Research Article
Volume 10:6, 2020
DOI: 10.37421/jtese.2020.10.421

Journal of
Textile Science & Engineering

ISSN: 2165-8064
Open Access

Recent Progress in Waterless Textile Dyeing

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Abstract

Two new processes of waterless textile dyeing known as air-dye and supercritical carbon dioxide ($scCO_2$) assisted dyeing is reviewed and discussed. The conventional textile dyeing industries use freshwater as a solvent and drain them as wastewater. Each year trillions of freshwater and over ten thousand dyes and pigments are used globally. The wastewater from these industries is dumped into the surrounding lakes, agricultural fields, rivers, etc. The impact of textile dyeing is therefore significant because it decreases the freshwater level and polluting the surface water unceasingly. Thus, from decades, researchers have tried to develop a technology that is waterless and pollution-free. Because of researcher's tremendous efforts, two such waterless dyeing method is in our hand now. These processes have multiple advantages over conventional techniques, such as emission of less waste and less greenhouse gases, shorter operating time, less energy consumption, etc. Moreover, they have good diffusivity, readily available, reusable, non-flammable and non-toxic, making the process economically feasible and environmentally attractive. Several textile converters in Europe, Asia and North America currently use AirDye. $scCO_2$ method has gained the attention of brands such as Nike, Adidas and IKEA, all of whom have used this process to dye their own products. With versatile advantages, there are some drawbacks. Such as the dyeing is only applicable to synthetic fabrics like polyester and the installation of machines are relatively expensive. In this report, the current status of research and development on resolving several issues like this is also summarized.

Keywords: Air-dye • Environmental sustainability • Freshwater • Supercritical carbon dioxide • Surface water • Textile dyeing • Waterless dyeing

Introduction

A textile dye is a chemical substance used to color the fabrics. It may be natural or synthetic. The use of natural dyes began around 4000 years ago in Egyptian tombs. In 1856, Perkin discovered the first synthetic dye called mauve. Since then, natural and synthetic dyes are readily used to color the fabrics, which give the cloth a beautiful look. Textile dyes are an essential part of the whole garment manufacturing industry. The global textile dyes market is estimated to reach USD 10.13 Billion by 2026 [1]. The dyeing industries use different techniques to color the fabrics [2,3]. The process depends on many characteristics, including the type of material such as fiber, yarn, fabric, fabric construction, etc. The conventional textile dyeing process uses a large amount of freshwater as a solvent. The textile industry is the third-largest consumer of water in the world after the agriculture and energy production sector. On average, an estimated 100-150 liters of water are needed to process 1 kg of textile material and 16% of this is consumed in the dyeing process [4,5]. Figure 1 show the total water consumed in different stages during wet processing in the textile industry.

The most precious natural resource of the world is the water, of which more than 97% is saltwater and approximately 2.5% is fresh water. More than two-thirds (68.7%) of 2.5% freshwater is frozen as snow and ice, and about one-third is stored below ground as groundwater. It seems that only 0.3% of all freshwater on the planet is readily available as surface water in lakes, swamps, rivers and streams [6]. Therefore, to conserve this limited source of freshwater, industrialists should develop alternative techniques of textile dyeing.

On the other hand, most of the dyeing industries discharge wastewater without pretreatment. The various dyes that are frequently used in the dyeing industries are toxic and hazardous, which has a direct and indirect

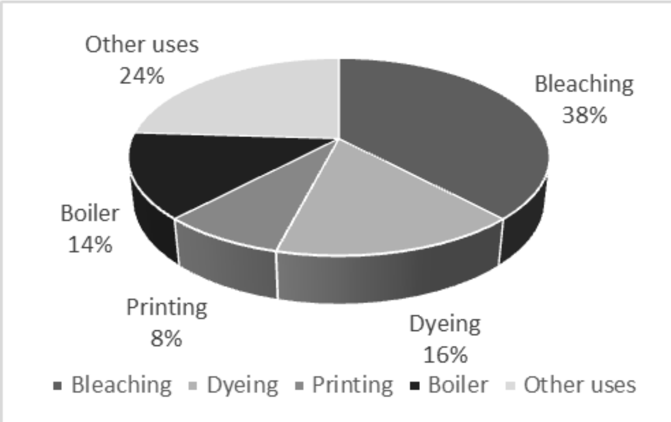

Figure 1. Total water consumption during wet processing of textile industry [4,5].

impact on human health. Even a simple chemical such as acetic acid can significantly increase the BOD. Therefore, it is an urgent requirement to keep water pure and pollution-free, especially during textile dyeing and hence to develop new methods. Most of the dyeing industries currently use the conventional wet chemical process for coloring fabrics, but few companies recently implemented waterless dyeing. Two such waterless dyeing's known as the air-dye process and supercritical carbon dioxide ($scCO_2$) assisted method, received considerable attention recently. These waterless dyeing techniques use less water, produce less waste, consume less energy and emit less greenhouse gases than the conventional dyeing. A vast number of research articles and scientific reports are published recently where many aspects and issues of waterless dyeing technology have been resolved and discussed [7-12]. This article aimed to summarize the current development, advantage and adoption of waterless dyeing processes based on the scientific literature and reports.

The recent development of waterless air-dye process and supercritical carbon dioxide assisted process

Air-dye process: Colorep, a California-based sustainable technology company, has proposed a new emerging airflow dyeing process [11]. In airflow dyeing machine, dyeing liquor is first atomized, then mixed with high-pressure airflow, finally sprayed on fabric to be dyed. Because water serves

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Received 03 September 2020; **Accepted** 30 September 2020; **Published** 07 October 2020

as a solvent of dyeing liquor and the dye chemicals directly contacts the fabric, only a little water is consumed. The air-dye process does not pollute water and uses air instead of water to convey dye, no hazardous waste is emitted and no water is wasted. The principle of air-dyeing is explained in detail by Murugesh [13].

In the last few years, two companies have developed their waterless air dyeing technology. These are American enterprises named AirDye(R) and Colorzen. In the AirDye(R) technology, cloths are put into printing machines instead of dipping them in the traditional bath filled with water and dye. This technique uses specially formulated colors from paper onto polyester fabric. AirDye(R) uses 95% less water depending on the fabric, 86% less energy and 84% less greenhouse gases than the conventional dyeing. The significant advantages of air-dye include less amount of hazardous waste emission, minimize water consumption, and many aspects are described in many scientific reports and journals [10-13]. However, this technology works only on synthetic materials like polyester, but natural fibers like cotton are not usable for the air-dye process. Several textile converters in Europe, Asia and North America currently use AirDye(R).

In 2012, a group of talented world-class engineers and apparel experts established ColorZen(R) technology to color the cotton fibers. They have modified the structure of cotton fibers considering a pretreatment process, which makes that cotton more receptive. ColorZen(R) is a revolutionary technology that makes cotton dyeing more efficient and environmentally friendly. Their advanced technology can use up to 90% less water, 75% less energy and 95% less chemicals with zero toxic discharge. Recently, the China-based Cleantech Solutions International, Inc. designs and produces airflow-dyeing machines, which use air instead of water. According to Mr. Jianhua Wu, Founder and CEO of Cleantech Solutions, the airflow-dyeing device atomizes the water under high pressure. Therefore, their products can save two-thirds of the water consumed by traditional models. They are also researching the water-less dyeing machine that is still in the early R&D and trial stage [14-15].

The air-dye technique is relatively new and the machine installation cost is expensive. Therefore, the development of low cost simple air-dye coloring approaches for natural and synthetic fabrics with less water consumption and nearly zero pollutants could be the researcher's future interest in textile dyeing. Some important features of AirDye(R) and ColorZen are summarized in Table 1.

Supercritical carbon dioxide assisted process: German Professor Schollmeyer and his research group first established supercritical fluid dyeing in the late 1980s. Since then, many research activities and experiments, from laboratory scale to pilot scale, have been developed [16,17]. Generally, carbon dioxide (CO_2) is used as a fluid because of its non-flammability, nontoxicity and availability. Additionally, its critical temperature (T_c=31.1°C) and pressure (P_c=74 bar) are lower than that of many other fluids, which makes CO_2 more attractive [18]. The supercritical CO_2 acts both as liquid and gas at above 31.1°C and 74 bar. The liquid-like densities are advantageous for dissolving hydrophobic dyes, and gas-like low viscosities and diffusion properties can lead to shorter dyeing times compared to water.

In 2008, DyeCoo developed a waterless dyeing method where they use the power of $scCO_2$ as a solvent for many synthetic and natural dyes. This process has multiple advantages such as shorter time and a 50% lower operating cost compared to the conventional water dyeing process. A good solubility, diffusivity and zero surface tension could be achieved by this method as well. Moreover, CO_2 and dyes can be reused, making the process economically feasible and environmentally attractive. The advantages of DyeCoo's methods have gained the attention of brands such as Nike, Adidas and IKEA, all of whom have used this process to dye their own products. DyeCoo is the world's very first supplier of CO_2 dyeing equipment as well. DyeCoo's waterless textile dyeing using $scCO_2$ technology has been in commercial use in mills in Thailand since 2010 and, more recently, in Taiwan and India. Some essential features of DyeCoo are also summarized in Table 1. However, the low polarity of $scCO_2$ is a clear hindrance to the dyeing of polar hydrophilic fiber; hence like AirDye(R), $scCO_2$ dyeing is only applicable to synthetic fabrics. The current research and development continue to focus on resolving several issues like this [19,21]. For instance, the most $scCO_2$ equipment usually had a vertical layout, which results in non-homogeneous fluid distribution, dye accumulation, and thus uneven textile dyeing caused by gravity. Recently Huang *et al.* constructed pilot-scale horizontal equipment for zipper tape dyeing in $scCO_2$ at relatively low temperature (90 ± 2ºC) and concluded that commercialization of waterless dyeing would have great practical and strategic significance [22]. Yan *et al.* developed a special dye and its application in the ecological dyeing of silk with supercritical carbon dioxide [23]. Excellent adsorption, uptake and fixation behaviors, and the highest color fastness graded at 4-5 in color fading test were reported for the synthesized special dye on

Table 1. Summary of important features of the $scCO_2$ and air-dyeing process in comparison to the *traditional dyeing processes.*

	Supercritical carbon dioxide process	**Air-dye process**
Main power source	Supercritical CO_2 as fluid	Uses air instead of water
Working Condition	High pressure and temperature is required	dyeing liquor is first atomized, then mixed with high-pressure airflow, finally sprayed on fabric to be dyed
Synthetic and natural dye	The technology developed and optimized for the dyeing of polyester, acetate and nylon while some experimental study on natural fibers available	The technique works on synthetic materials. Dyeing in cotton fabrics with specialized treatment to the raw cotton is reported.
Colorfastness	Good Colorfastness	Good Colorfastness
Design potential	The dye is distributed evenly over the fabric	Print or dye both sides of the fabric simultaneously
Speed and efficiency	Due to the favorable diffusion properties, the times needed for the dissolution of the solid dyestuff will be cut to a negligible minimum	Coloring and printing can be done in a short time with full accuracy and efficiency. A reduction in the overall process time of approximately 25 percent.
Uniformity of dye distribution	The non-uniformity of the fluid may result in staining of the textile and affect the evenness of dye distribution	Unlimited flexibility with regard to all-fiber except for pure wool
Co-solvent	addition of small amounts of a co-solvent can considerably increase the solubility of solutes in $scCO_2$	Dyes penetrate deeply into the filaments of the yarn to create rich, deep, and brilliant colors
Water and energy use	CO_2 dyeing is a dry process, eliminating the need to evaporate water. Technology is very energy efficient.	use 90 to 95% less water and save 86% of the energy
Reuse	CO_2 can be vacuumed out after use, allowing for 95% recovery and reuse	Air-dye recycles paper used in the process and the dyes are inert, which can go back to their original state and be reused
Environmental sustainability	Ecologically harmless, non-toxic and non-explosive. A green method for the sustainable and eco-friendly textile industry.	Causes minimum harm to the environment and reduces the industry's share of global warming by 84%
Installation cost	Expensive	Expensive

silk. Elmaaty *et al.* synthesized five especial disperse dyes and applied for coloration of polypropylene (PP) fabrics in supercritical carbon dioxide media. One of these dyes applied on a pilot scale showed good coloration behaviors, characteristics, and colorfastness. The dyestuff, as well as the methodology, proves that an industrial scale dyeing of PP under $scCO_2$ is possible. Overall, $scCO_2$ dyeing received considerable attention, and many scientific papers are published during recent years, where many issues of $scCO_2$ assisted dyeing is resolved and discussed [17-24]. Hence it is clear that $scCO_2$ assisted textile dyeing has a bright future for conserving freshwater as well as reducing waste.

Conclusion

Two waterless dyeing methods have undoubtedly proven their feasibility of industrial-scale dyeing. Adoption of these technologies can reduce the loss of the most valuable natural resource, of which only 2.5% is available as freshwater. As this waterless dyeing produces less waste and uses minimum energy, short production time and reusable, it can be the future interest of the global textile dyeing industry. However, waterless dyeing technology has been around for over twenty years, and it has still not been accepted by the textile industry. The main reasons for this may be the industrialist not wants to replace waterless dyeing for the conventional process, which they are using for the centuries, or the higher machine installation cost of the waterless dyeing process. Therefore, the price of waterless dyeing machines should be reduced so that dyeing industries around the globe can able to make such investment.

Bangladesh, the second-largest readymade garment manufacturing country, has a 240-registered dyeing-printing-finishing unit under BGMEA in 2018-19 FY. However, the number of unregistered dyeing industries is far higher than 240. Furthermore, the technology is spreading and the dye application has become a massive industry. Rivers like Buriganga, Turag, Shitalakhyya are affected mostly as these are the common industrial area of Bangladesh. Therefore, pioneer industries of Bangladesh should think about the adoption of waterless dyeing among their textiles as a whole or partially.

Acknowledgment

None. No funding to declare.

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How to cite this article: Iqbal Mahmud and Shantanu Kaiser. Recent Progress in Waterless Textile Dyeing. *J Textile Sci Eng* 10 (2020) doi: 10.37421/jtese.2020.10.421