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An Overview of Dyeing without Water Techniques

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Abstract

An enormous quantity of water, chemicals, and energy are used in the traditional textile coloring process. Furthermore, hazardous byproducts from the dye house, including excess dyestuff, salts, auxiliary chemicals, and solvents, are released into the environment and represent a major risk to public health. Owing to the growing worldwide consciousness about environmental concerns and the scarcity of water in several regions, the textile sector is compelled to explore for substitute eco-friendly technologies that may curtail the usage of freshwater and the corresponding hazardous waste products. In this review we will discusses some of the water- and environmentally-friendly dying techniques such as air dyeing , foam dyeing and supercritical carbon dioxide ($scCO_2$) assisted dyeing technologies, which have been developed to support safe, economical, and sustainable textile dyeing process. These methods offer several benefits when compared to traditional ones, including less waste and greenhouse gas emissions, shorter working times, lower energy usage, etc. In addition, their high diffusivity, easy availability, reusability and non-toxicity render the procedure both eco-friendly and economically viable.

Keywords: Eco-friendly, Air dyeing, foam dyeing, $scCO_2$

Introduction

Textile dye is a chemical substance used to color the fabrics, which may be natural or synthetic. It is an essential part of the whole garment manufacturing industry. Dyeing industry uses different techniques to color the Textile. the problem is that conventional textile dyeing process uses a large amount of freshwater as a solvent for the dye and the other chemicals, so it is classified as the third-largest consumer of water in the world after the agriculture and energy production sector. One kilogram of textile material is thought to require between 100 and 150 liters of water on average, of which 16 percent is used during the dyeing process. Fresh water represents approximately 2.5% only of the world's water, more than two-thirds of it is frozen as snow and ice, and about one-third is stored below ground as groundwater, so it seems that only 0.3% of all freshwater on the planet is readily available as surface water. Thus, producers should create alternate methods of textile dyeing in order to protect this limited resource of freshwater.[1-7]

However, the majority of dyeing manufacturing release untreated liquid waste into the environment. This affects human health both directly and indirectly by those poisonous and dangerous dyes and other chemical, because the BOD may be greatly raised by even a basic substance like acetic acid. Thus, it is important to create innovative techniques in the process. However a small number of businesses have lately started using new techniques of waterless dying such as air-dyeing process, supercritical carbon dioxide ($scCO_2$) assisted method and foam dyeing technique.[3, 8, 9]

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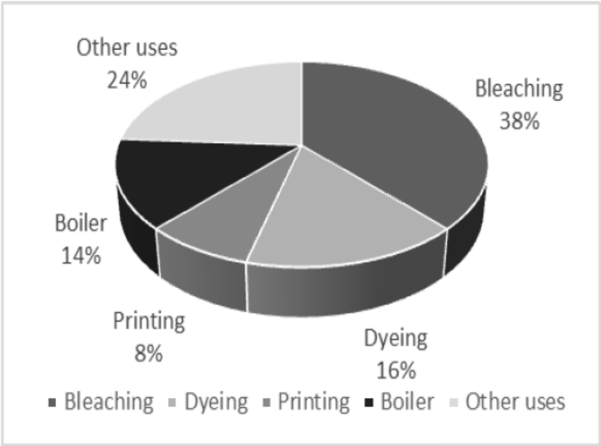


Total water consumption during wet processing of textile industry

Air-dye technique

Thanks to Air-dye technology, water is not needed for the application of color to fabrics. Instead of using water air-dyeing process uses air. That consumes less energy and no water than standard dyeing procedures, as air-dyeing method consumes up to 95% less water and up to 86% less energy, contributing 84% less to global warming depending on the fabric type and the dye. Because the dye is truly absorbed into the fibers, air-dyed fabrics do not fade or lose colors as readily as vat-dyed fabrics.[9] Air-dye technology is presently exclusive at the United States and is only effective on synthetic fabrics only and is not compatible with natural fibers like cotton.[2, 9] Air-dyeing technology is also known as air-jet dyeing technology which is similar to the jet dyeing technique but it uses air instead of water. . The air-dyeing concept was developed and the prototype machine was invented in 1978.[8]

Air-dyeing (Air-Jet dyeing) method

Air-jet dyeing principle is similar to the jet dyeing system, but in it the fabric is circulated by air that makes it is simple and relatively faster than the conventional jet dyeing method, in which textile goods are dyed in rope form in a closed tubular system.[8] Airflow is the primary component of this technology as air is the perfect medium for transportation. Reducing the amount of water and chemicals used in jet-dying equipment was greatly aided by the use of air for dye liquid, The mass flow theory behind the operation of the air dyeing method greatly improves the fabric's hand laying, preventing creases.[2, 10]

The fundamental idea behind the airflow system is that a mechanical roller directs the fabric as it moves through a combination of high-pressure air streams that are released from a blower. The dye liquid, which consists of dye and chemical auxiliaries, is first atomized using a specially designed nozzle, then pumped into a high-pressure airflow, and lastly deposited in a spray form with a precise amount onto the moving textile using a number of nozzles. The atomized dye has a strong infusion into the fiber and wide contact regions with the fabric during spraying, which quickens the dye's diffusion rate.

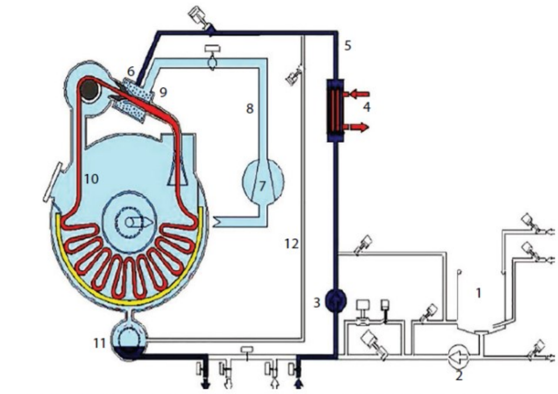


Illustration of an airflow dyeing machine with an indication of air circulation and injection of the dye liquor. (1) Dye tank, (2) dye pump, (3) injection or main pump, (4) heat exchanger, (5) dye liquor pipe, (6) dye liquor nozzle, (7) blower, (8) air pipe, (9) air nozzle, (10) fabric, (11) collector, (12) return pipe for excess liquor.

With the air-jet dyeing procedure, it is possible to reach lower liquor ratios (1:2 to 1:5) and a fabric speed of up to 1,000 m/min without causing damage to the fabric. It is possible to circulate the extra liquor and the air compressed with dye that was pressed to the textile.[8]

Advantages of Air-dyeing technology

According to an objective evaluation, Air-dye consumes up to 95% less water and up to 86% less energy, contributing 84% less to global warming depending on the fabric and type of dyes used. Furthermore, according to some businesses, Air-dye technology allows them to work on demand, eliminating waste and extra output.[8, 9]

Reduces the need for boilers, drying ovens, and offers cleaning steps while streamlining the dyeing process.[9]

The procedure of applying color doesn't pollute the water, because the air transport of dye eliminates the need for water, therefore saving both water and hazardous waste emissions.[9]

Since the Air-dye technique injects the dyes into the fabric rather than onto it, bleaching agents and other cleaning chemicals have no effect on the fabric, allowing it to be washed at any temperature, with white or colored fabrics, and with or without bleaching agents.[9]

Significantly lowers energy needs, which lowers costs and satisfy the most stringent requirements for global accountability.[8, 9]

Air-dyeing process eliminates the harmful wastewater that is produced as a byproduct of fabric dyeing process.[9]

Supercritical carbon dioxide dyeing technique

A supercritical is the phase in which the substance is at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist, but below the pressure required to compress it into a solid. Supercritical fluids do not turn into a liquid or a gas by condensation or evaporation. A liquid can become a supercritical fluid by raising its temperature and pressure at the same time. Thus, a closed system approaches critical values, or the supercritical state, when it is impossible to detect the border between the liquid and gaseous states.

Carbon dioxide is the gas that is utilized and studied the most in the supercritical fluid dyeing process. It is a naturally occurring substance that is chemically inert, reasonably priced, and easily accessible for use in industry. Both environmentally and financially, the idea of using supercritical CO_2 to color fabrics might be viewed as green. Supercritical fluids are gasses that are very compressed and have advantageous characteristics of both liquids and gases. Above its critical temperature, a gas maintains its gaseous state's free mobility; nevertheless, as pressure increases, its density moves closer to that of a liquid. Pressure regulates these characteristics, which lie in between those of gases and liquids. [11, 12]

These fluids are advantageous in the dyeing process because they have solvating power, or the capacity to function as both a solvent and a solute. Disperse dyes are used in this procedure. **[13]** Using carbon dioxide (CO_2) in its supercritical form as a solvent and transport medium in place of water is known as supercritical carbon dioxide ($scCO_2$) dyeing. This eco-friendly dyeing process doesn't need water, auxiliary materials, or release effluent. The field of supercritical CO_2 dyeing was initially developed in the late 1980s. The first commercial $scCO_2$ dyeing system was introduced by Dye-Coo Textiles Systems B.V., a company located in the Netherlands. Polyester fiber dyed using $scCO_2$ has achieved its commercial success at this point, and it is currently accessible on an industrial scale. These days, there is a noticeable increase in interest throughout the whole world in using $scCO_2$ dyeing technology as an alternative to traditional aqueous dyeing and finishing procedures. **[8, 14, 15]**

Carbon dioxide (CO_2) is generally utilized as a fluid due to its availability, non-toxicity, and non-flammability. Above 31.1°C and 74 bar, supercritical CO_2 behaves as both a liquid and a gas. Hydrophobic dyes may be dissolved more easily by the liquids with similar densities, and dyeing periods can be shortened in comparison to water by the gas-like low viscosity and diffusion characteristics. **[2, 11, 16]**

Supercritical carbon dioxide dyeing method

Supercritical CO_2 fluid enables dyeing of polyester with modified disperse dyes, as it causes the swelling of the polymer fibre which allow the diffusion and penetration of disperse dye in the pore and capillary structure of the fibres. The system of supercritical carbon dioxide dyestuff-fiber represents a three-component with three-phase which are (the gas, the dyestuff and the fiber polymer). The dyestuff and the polymer are present in the form of three separated phases with the supercritical mixture, as the dyestuff is dissolved in the supercritical fluid then transferred, absorbed and diffused into the fiber. **[13]**

A typical dyeing apparatus for CO2 assisted dyeing

Dyeing procedures [8]

The fabric is wrapped around a perforated stainless tube and mounted inside the autoclave then the autoclave is closed, evacuated and cooled with ice water.

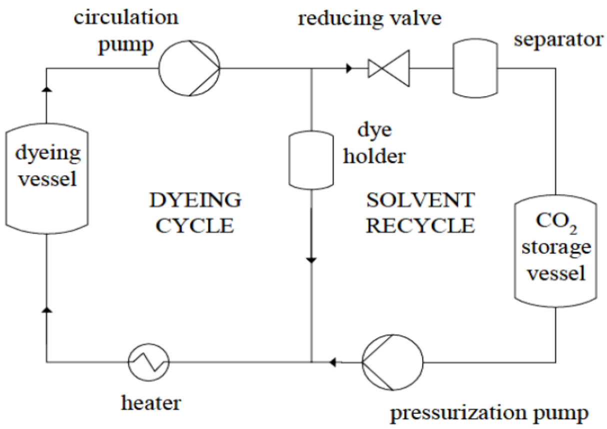
A required quantity of liquid carbon dioxide is filled into the autoclave in condensed form.

After reaching the autoclave room temperature again, polyglycol, which works as a heat carrier, is added to the bath, and then the pressure rises to 250 bars within about 7 minutes in isochoric process that is achieved by heating the glycol bath to 130 ^{0}C.

After 10 minutes of dyeing process the pressure within the autoclave is reduced to atmospheric temperature in about 2-3 minutes and carbon dioxide is routed through a separating vessel in order to get the residual dyestuff back.

Dyestuff is placed in the bottom of the vessel then the apparatus is locked and purged with gaseous carbon dioxide and preheated, then when it reaches to working temperature, carbon dioxide is isothermally compressed to the chosen working pressure under constant stirring.

All the dyeing period of 60 min. the pressure is maintained, afterwards the fabric is rinsed with acetone to remove residual dyestuff, and the compressed carbon dioxide is recycled and used again.



Simplified flow diagram for dyeing of polyester using supercritical CO2 dyeing system

Advantages of Supercritical carbon dioxide dyeing technique

- Save time, energy and water.**[13]**
- Compared to the traditional dyeing method, $scCO_2$ offers 50% cheaper operating cost.[2]
- There is no need for chemicals such as leveling agents, pH regulations, auxiliary agents, disposing agents, adulterants, etc.**[13]**
- This approach might also lead to high solubility, zero surface tension, and diffusivity. [2]
- Supercritical fluids combine the advantageous qualities of a liquid and a gas, which makes them advantageous in the textile processing industry.**[13]**
- The process of dyeing and removing the excess dye can be carried out in the same vessel, and the remained dyestuff is low and can be extracted and recycled.**[13]**
- The procedure is eco-friendly and economically viable because to the reusability of CO_2 and dyes.[2]
- No effluents, no contaminated waste water streams.[13]
- Beside polyester, the process can also be used for dyeing of protein and cellulose fibres

Comparison between $scCO_2$ and air dyeing process

Disadvantages of Supercritical carbon dioxide dyeing technique

- Like air-dying, scCO2 dyeing is limited to synthetic materials due to its low polarity, which makes it unable to color polar hydrophilic fiber.[2]
- The majority of scCO2 equipment was often arranged vertically, leading to uneven textile dying due to gravity and non-homogeneous fluid dispersion and dye accumulation.[2, 13]
- High pressures required for dye solubility.[13]

Foam dyeing technique

- Efforts to reduce water usage and wastewater generation in textile wet processing have included the application of foamed finishes to fabrics to modify their surface chemistry. More recently, the technology of foam dyeing has been emerged. It enables dyeing of 1,100 m of pretreated fabric with only 400 L of dye solution. The resulted dyed fabric, 1) during dye application the fabric has only 15-30% wet pick up so it dries quickly. 2) the fabric does not require wash-off step which save at least 90% water and energy and eliminating the production of wastewater, making this technology eco-friendly. [3]
- The first application of foam in textile processing was in about 1906 and 1907, then developed in the 1970s and 1980s because the shortages of energy and rising costs of energy so foaming received a great attention and was applied in continuous production including foam dyeing, foam printing, foam mercerization and foam finishing. Foam technology is a low-add-on technique used in textile processing that replaces water with air to apply chemicals and colorants to fabrics, saving a significant amount of energy and water. While conventional pad dyeing the wet pick-up is about 60–100%, foam technology is typically applied at a wet pick-up of 20–40%.

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

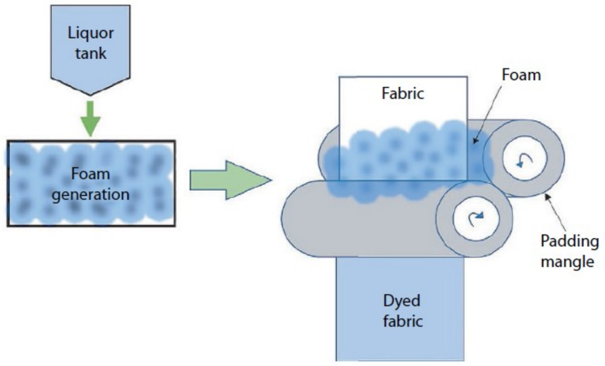
	Supercritical carbon dioxide process	Air-dye process
Main power source	Supercritical CO_2 as fluid	Uses air instead of water
Working Condition	High pressure and temperature is required	dyeing liquor is first atomized, then mixed with high-pressure airflow, finally sprayed on fabric to be dyed
Synthetic 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

The textile industry has shown interest in foam technology because it facilitates single-side treatment, speeds up production with shorter drying times, reduces the need for chemicals, reduces the risk of migration and achieves an excellent levelness of dyeing.**[17, 18]** Foam is defined as a dispersed gas in a liquid phase of another substance. Usually, this gaseous phase is air which forms agglomeration of gaseous bubbles that are dispersed in the liquid substance and separated from each other by liquid lamellae or thin films. Foam formation require careful ingredient selection and preparation as higher concentrations of chemicals (dye, auxiliaries) and additional foaming agent, foam stabilizer, viscosity modifier are used. When creating foam, the main factors taken consideration are the compatibility of the dye formulation with the foaming agent, the stability of both foamed and un-foamed compositions, the potential impact of the foaming agent on fabric, and lastly the foam's cell structure. The foaming agent needs to be compatible with the various chemical combinations found in dyeing solutions. The foaming agent should also be able to endure water hardness, as this might destroy the foaming effect, and the foam itself should be readily stabilized. The two well-known methods of foam generating are 1) air blown method: in it the air is injected into the liquor under pressure, 2) the stirring method: in it the liquor is uniformly stirred for some time strongly. [8]

Foam dyeing method

In foam dyeing the dye is applied to the fabric in the form of foam in contrast to the traditional dyeing process that depends on impregnation of the fabric in aqueous solution. Generating foam requires the same way in which the air is dispersed in water. Dye liquor is added to the foaming agent that contains a surfactant to facilitate the formation of bubbles, and also adsorbed on the bubbles surface forming a film that gives some stability to the bubbles.[8] Generally, foam is generated by strong mechanical stirring to the prepared dyeing liquor using foam generators. The generated foam needs a certain degree of stability to be applied onto the fabric and also should be collapsible easily after being applied. **[8, 19]**

The fundamental idea of foam dyeing is that a regulated amount of foam is applied to the fabric uniformly using various kinds of application techniques after foam containing the dye liquid is created in a controlled way. The foam is continuously created and drained during the dyeing process as the bubbles burst and transfer the dye liquid to the substrate. Fixation and washing then occur in the same way as in the conventional continuous method. The effectiveness of dyeing and dye fixing are caused by regulation foaming and draining. The creation of foam with the suitable characteristics, such as consistent bubble size, homogeneity, and finesse, is usually necessary. The foamed liquid should also be applied using correct methods to ensure uniform distribution within the fabric. Both direct and indirect methods can be used to apply foams to textile surfaces. In the direct pressured method foam is directly applied to fabric using a rotary screen or holed injector simultaneously with pushing the fabric up towards the backing roller, while the foam is kept under pressure in a box throughout this process. But in the indirect technique, the foam is transferred into the cloth using a carrier (blanket, drum, etc.), and the foam is applied when the fabric and carrier come into contact. Furthermore, in order to speed up the dye fixing process, the foam has to burst in a right away to allow the dye to permeate the fabric. **[19]**



Advantages of foam dyeing technology

- Foam dyeing technology saves in the cost of drying energy as a very low wet pickup is generally obtained.
- One of the main advantages of foam dyeing is the reduction of the amount of used water in the range from 30–90%.
- Reducing in the amount of wastewater discharge which results in 50 to 60% lower cost of effluent treatment.
- Foam dyeing is much better when compared to conventional dyeing in terms of productivity, cost, performance, and sustainability.
- Stable dye fixation due to the rapid wetting of the substrate, improved dye diffusion, high stability of the dyes after diffusion (less dye migration).

Conclusion

The amount of water needed in dyeing can be decreased or eliminated with non-aqueous techniques. Saving money and the environment are two advantages for these techniques. Application of supercritical carbon dioxide, air-dyeing and foam dyeing of textiles are some of the revolutionary ways to advance the textile wet processing. Furthermore, these water-saving technologies are currently the best alternative for traditional textile dyeing methods, especially with the limited supply of water in many regions of the world and the growing requirements of wastewater treatments. For this reason, it makes sense to apply these dyeing methods widely in order to gain their benefits in terms of both the economy and the environment.

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Conflict of Interest

There is no conflict of interest in the publication of this article.

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