutionizing Textile Dyeing: Investigating Water-Saving Strategies From A Research Perspective

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Abstract

Water scarcity poses a significant challenge to the textile industry, prompting the exploration of innovative solutions to reduce water consumption in manufacturing processes. One such solution gaining traction is waterless dyeing technology. Unlike traditional dyeing methods that heavily rely on water as a solvent, waterless dyeing technology utilizes alternative mechanisms to impart colour to textiles without the need for extensive water usage.

Waterless dyeing technology represents a paradigm shift in textile manufacturing, offering numerous advantages over conventional methods. By eliminating the need for large volumes of water, this technology significantly reduces the environmental footprint associated with textile dyeing processes. Moreover, it mitigates the discharge of effluents, thereby addressing concerns related to water pollution and wastewater management.

The implementation of waterless dyeing technology also holds economic benefits for textile manufacturers. By minimizing water consumption, companies can reduce operational costs associated with water procurement, treatment, and disposal. Additionally, the efficient use of resources enhances production efficiency and enables cost savings in the long term. Furthermore, waterless dyeing technology aligns with sustainability objectives and corporate responsibility initiatives adopted by many textile companies. By embracing innovative and eco-friendly practices, organizations can enhance their reputation, attract environmentally conscious consumers, and contribute to global efforts towards sustainability.

Despite its potential, the adoption of waterless dyeing technology in the textile industry faces certain challenges. Technical feasibility, scalability, and initial investment costs are among the factors that need to be carefully considered. However, ongoing research and development efforts aim to overcome these obstacles and facilitate the widespread implementation of waterless dyeing technology.

In conclusion, waterless dyeing technology represents a promising avenue for reducing water consumption and promoting sustainability in the textile industry. As companies strive to minimize their environmental impact and meet evolving consumer demands, the adoption of innovative solutions such as waterless dyeing technology is poised to play a pivotal role in shaping the future of textile manufacturing

Keywords: # Water-Saving # Supercritical Fluid Dyeing # Environmental sustainability
Freshwater # Supercritical carbon dioxide # Surface water # Textile dyeing
Waterless dyeing

1. Introduction

The textile sector is widely recognized as one of the foremost consumers of water resources. Water plays a pivotal role in traditional textile dyeing processes, encompassing both the input of fresh water and the discharge of effluents. Various pretreatment and finishing procedures, including washing, scouring, bleaching, and dyeing, necessitate water as a primary solvent. On average, the processing of 1 kg of textile material demands 100-150 liters of water, with the dyeing phase alone consuming approximately 16% of this quantity. Notably, water stands as the most precious natural resource globally, with over 97 percent comprising saline water and only 2.5 percent constituting fresh water. Within this fraction, more than two-thirds (68.7%) exists as frozen snow and ice, while the remaining portion is stored as groundwater beneath the Earth's surface. Merely 0.3 percent of the world's freshwater is readily accessible as surface water in forms such as lakes, ponds, rivers, and streams. Consequently, in order to conserve this finite freshwater resource, it is imperative for manufacturers to explore alternative techniques for textile dyeing.

2. Water Consumption in the Textile Industry

Excluding agriculture, the textile industry stands as one of the most water-intensive sectors globally. Projections indicate a 40% surge in the global demand for fresh water by 2030, driven by population growth. By 2050, it is anticipated that over a billion individuals will face water scarcity issues on a daily basis. Illustrating the magnitude of water utilization in textile processes, the dyeing of a mere two pounds (one kg) of cotton fabric necessitates up to 26 gallons (100 liters) of water. An average-sized textile mill consumes approximately 1.6 million gallons of water per day.

Water consumption varies depending on the dyeing method employed. For instance, dyeing processes typically consume between 30 to 50 liters of water per kilogram of cloth, while yarn dyeing operations utilize around 60 liters of water per kilogram of yarn. Notably, the dyeing sector contributes to 15–20 percent of the total wastewater discharge from industrial activities. In response to mounting environmental concerns, stakeholders including governments, non-governmental organizations (NGOs), and consumers have exerted pressure on the textile industry to enhance its environmental stewardship. This scrutiny is anticipated to persist, with governments worldwide intensifying regulatory measures to monitor and mitigate water pollution stemming from textile manufacturing activities. Consequently, the industry is poised to face heightened regulatory oversight in the foreseeable future.

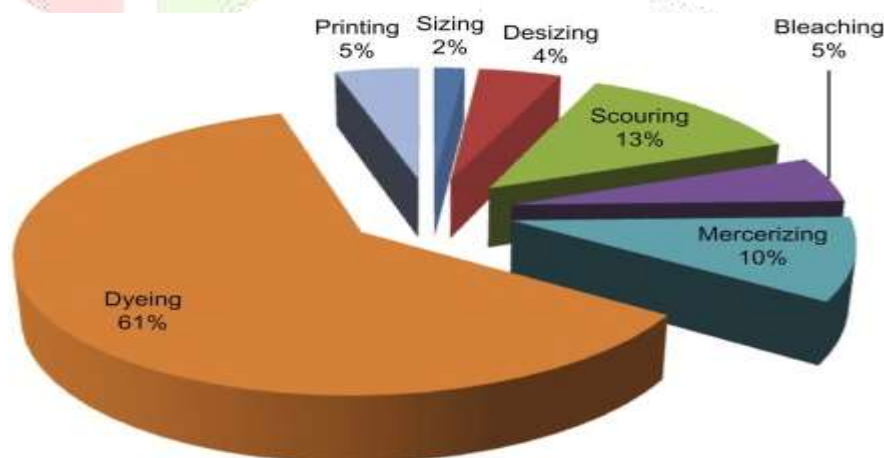


Figure 1: Water consumption in textile industry

In order to genuinely mitigate its environmental impact, the textile industry must assume responsibility and actively implement sustainability initiatives. Over the years, the industry has dedicated significant efforts to exploring innovative strategies aimed at reducing water consumption. These efforts include initiatives such as decreasing the liquor ratio and adopting textile dyes that demand less water during the dyeing process. By embracing such measures, the textile sector can progress towards achieving more

sustainable and environmentally conscious practices, contributing to the collective effort to safeguard natural resources and mitigate ecological harm.

3. Waterless Dyeing

Waterless dyeing is a dyeing method that eliminates the need for water. This process not only conserves water but also reduces energy consumption compared to conventional dyeing techniques, all while yielding vibrant colours in both solids and designs. The implementation of waterless dyeing involves a reduction in the usage of time, chemicals, and auxiliaries typically associated with traditional dyeing processes. There are two prominent waterless dyeing technologies:

3.1 Air Dyeing Technology

3.2 Supercritical Fluid Dyeing Technology

3.1 Air Dyeing:

In air dyeing, the dyeing fluid undergoes atomization before being mixed with high-pressure airflow and subsequently sprayed onto the fabric within an airflow dyeing machine. Typically, only a minimal amount of water is employed, as water primarily acts as a solvent for the dyeing liquor, facilitating direct contact between dye chemicals and the fabric. Airflow dyeing machines offer notable advantages over conventional overflow dyeing machines, including heightened efficiency, energy savings, and environmental sustainability.

The fabric progresses through an air-steam mixture generated by a blower, forming the foundation of the aerodynamic system. Unlike hydraulic dyeing machines, cloth transportation in air dyeing processes does not necessitate immersion in a dye bath or aqueous medium. In essence, fabric transfer occurs without the utilization of liquor, facilitating continuous movement of the material from feeding to completion of the operation, as well as during drainage and filling procedures.



Figure 2: Air flow dyeing machine

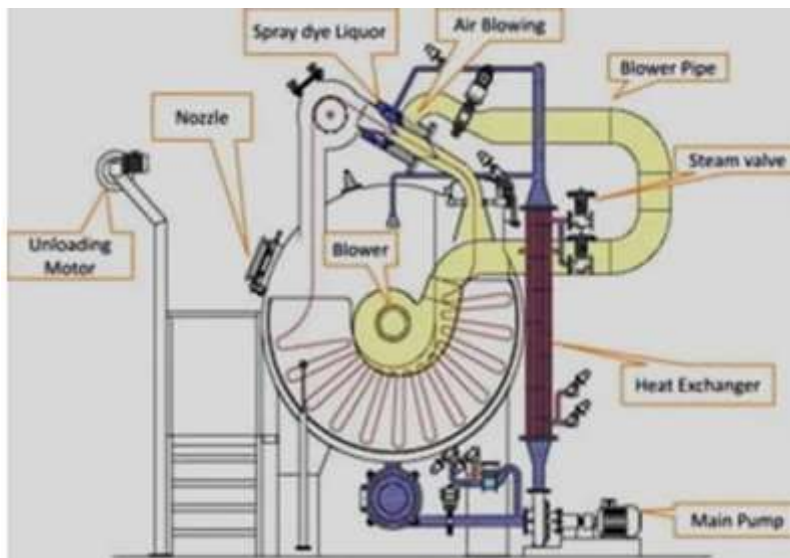


Figure 3: Flow Diagram – Air Flow

3.1.1. Advantages of Air Dyeing:

3.1.1.1. Environmental Preservation:

- ✓ Air dyeing eliminates water pollution during the color application process. By transporting dye via air rather than water, it prevents the emission of hazardous waste and conserves water resources.
- ✓ This technology significantly reduces energy requirements, leading to cost savings and compliance with stringent global environmental standards.
- ✓ Air dyeing circumvents the generation of toxic wastewater typically associated with traditional textile dyeing processes. Given the escalating issue of water scarcity affecting a substantial portion of the global population, particularly with urbanization and increased water usage, this advantage is particularly significant.

3.1.1.2. Resource Efficiency:

- ✓ According to an independent assessment, air dyeing technology can reduce water usage by up to 95% and energy consumption by up to 86%, resulting in an 84% decrease in contributions to global warming, depending on the fabric and dyeing method.
- ✓ Some companies assert that air dyeing technology facilitates print-to-order capabilities, minimizing waste and excess production.

3.1.1.3. Chemical Reduction:

- ✓ Since dyes are injected directly into the fabric rather than applied onto it, air dyeing eliminates the need for bleaching and cleaning chemicals, further reducing environmental impact.
- ✓ Despite its numerous benefits, air dyeing technology remains relatively nascent, with the initial cost of machine installation being high. Consequently, future research in textile dyeing may focus on developing cost-effective air dyeing processes for both natural and synthetic materials, prioritizing reduced water usage and minimal pollutant emissions.

3.2 Supercritical Fluid Dyeing:

Supercritical fluid dyeing is a waterless dyeing method that utilizes supercritical carbon dioxide (CO₂). When carbon dioxide is subjected to temperatures exceeding 31°C and pressures above 74 bars, it reaches a state known as supercritical, exhibiting properties akin to both an expanded liquid and a highly

compressed gas. Essentially, beyond its critical point, carbon dioxide manifests characteristics of both liquid and gas phases. This unique property renders supercritical CO₂ capable of achieving liquid-like densities, facilitating the dissolution of hydrophobic dyes, while also possessing gas-like low viscosities and diffusion properties, which can expedite the dyeing process compared to traditional water-based methods.

The carbon dioxide dyeing process integrates various stages such as extraction of spinning oils, dyeing, and removal of residual dye within a single facility. These stages only necessitate adjustments in temperature and pressure conditions, obviating the need for drying as CO₂ is naturally expelled in a gaseous state at the conclusion of the process. Moreover, carbon dioxide can be readily recycled, with up to 90% of the extracted material precipitated in a separator for reuse.

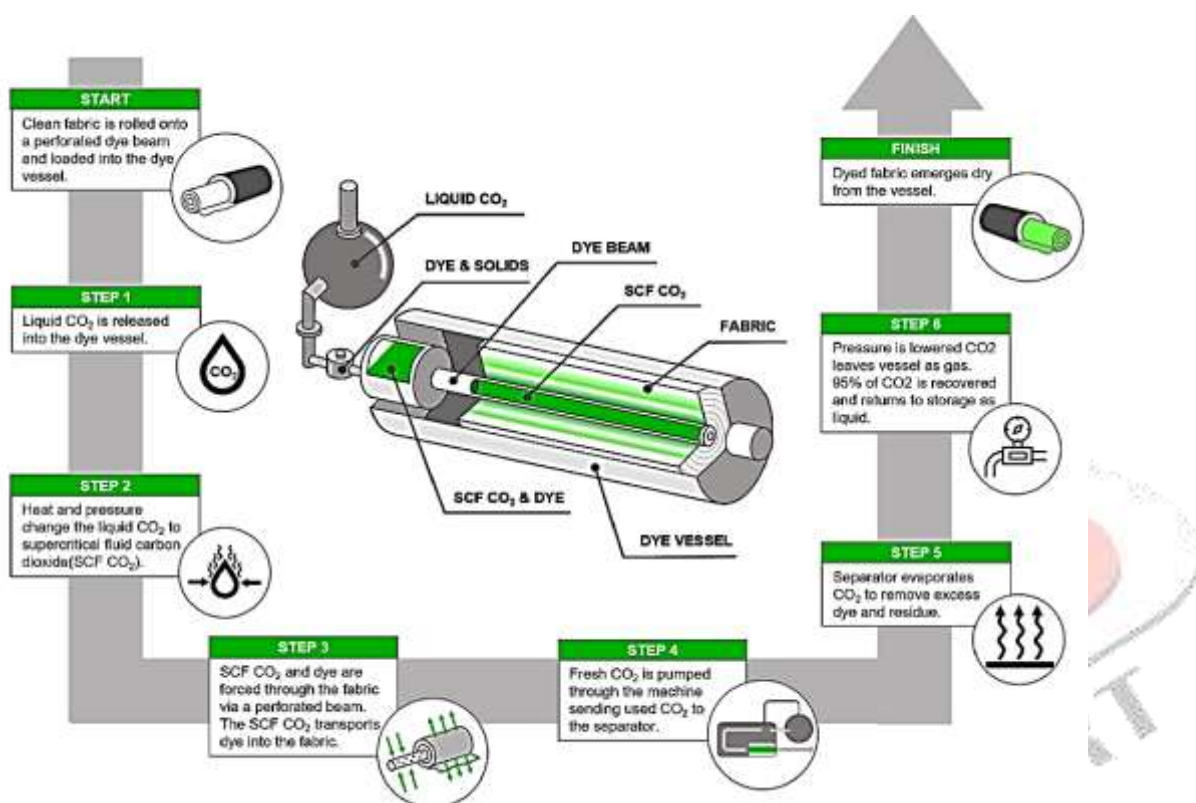


Figure 4. Supercritical carbon dioxide dyeing process

3.2.1 Advantages of Supercritical Fluid Dyeing:

1. Sustainability:

- The CO₂-based dyeing process presents a sustainable alternative to conventional water-based dyeing methods, reducing reliance on finite water resources.

2. Reduced Energy Consumption:

- This process eliminates the need for processing water and chemicals, resulting in a 50% reduction in energy consumption compared to traditional dyeing processes.

3. Environmental Preservation:

- By eliminating water contamination and the need for water treatment, supercritical fluid dyeing minimizes environmental impact and mitigates concerns related to water pollution.

4. Elimination of Drying:

- Textiles dyed using this method do not require drying, streamlining the production process and reducing energy usage further.

5. Enhanced Performance:

- The resulting textiles exhibit high rubbing fastness, ensuring durability and longevity of colour retention.

6. Uniform Dyeing:

- Dyeing occurs with a high degree of uniformity, ensuring consistent coloration across the fabric.

7. Non-Toxicity:

- Carbon dioxide, the primary medium used in the dyeing process, is a non-toxic substance that can be easily regenerated, posing minimal environmental and health risks.

8. Flexibility in Location:

- In regions with limited water availability, dyeing facilities can be established without reliance on abundant water resources, offering operational flexibility and adaptability.

Overall, supercritical fluid dyeing offers a multitude of advantages, ranging from environmental sustainability and resource efficiency to improved performance and operational flexibility, making it a compelling choice for the textile industry's quest for more sustainable and environmentally responsible dyeing practices.



Figure :5 - Machine used in supercritical fluid dyeing

3.2.2. Disadvantages of Supercritical Fluid Dyeing:

1. High Operating Conditions:

- The dyeing process necessitates operating at pressures ranging from 260 to 280 bar and temperatures of 130°C. These elevated conditions require specialized textile machinery designs and significant investment for upgrades. The exceptional pressures involved may also pose mental barriers for textile businesses.

2. Safety Concerns:

- Due to the use of carbon dioxide, a suffocating gas, industrial labour safety considerations necessitate the installation of a control device to monitor CO₂ concentrations in the air.

3. Measurement Challenges:

- Traditional colour measuring techniques may encounter additional challenges due to the non-additive behaviour of dye components in supercritical fluid dyeing applications.

4. Limitations with Natural Fabrics:

- The technology is currently unsuitable for dyeing natural (hydrophilic) fabrics since it cannot disrupt hydrogen bonds, impeding the diffusion of supercritical carbon dioxide.

5. Dye Stability:

- Reactive dyes, direct dyes, and acid dyes may face degradation at the high temperatures and pressures characteristic of supercritical fluid dyeing processes.

In summary, while supercritical fluid dyeing offers notable advantages in terms of sustainability and efficiency, it also presents significant challenges related to equipment requirements, safety considerations, colour measurement, fabric compatibility, and dye stability. Addressing these drawbacks will be crucial for further development and adoption of this technology within the textile industry

4. Conclusion

The techniques discussed above offer promising avenues for conserving fresh water resources by circumventing the extensive water consumption inherent in conventional water dyeing processes. As the demand for fresh water continues to escalate due to growing global populations and expanding urbanization, the adoption of waterless dyeing technologies becomes increasingly imperative for sustaining essential daily activities.

Waterless dyeing technologies not only eliminate the need for large volumes of water but also eliminate the washing step, thereby preventing water contamination resulting from wastewater discharge into fresh water resources. By embracing these innovative techniques, the textile industry can play a significant role in water conservation efforts. As more of these waterless dyeing technologies are implemented, the cumulative effect of water conservation becomes increasingly substantial. By reducing water consumption and minimizing environmental impact, these technologies contribute to the preservation of precious fresh water resources for current and future generations.

In conclusion, the adoption and advancement of waterless dyeing technologies represent essential steps toward achieving sustainable and responsible water management practices within the textile industry, ultimately contributing to broader conservation efforts on a global scale.

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