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Reducing Water and Energy Consumption in the Textile Industry: Exploring Foam-Assisted Systems and Supercritical Dyeing Technology

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Abstract

The textile industry's wet processing division requires a significant amount of water and energy. Furthermore, the textile sector produces a substantial amount of wastewater. Consumer awareness, environmental rules and regulations, scarcity of water, and high energy costs have compelled textile producers to cut their water and energy consumption. Altering chemical finishing processes from traditional water-assisted systems to foam-assisted systems is another option to reduce water and energy usage in the textile industry. As one of the major components of supercritical CO_2 dyeing apparatus, the separator performs the role of separating CO_2 and dyes, influencing CO_2 reutilization and subsequent dyeing production.The review cotains comparing between traditional and supercritical dyeing, advantage of supercritical dyeing and dyeing process and foam dying technology, principl and application.

Keyword: Supercritical, Carbon Dioxide , Foam Dyeing

Introduction

The textile sector consumes a lot of electricity, fuel, and water, which results in a lot of greenhouse gas emissions (GHGs) and contaminated effluent. In terms of energy use, the textile industry's percentage of total final energy use in any given country is determined by the structure of that country's textile sector. Electricity, for example, is the dominating energy source for yarn spinning, whereas fuels are the primary energy source for textile wet processing. [1]

Traditional textile dyeing in aqueous medium is a water- and energy-intensive technique, requiring 100 - 150 L of water and 8 -18 MJ of energy per kg of processed fiber see [2, 3]. According to estimates, over 280,000 tons of dyes and chemicals are expelled directly into effluents after dyeing each year, posing a significant threat to water environment security[4]. Faced by growing pollution and scarcity of water resources, the transition from traditional water-based technologies to environmentally friendly and sustainable approaches is shifting toward high temperature and high pressure processes[5].

Supercritical CO_2 has been extensively used as an environmentally friendly medium for textile dyeing and has been marketed in the preliminary stages. CO_2 exhibits nontoxicity, cheap cost, and chemically benign nature due to its lower critical pressure and temperature (7.37 MPa and 31.0 ℃) in compared to other mediums[6-8]. When CO_2 enters supercritical conditions, its gas-like viscosity and liquid-like density allow it to be adjusted for the dissolving ability of dyes without intermediaries via pressure and/or temperature modulation, which can be employed for textile dyeing[9-15].

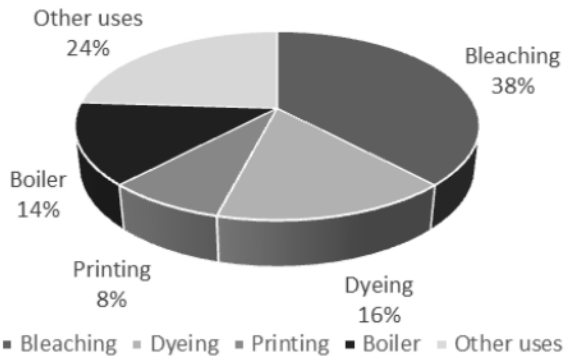

Figure 1: Total water consumption during wet processing of textile industry[16]

Additionally, because the dyeing process is waterless, multiple rinse and drying steps are removed. As a result of the high absorption rate, fast dyeing

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process, ease of recovery, and zero waste emission, supercritical CO_2 dyeing is becoming one of the most important choices for replacing the high-polluting water-based dyeing approach[17, 18].

The use of supercritical CO_2 for coloring synthetic and natural fibers has received a lot of attention [19-21].

Textile wet-processing

Electron-beam treatment

E-beam irradiation is being used more and more to change the surfaces of polymer materials like fibers, textiles, and films. Electron beams initiate free-radical polymerization processes, which can subsequently be employed for coating, lamination, and graft co-polymerization on pre-coated textiles with monomers or polymers. E-beam irradiation has a benefit over heat curing in that it allows for the use of solvent-free formulations, which decreases volatile organic compound emissions during drying. The approach is already well-established in other industries, therefore its adoption in the textile industry is likely in the near future[22].

Ciba, a textile chemical producer, has created a line of dyes with polymerizable vinyl groups that are appropriate for printing. After printing with a paste containing a dye monomer and a carefully selected cationic monomer, e-beam irradiation can be employed for fixing. In lab experiments, the aim of 100% dye use was approached, with just minor washing required[23].

Plasma treatment of textiles

The surface properties of a textile fiber are critical to its moisture management, dyeing, and performance features. Because surface properties have a direct influence on the hygroscopic behavior of fibrous materials, several processes for surface modification of textiles have been developed. Plasma treatment is one of the most promising technologies considered as an alternative for several textile wet processes while reducing energy, water, and chemical consumption. Surface modifications such as contamination removal, bond breaking (creation of free radicals), crosslinking, etching (creation of roughness), functionalization, polymerization, and post-irradiation grafting are all possible with careful plasma gas and processing condition selection[24-35].

As the fourth state of matter, plasma is made up of a high concentration of reactive species capable of triggering physical and chemical changes on polymeric surfaces. Heating or exposing a neutral gas to electromagnetic fields produces plasma. Several active species, including ions, electrons, neutrons, excited molecules, free radicals, metastable particles, and photons, exist in a quasi-neutral mixture in this state. Plasma reactive species have high energy and can dissociate a wide range of chemical bonds, resulting in a large number of simultaneous recombination mechanisms that provide effective surface modification of any substrate within the plasma medium in an environmentally friendly manner. This surface-specific technique makes use of only a little amount of working gas (or vaporized liquid).Cleaning, activation, grafting, etching, and polymerization are all possible outcomes of plasma therapy on the surface of the substrate. The type and extent of the effect are determined by the gas utilized as well as process parameters such as pressure, flow rate, power, frequency, and duration. Plasma alters the material's surface to a depth of 10 nm while leaving the bulk properties untouched[36].

There are two types of plasma based on working pressure: hot and cold. Because high temperatures cause textiles to degrade, only cool (non-thermal) or low-temperature plasma can be used on textile materials[37]. Furthermore, plasma treatment is divided into several types based on the chamber pressure, voltage, and frequency of the power generator. For plasma generation, several frequencies of direct current (DC) or alternating current (AC) can be applied to a gaseous medium. Low frequency (LF, 1e500 kHz), radio-frequency (RF, generally 13.56 MHz or 27.12 MHz), and microwave (MW, usually 915 MHz or 2.45 GHz) alternating current power supply can be utilized for plasma formation[38].

Plasma can be produced at either atmospheric or low pressure. The chamber pressure in lowpressure plasma generators is typically in the region of 1e100 Pa, and RF or MW power supply are used see **Figure 2**. While low-pressure plasma systems are homogeneous, reproducible, and require a small amount of gas, they are costly and difficult to adapt for continuous textile treatment[38]. Atmospheric-pressure plasma systems can be divided into four types:

Corona discharge - Dielectric barrier discharge (DBD) - Atmospheric-pressure glow discharge (APGD) - Atmospheric-pressure plasma jet (APPJ).

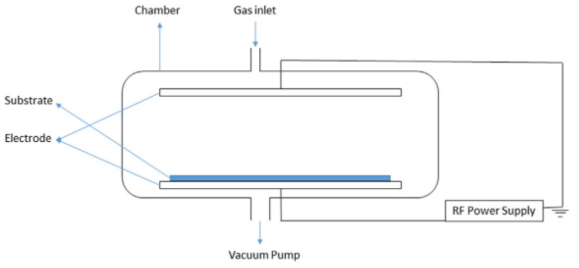

Figure 2: Schematic presentation of low-pressure glow discharge plasma

Two asymmetric electrodes are employed in corona discharge systems see Figure 3. One electrode is typically a highly curved metal, such as a needle or wire, and the other electrode is a plate or cylinder with a low curvature. The plasma is commonly found in a portion of the gas about 0.5 mm away from the needle tip (ionization area). Charged species diffuse toward the grounded electrode in the drift zone outside this volume. Corona discharge is rarely used for textile treatment due to inhomogeneity and limited area.

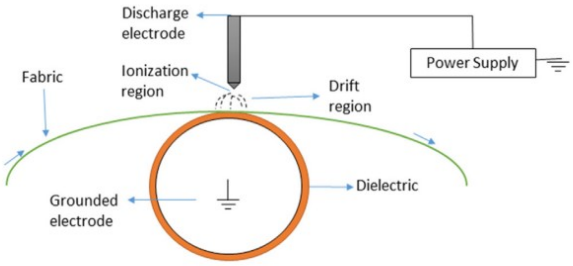

Figure 3: Schematic presentation of corona discharge

DBD devices employ two parallel electrodes, at least one of which is coated by a dielectric layer see **Figure 4**. DBD can take two forms: filamentary and homogenous. Homogeneous DBD plasma can be created and used for homogeneous surface treatment of textiles by carefully controlling the processing parameters see . Typically, the distance between the electrodes is several millimeters, and the applied voltage is around 20 KV (AC)[39, 40].

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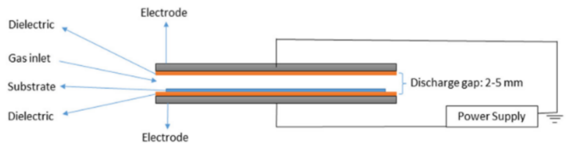

Figure 4: Schematic presentation of DBD

The APGD system requires a low voltage (about 200 V) and a high frequency (2e60 MHz) delivered between two bare metal electrodes (flat or curved). The space between the electrodes might be as small as a few millimeters. This arrangement can result in the development of a bright, uniform, and homogeneous light between the electrodes. Due to the expensive expense of this noble gas, helium is typically employed as the processing gas in APGD systems to prevent the creation of arcs between the electrodes. Instead of helium, argon or nitrogen are sometimes utilized[38].

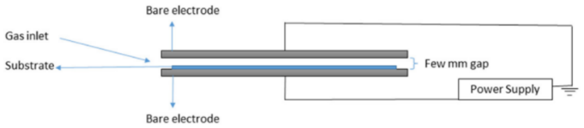

Figure 5: Schematic presentation of APGD

The plasma jet is made up of two concentric electrodes, and the processing gas travels past the electrodes before being converted to plasma by delivering RF power (100e250 V) to the inner electrode. The ionized gas (plasma) is guided to the substrate's surface via a nozzle.

Fig. 6. Schematic presentation of APPJ.

Figure 6: Schematic presentation of APPJ

The dye uptake, finish, and adhesion qualities of a plasma-treated wool surface are all positive.Because plasma-treated woolen materials have superior dye pick-up, these wool fabrics can attain more color value than untreated fabrics for the same dye strength. The plasma treatment increases the surface tension of the wool, which improves the fabric's adherence during coating. The plasma treatment also considerably enhances the shrink-proofing of the wool. Because plasma treatment is a physical process that does not include any industrial waste, it eliminates the pollution associated with chemical treatments[41].

Microwave energy in textile wet processing

Microwaves are electromagnetic waves with frequency ranging from 1,000 to 10,000 megahertz (MHz). Microwave energy has found a variety of applications in industrial processes in a variety of sectors where it is used as an alternative to traditional heating techniques because it provides fast, uniform, and effective heating by penetrating matter particles and enabling their simultaneous heating. Microwave energy has several advantages, including shorter application times, faster heating and drying, the flexibility to flexibly modify process duration to heat varied amounts of material, and energy conservation[42].

In the textile industry, microwave energy has been tested in heating, drying, condensation, dyeing, pressing, finishing, and modifying the surface of materials. The first attempt to use microwaves in the textile finishing process was during the 1970s when cellulose fabrics were treated with durable press finishing agents and cured in a microwave oven. Microwave dyeing is one application of microwaves in textile production that takes into account the dielectric and thermal properties of the process. The dielectric property refers to the intrinsic electrical properties of the dye that influence the microwave field on the dipoles during dyeing. There are two polar components in an aqueous dye solution. The vibration energy in the water and dye molecules is influenced by a high-frequency microwave field oscillating at 2,450 MHz. Ionic conduction, a type of resistance heating, is the heating mechanism. The collision of dye molecules with fiber molecules is caused by the acceleration of the ions through the dye solution[43].

Supercritical carbon dioxide technology

A "supercritical fluid" (SCF) is a material that exists at temperatures and pressures greater than its critical temperature (Tc) and critical pressure (Pc). The critical point is the highest temperature and pressure at which the substance may exist as a vapor and a liquid in equilibrium see **Figure 7**. The events are conveniently described using the pure carbon dioxide phase diagram. See **Figure 8** this figure displays carbon dioxide in its many forms as a gas, liquid, solid, or SCF. The charts depict temperatures and pressures when two phases coexist in equilibrium. (At the triple point, three phases coexist)[44].

When carbon dioxide is heated over 310°K and pressured above 74 bar, it enters supercritical state, which resembles an expanding liquid or a forcefully compressed gas. In other words, carbon dioxide possesses both liquid and gas qualities above the critical point. As a result, supercritical CO_2 has liquid-like densities, which is advantageous for dissolving hydrophobic colors, as well as gas-like low viscosities and diffusion properties, which can result in faster dyeing times than water. Unlike water dyeing, the extraction of carbon dioxide dyeing involves only changing the temperature and pressure conditions; drying is not required because CO_2 is discharged in a gaseous state following the process[45].

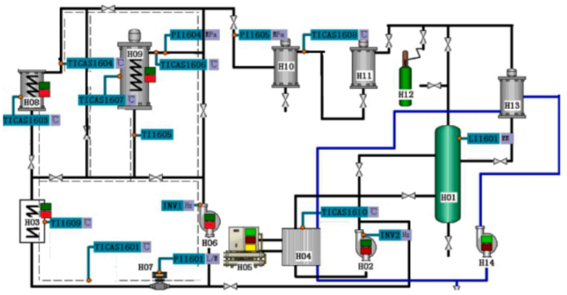

Figure 7: Schematic diagram of supercritical CO_2 beaming dyeing machine

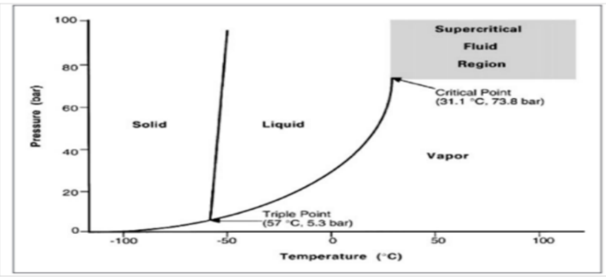

Figure 8: Phase diagram for pure carbon dioxide

Carbon dioxide is the most commonly used supercritical fluid

- Low cost and widespread availability of high purity.
- Chemically inert, non-toxic, non-flammable, and free of microorganisms.
- 31°C and 74 bar are the low critical points.
- Allows the fluid to be used in low-temperature circumstances, protecting thermo-sensitive components.
- CO_2 is recovered from industrial waste and recycled.
- The items are resistant to oxidation.
- The products and residues contain no solvents.

Advantages of supercritical carbon dioxide for textile dyeing

The usage of $scCO_2$ as a dye solvent can substantially assist the textile industry. Because of the low mass transfer resistance and rapid diffusion rates found in $scCO_2$, dye penetration into the fibers is aided, resulting in shorter dyeing periods. The drying stage is omitted because the dyeing process is waterless, saving electricity and time. Furthermore, because the dye cannot be hydrolyzed, nearly all dye molecules are ready for reactivity with the fiber. The dye concentration required for a certain hue is projected to be lower in supercritical dyeing see **Table 1**[44].

Table 1: . Comparison of textile dyeing processes

Conventional water textile dyeing	*Alternative textile dyeing with $scCO_2$*
Large usage of water	Elimination of water usage
High levels of salt and alkali	No additives
Hydrolysis of dye molecules	No hydrolysis of dye molecules
Costly water purification	No production of polluted water
Drying step of textile	No drying step (energy saving)
	Shorter process time due to high diffusion coefficients and low mass transfer resistance
	Easy separation of the dye from $scCO_2$ with dye recovery
	Carbon dioxide can be reused

Foam Dyeing Technology

Foam technique is a low-cost technique that is used as a driving tool to apply various chemicals (dye, finishing agent, etc.) on textile substrates by replacing water with foam. When compared to the traditional pad dying method, foam dyeing has a lower wet pickup, which results in fewer water and energy requirements, a shorter drying time, increased productivity, and less waste. Because of these economic and environmental benefits, foam technology has been used in various textile wet processing areas such as sizing, printing, finishing, and dyeing[46].

Principle of Foam Dyeing

In contrast to impregnation of the cloth in aqueous solution, the dye or finishing agent is given to the fabric in the form of foam in foam dyeing or finishing. The essential idea of foam dyeing is that foam containing the dye liquor is formed in a controlled manner, and a regulated amount of foam is applied to the fabric uniformly using various application methods. The foam is constantly created and deflated during dyeing as the bubbles break and transfer the dye liquor to the substrate, and fixing and washing continue in much the same way as in the classic continuous method. This constant foaming and draining is what allows for successful coloring and dye fixing[47]. In overall, it is necessary to form a foam with the desired properties like continuous bubble size, homogeneity, and finesse, and the foamed liquid should be dispersed equally throughout and along the substrate using appropriate application methods. Furthermore, the foam must collapse soon in order for the dye liquid to seep into the substrate and aid in the dye fixing process. Foam dyeing can be done in both batch and continuous mode[48].

Foam and Properties

Foam can be described as a gas spread in another substance's liquid phase. The gaseous phase is often air, which forms an aggregation of gaseous bubbles scattered in the liquid and separated by thin films called liquid lamellae. In general, foams can be gaseous (made from gas and liquid) or solid (produced from gas and solid). The gaseous foams that are suited to textile substrates are divided into two major types[49].

- Dispersion foams are created when a gas is supplied and mixed into a liquid phase from a peripheral source. This is the most frequent type of foam used on the textile substrate. The foam-forming surfactant aids in the conversion of air into a water solution, allowing for liquid-phase applications to the textile substrate.
- Condensation foams: Foams can be created within a liquid by either chemical vapor deposition (chemical reaction) or physical vapor deposition (physical change), both of which are triggered by a change in temperature or pressure.

Foam Processing Steps

Many steps are involved in foam processing, including liquor preparation, foam formation, foam application, foam destruction, drying, and fixing.

Liquor Preparation

Because higher quantities of chemicals (dye, auxiliaries) and additional foaming agent, foam stabilizer, and viscosity modifier are employed in foaming recipe formulations, careful ingredient selection and preparation are required see **Figure 9**.

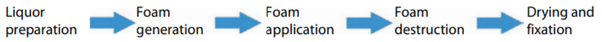

Figure 9: Foam sequence of processing [49]

when compared to traditional reagent preparation processes. The interaction of the dye formulation with the foaming agent (compatibility), the stability of both un-foamed and foamed compositions, the possible effect of the foaming agent on the fabric, and finally the cell structure of the foam are the main factors considered during foam formulation. Dyeing solutions comprise several chemical combinations, all of which must be compatible with the foaming agent. Furthermore, the foaming agent should be able to endure water hardness, which might degrade the foaming effect, and the foam should be easily stabilized[49].

Foam Generation

To aid the creation of bubbles, foam is formed in such a way that the air is disseminated in water, such as the dye liquor coupled with the foaming agent-containing and a surfactant. The surfactant adsorbed on the bubbles will form a film, which will give the bubbles some stability. In general, foam is generated by strong mechanical churning of the produced liquor utilizing foam generators. There are two well-known methods: the air blown method, in which air is injected under pressure into the liquor, and the stirring method, in which the liquor is consistently agitated for a period of time by stirring. To accomplish quick foam formation, a mixture of these approaches is sometimes used. The created foam must be stable enough to be applied to the cloth and should be quickly foldable once applied to the fabric. A warmed dye solution was foamed and used to color a continuous strand of yarns. This apparatus's foam produced a homogeneous coloring effect on the yarn.

Foam Application

Direct (pressurized and non-pressurized) and indirect systems can be used to apply foam to the textile surface. The foam is held under pressure in a box and directly applied to the fabric via a slot applicator or rotary screen with the cloth placed against a backing roller in the direct pressured system. In the case of a direct non-pressurized system, however, the foam reservoir is not kept under pressure, but there is still pressure involved during application. A carrier (drum, blanket, etc.) is employed in the indirect approach to transmit the foam into the cloth. When the carrier and the fabric come into contact, the foam is applied. By generating a foam with the liquid, a liquid treatment bath in the form of foam can be applied to the textile surface. The foam can also be fed into appropriate vessels that allow it to reach the surface of the textile material[50].

Foam Destruction

A foam should function as an enzyme and should be wiped away quickly after application. After the foam has been applied and destroyed, the dye fluid discharged on the cloth can be used as a transport medium for the dye's penetration and diffusion prior to fixation. Depending on the application process, foam can be removed by squeezing or vacuum removal devices. After application, Elbadawi et al. claimed the following main foam elimination techniques[51]:

- Employing temperatures: Raising the drying temperature will result in decreased viscosity, increased molecular movements in the bubble, and loss of foaming characteristic, allowing foam to be avoided.
- Add a de-foaming agent: Defoaming products can aid in the disappearance of foams, resulting in foam-free bubbles.
- Applying pressure: When more pressure is applied, the bubbles can rupture.

Drying and Fixation

Because the volume of water used in the foam system is so small, higher speeds and lower temperatures are typically used throughout the fabric's drying and fixing following foam application. However, the temperature should be properly managed so that only the necessary quantity of moisture remains on the fabric to minimize dye migration issues. Drying and curing do not require the installation of extra machinery because existing curing chambers or stenters can be used[48].

Foam Dyeing of Textiles

The foam dyeing method replaces water with air to apply dyes to cloth, resulting in significant water and energy savings during the dyeing and drying processes. Foam dyeing technology has been used to dye various fabrics due to its numerous advantages and versatility. Previous research has shown that a wide range of fibers and fabric constructions, including yarns, can be dyed using the foam dyeing procedure with multiple dye classes[50]. This section discusses briefly the applications of foam dyeing for fibers and fabrics manufactured from natural and synthetic sources. The typical foam dyeing process for textiles is shown in **Figure 11** and Error! Reference source not found..

Foam Dyeing of Natural Fibers

Natural fiber fabrics are the most popular and favored because of their comfort, sustainability, and ease of usage. Natural fibers have a higher wet uptake in a traditional water bath and require more water (as a solvent and washing agent), energy, and chemicals.

Figure 10: Foam dyeing process stages [52]

In this aspect, foam dyeing can be a good substitute for water-based dyeing procedures because it is a low-cost technology that requires less chemical and energy. Water is replaced by air in this method, resulting in less wet pick up and less water consumption. Wet-pickup can be decreased to 40-80%, which is significantly lower than in conventional systems. Cotton fiber fabrics have been treated with foam finishing treatments, resulting in energy savings of 70-80%[53, 54].

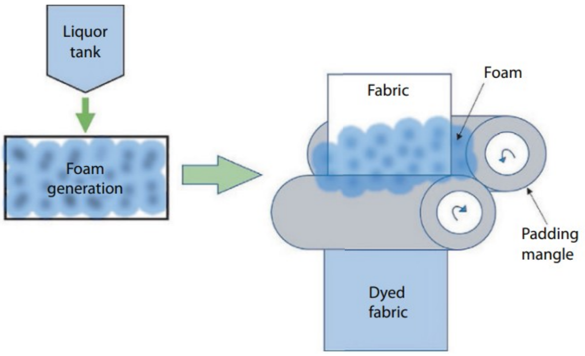

Figure 11: Foam dyeing application using a padding mangle principle. Typically, the padded fabric is introduced into steam fixation followed by soaping and washing

The foam dyeing process was stated to be successful for reactive dyeing of cotton and acid dyeing of wool materials, yielding results comparable to the usual pad dyeing approach. Furthermore, many approaches to the use of foam dyeing process to dye clothes manufactured from natural fibers have been claimed, including recycled pigment foam to dye cotton, silk, and polyester, reactive dyeing of cotton, and dyeing of cotton with pigment dispersion. The findings of these research confirmed that foam dyeing technology is a viable approach for dying natural textiles, and it was discovered to be both ecologically benign and energy efficient[55, 56].

Foam Dyeing of Synthetic Fibers

The majority of synthetic fibers are colored at higher temperatures, where the dyeing temperature exceeds the glass temperature (Tg). A similar foam dyeing setup **Figure 11** can also be used to dye synthetic fabrics. However, in the case of synthetic fiber foam dyeing, greater temperatures (above the Tg value) and a relatively lengthy time of steam fixation are commonly used. David et al. were the first to demonstrate foam dyeing of polyester and other synthetic fibers in a patent. Wang et al. described a clean, easy, and cost-effective foam dyeing of polyamide materials with acid dyes. Aside from being environmentally friendly, the achieved colorfastness was comparable to the standard exhaust dyeing procedure with stronger color strength, as demonstrated by the findings. Recently, claims have been made for a versatile (both synthetic and natural fabrics) and simple foam dyeing technique with practically negligible pollution emission. Overall, foam dyeing was found to be superior than conventional pad dyeing in terms of cost, productivity, and sustainability[57, 58].

Ink-jet printing (Digital printing)

Ink jet printing of textiles is a contactless technology that functions similarly to an office printer. It allows for quick responsiveness and a considerable level of versatility, particularly in patterning. Color type and position on the material are digitally captured and fed into the printing system. The sample on the substrate is transformed by numerous ink drops squeezed out of printing nozzles. Each "dot" of the dots per inch (dpi) that comprise the digital image is created by many drops of one color. Using an organizational concept based on base shade, tinctorial power, and pattern, a raster software arranges these drops one on top of the other or side by side. The two types of ink-jet printing for textiles are continuous flow and drop on demand see **Figure 12** and **Figure 13**[59].

Most fabrics require pre-treatment before digital printing; the amount of pre-treatment required is determined by the inks to be used. Pre-treatment chemicals keep dye from migrating once it hits the substrate and can also be used to adjust pH. To facilitate flow through the print head, digitally printed inks have a low viscosity; for instance, screen-printing pastes have a viscosity of about 5,000 mega-Pascals (mPas), whereas ink jet fluids have a viscosity of 3 to 15 mPas. This low viscosity causes issues when the ink reaches the textile substrate since the fluid wicks away from the target. As a result, the textile substrate must be prepared by adding a thickening with increased absorbency to avoid wicking. The thickening might cause the cloth to have a hard handle in some circumstances. If this has an undesirable effect on its end usage, the thickener (as well as unfixed dye) must be removed after printing. In other circumstances, there may be no negative handle effects, removing the need for scouring[60].

To complete the printing process, every printed cloth (excluding those used for temporary purposes such as photo shoots) requires post-treatment. Steaming opens up the fibers of the fabric, allowing the dyes to be fixed. In general, steaming for a short period of time (8-10 minutes at 102 oC) produces prints with weak colors; strong, brilliant colors require steaming for at least 17 minutes. Because the uptake of acid and reactive dye is never 100%, washing is frequently required; this presents special needs for processing small batches. Post-treatments are not performed for commercial reasons unless the end usage necessitates them. As a result, printed fabrics used for photo shoots, for example, are not even fixed. Pre-treated fabrics are not scrubbed unless contaminants must be removed[60].

Application

Application of supercritical carbon dioxide for textile dyeing

Abate, M.T., et al. used Supercritical CO_2 dyeing of polyester fabric with photochromic dyes to fabricate UV sensing smart textiles.

The uniqueness of water-free dyeing of UV sensing smart textiles employing photochromic dyes with enhanced color performance compared to conventional dyeing procedures is shown in this work. Using $scCO_2$ dyeing, two photochromic dyes from the spirooxazine and naphthopyran dye families were successfully applied to polyester fabric. When exposed to UV light, the uniformly colored photochromic polyester textiles created using the $scCO_2$ dyeing process exhibit considerable reversible color changing capabilities. On polyester fabrics, the two photochromic dyes performed similarly in terms of color yield but had distinct characteristics in terms of reaction kinetics, background color, and wash fastness. When compared to the naphthopyran dye class, sea green from the spirooxazine family displayed faster reaction kinetics, lower background color, and lower wash fastness qualities. Notably, photochromic fabrics generated with $scCO_2$ dyeing had faster dye kinetics than photochromic textiles created using traditional exhaust and solvent dyeing processes. Improving the endurance features of this approach may be of interest in future study for practical use. Overall, the experimental results indicate that the $scCO_2$ dyeing technique is a promising alternative to conventional processes for uniform coloration, not only because of its economic importance, but also because of its environmental benefits, such as avoiding the use of water, organic solvents, and auxiliary chemicals, requiring small amounts of dye, and having a short dyeing time.The photochromic fabrics created can be employed in applications such as UV detecting smart textiles[61].

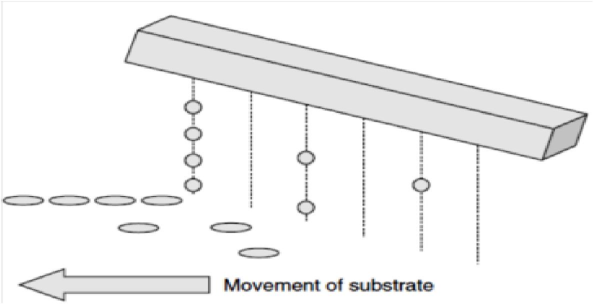

Figure 12: Drop-on-demand concept (a drop of ink is produced in reponse to a signal to fire the nozzle)

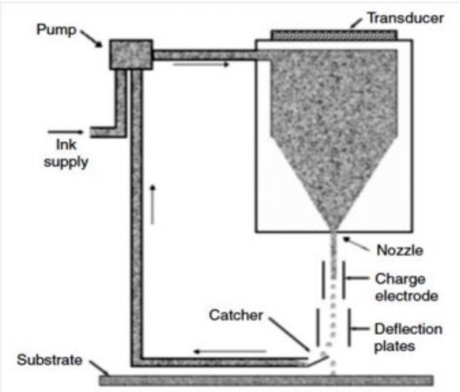

Figure 13: Continuous ink-jet concept (drops of ink are produced continuously and either fall on the substrate or are recycled)

Table 2: Emerging wet-processing technologies

Technology Name	Energy/Environment/Other Benefits/Costs	Ref
Ultrasonic treatments	Ultrasonic wet processing has the following benefits: • Energy savings resulting from lower process temperatures and shorter cycle times • Reduced consumption of dyes and chemicals, which allows for a 20-30% reduction in the amount of effluent • Water savings of around 20% • Improvement in product quality • Increased productivity because of shorter cycle times	[62]
Electron-beam treatment	E-beam textile surface treatment is said to provide the following advantages over traditional thermal curing: -Allows for the use of solvent-free formulations, which decreases environmental impact. -Emissions of volatile organic compounds during drying -Can be conducted at room temperature, saving energy. -Cuts processing time and boosts productivity	[63]
Super-critical CO2 in dyeing	Supercritical CO2 dyeing has the following benefits compared to conventional dyeing: • Almost zero water consumption • Zero off-gas emissions (CO2 can be recycled) • No drying step necessary after dyeing, which saves significant energy • Leveling and dispersing agents not needed, or, in some cases, used only in very small amounts • Recyclability of dyestuff residues	[64]
Electrochemical dyeing	Electrochemical dyeing is said to provide the following advantages over traditional dyeing: -Recycling of the mediator system and dyeing liquors saves chemical and water use dramatically. -There are no hazardous sulphates or sulphites in the wastewater, hence there is no impact on aquatic life. -Lower chemical concentrations -Significantly reduced wastewater discharges, resulting in energy savings at wastewater treatment plants. -Avoidance of odor and other issues caused by sulfur-containing reducing agents	[65]
Ink-jet (digital) printing	Ink-jet textile printing has the following benefits compared to conventional printing: • Reduced energy consumption • Reduced water consumption (washing of printing equipment is not necessary) • Indirect printing method (no requirements for printing screens, etc •No (or smaller amount of) thickeners required • Higher fixation rate • Only a small dyestuff palette is needed • Almost no dyestuff surplus, which reduces load on wastewater treatment plant • Flexibility in production and patterns	[66]
Plasma technology	When compared to traditional treatment methods, lasma treatment provides the following advantages: -Low application temperature, resulting in energy savings -There is no need for (or a minimal amount of) water or solvents. -There is no need for drying procedures after plasma finishing, which saves energy. -Significant dyestuff and finishing auxiliary savings -Significant improvement in wool prints due to shorter treatment time	[67]
Microwave energy	Microwave heating in textile wet processing has the following benefits compared to conventional heating techniques: • Lower energy use	[68]

	• No direct air pollution (indirect air pollution from electricity use is still less than that resulting from conventional heating) • Localized heating, which reduces energy waste in the heating process • Faster heating, which increases productivity and reduces energy use • More uniform heating	

Gong, D., et al., used supercritical CO_2 to achieve color matching of polyester with dye mixtures.

In the supercitical CO_2 dyeing of polyester, stable tones of black, dark blue, and dark purple with excellent repeatability are produced by binary combinations of Disperse Red 54 and Disperse Blue 79. Additionally, commercially acceptable colorfastness of wash, rubbing, and light fastness are shown. After supercitical CO_2 dyeing, the dyed polyester materials with exceptional color qualities indicate a good foreground. Additionally, because azo dispersion dyes are the most commonly used dyes in supercritical CO_2 dyeing, developing green and harmless dyes in the future to reduce environmental and human dangers is crucial[69].

Liu, M., et al., used curcumin-based dyes for supercritical carbon dioxide natural fabric dyeing.

Alkyl group grafting increased the solubility of curcumin in SC-CO_2. Butyl curcumin had the greatest solubility, resulting in the greatest coloring ability in SC-CO_2 for natural materials and the K/S value of butyl curcumin-dyed silk reached as high as 5. The staining fastness of alkyl curcumin dyed natural fabrics was higher than 4e5, and the dry and wet crocking fastness was 4e5 and 4, correspondingly[19].

Application of Foam Dyeing for textile dyeing

Mohsin, M., et al., used foam dyeing and finishing method for dyeing cotton fabric for Performance enhancement of water and energy .

Three foaming agents: alkane sulfonate sodium salt, ethoxylated decanol, and alkyl dimethyl amine oxide, all seven dyes and three finishes were successfully applied. For all three foaming agents, optimizing the foaming agent dosage and rpm was important to the successful development of foam.

Foam finishing, whether with softener, oil and water repellent, or fire retardant, demonstrated good performance properties but retained superior physical properties such as tensile strength, air permeability, and bending length when compared to padding due to less chemical application on the treated fabric surface. [70].

Wang, Q., et al. used foam dyeing technology on ultra-fine polyamide filament fabrics with acid dye.

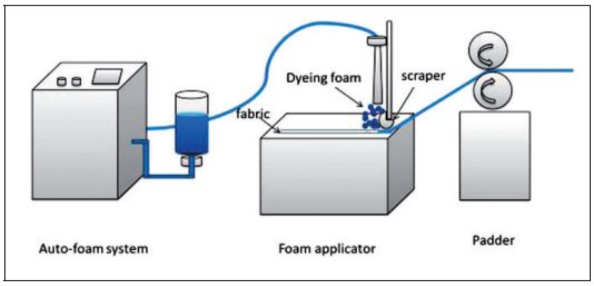

Figure 14: Diagram of the foam dyeing process

Acid dye foam dyeing of polyamide filament fabrics is practical and effective. A dodecanol and CMC-Na combined stabilizer can increase foam stability and lessen health risks.The best batch formula for dodecanol and CMC was 4:6. At 11 BR, 100℃ steaming temperature, 20 minutes of steaming duration, and 6.59% cloth moisture content, the K/S value was 3.58. When compared to exhaust dyeing, foam dyeing achieves the same amount of color fastness with a greater K/S value. These findings imply that foam dyeing is a simple and efficient process for dyeing polyamide filament materials with acid.Colors that may decrease water use, chemicals and energy, as well as accelerating production[57].

Foam finishing

On cotton fabrics, easy-care or durable press finishing is often used to enhance shrinkage resistance and promote wet and dry wrinkle recovery; this is typically accomplished by the use of cross-linking agents. Water absorption during washing and drying causes hydrogen bond breaking and sliding of the cellulose chains in the amorphous areas, resulting in wrinkle formation. Cross-linking enables for the fixing of cellulose chains by forming covalent connections that limit their mobility[71, 72].

To cross-link cellulosic material, DMDHEU and its derivatives, triazones, melamines, and carbamates, are utilized. DMDHEU is the most often used cross-linker for cotton textile material, despite being associated with environmental and health problems owing to the production of formaldehyde. The reaction of DMDHEU with cotton cellulose is depicted in **Figure 15** .For better mechanical qualities of cross-linked textile materials, foam technology may be a feasible alternative to traditional approaches.

Many investigations on foam-assisted easy-care or durable press finishing on cotton textile fabrics utilizing DMDHEU have been undertaken. An osnaburg cloth was examined for its properties and the dispersion of reagent residues after being treated with a foamed solution of DMDHEU. The specified uniformity standards were reached by foam finished fabric (35% WPU)[73, 74].

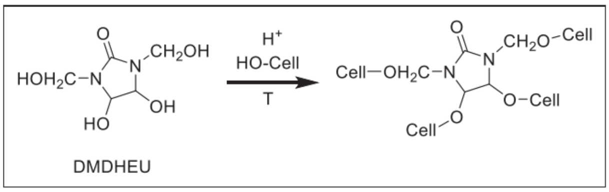

Figure 15: Crosslinking of cellulose with dimethyl dihydroxy ethylene urea (DMDHEU)

Later, etherified DMDHEU was utilized as a crosslinking agent for foam-finishing cotton woven fabric in the presence of a strength-retaining agent. In comparison to traditional padding systems, foam finished fabric provides better wrinkle recovery and tear and breaking strength. Sarwar et al. investigated the foam-finishing system's ability to provide long-lasting press finishing of cotton denim fabric using dihydroxy ethylene urea (DHEU). When the performance properties were compared, it was obvious that the tearing strength in the foam application system was greater than in the standard padding system. The authors attributed this improvement to the foam-finished fabric's reduced WPU, equal distribution of reagent, and regular cross-linking.

In a study that used a statistical experimental design and multiple stepwise regression analysis, the physical qualities of cotton fabric finished by foam application of formaldehyde were described in terms of processing parameters. The combined effect of the curing temperature and the catalyst ratio was shown to be responsible for the loss of tensile and tearing strengths. Later, the formaldehyde release property of finished fabric was investigated, and it was determined that formaldehyde concentration in conjunction with WPU is responsible for formaldehyde release[72].

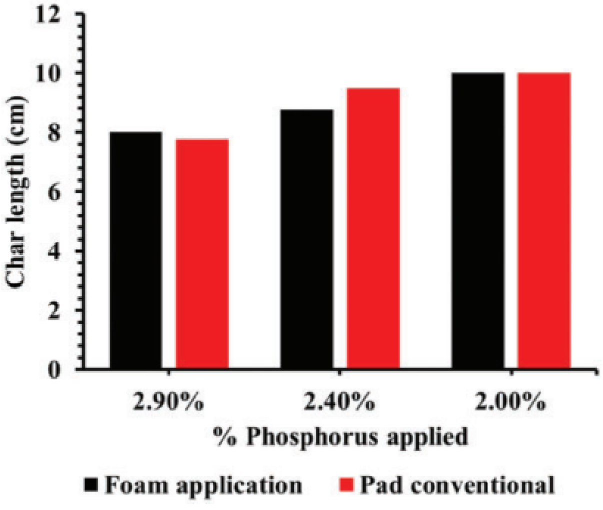

Figure 16: Char length of foam-finished and conventional pad-finished flame-retardant fabric

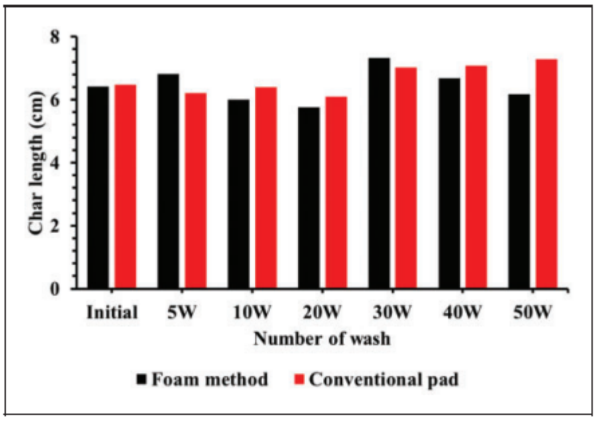

Figure 17: Durability of foam-finished and pad-finished flame-retardant fabric

The capacity to slow or stop the spread of flames is referred to as flame retardancy. Flame-retardant materials are utilized in a variety of applications, including firefighter and military/police uniforms. Sulfamic acid, ammonium sulfamate, zinc chloride, and phosphoric acid are common flame retardants.

When heated, they emit acids, causing cellulose to dehydrate and char to develop. 1-2% of the phosphorus concentration relative to the weight of the fabric is usually adequate to generate flame-retardant cotton. Foam application was used to apply phosphorus-based flame-retardant coatings to cotton textiles. The char length of a foam-finished flame-retardant cloth sample was comparable to that of a traditionally finished sample **Figure 16**. In terms of flame retardancy, the foam technique had no significant advantage over the old process[75].

Another investigation used flame-retardant, antimicrobial, and water-repellent chemicals to create multifunctional cotton fabrics. A foam system applied 400 g/L dialkylphosphono carboxylic acid amide (flame retardant) to cotton fabric for this purpose.The foam-finishing procedure produced char length (cm) and durability comparable to the traditional pad-finished fabric see **Figure 17** [76].

A one-sided foamed application of fluorochemical (FC) was examined on two distinct pre-treated cotton fabrics. The finished side displayed excellent water and oil repellency, whereas the unfinished side of the fabric was waterabsorbent. Water and oil repellency rose with fluorinated agent concentration from 0.75 to 1.00 to 1.25%, as expected see **Figure 18** [77].

Another research presented a straightforward foam-finishing technique for producing single-faced superhydrophobic cotton fabrics. The fluoropolymer emulsion foam was sprayed to cotton fabric and dispersed evenly across the fabric surface with a knife coater. The resulting material exhibited considerable hydrophobicity on the treated side while remaining hydrophilic on the unapplied side. Fluoropolymer could withstand five washing and drying cycles[1].

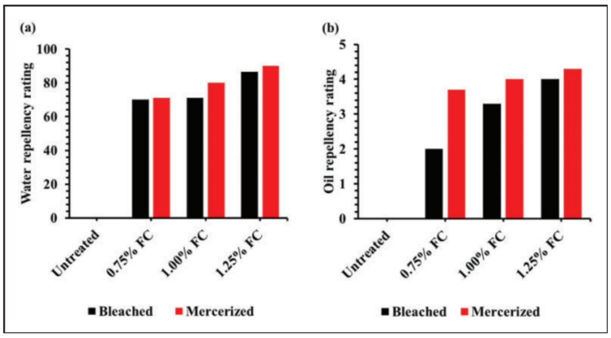

Figure 18: Water repellency (a) and oil repellency (b) ratings of fluorochemical (FC) finished fabric.

Conculsion

This article discusses emerging energy-, water-, and pollution-reduction methods for the textile sector. The data offered for each technology was gathered from a variety of sources, including manufacturers. It is likely that no single technology will be the best or only solution, but that a portfolio of technologies should be developed and deployed to address the textile industry's increasing energy and water demand and emissions. When compared to conventional technologies, the majority of the methods reviewed result in significant energy savings, water savings, time savings, material savings, and/or wastewater pollution reduction. However, because the majority of the new technologies assessed have not yet been commercialized, additional effort is required to prepare these innovations for full commercialization and market deployment.

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Conflict of Interest

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

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Reference

1. Liu, Y., Xin, J.H. and Cho, C.-H. Cotton fabrics with single-faced superhydrophobicity, *Langmuir*, **28**(50) 17426-34 (2012).
2. Banchero, M. Recent advances in supercritical fluid dyeing, *Coloration Technology*, **136**(4) 317-335 (2020).
3. Zheng, H., Zhang, J., Yan, J. and Zheng, L. An industrial scale multiple supercritical carbon dioxide apparatus and its eco-friendly dyeing production, *Journal of CO2 Utilization*, **16** 272-281 (2016).
4. Hussain, T. and Wahab, b. A critical review of the current water conservation practices in textile wet processing, *Journal of Cleaner Production*, **198** 806-819 (2018).
5. Zheng, H., Zhang, J. and Zheng, L. Optimization of an ecofriendly dyeing process in an industrialized supercritical carbon dioxide unit for acrylic fibers, *Textile Research Journal*, **87**(15) 1818-1827 (2016).
6. Yang, M.-Y., Liu, J., Zhang, Y.-Q., Chen, C., Wang, K., Peng, C. and Long, J.-J. Rope dyeing of fabric in supercritical carbon dioxide for commerical purposes, *Coloration Technology*, **130**(2) 102-111 (2014).
7. Elmaaty, T.A., Sofan, M., Elsisi, H., Kosbar, T., Negm, E., Hirogaki, K., Tabata, I. and Hori, T. Optimization of an eco-friendly dyeing process in both laboratory scale and pilot scale supercritical carbon dioxide unit for polypropylene fabrics with special new disperse dyes, *Journal of CO2 Utilization*, **33** 365-371 (2019).
8. Huang, T., Kong, X., Cui, H., Zhang, T., Li, W., Yu, P. and Lin, J. Waterless dyeing of zipper tape using pilot-scale horizontal supercritical carbon dioxide equipment and its green and efficient production, *Journal of Cleaner Production*, **233** 1097-1105 (2019).
9. Liu, G., Han, Y., Zhao, Y., Zheng, H. and Zheng, L. Development of co2 utilized flame retardant finishing: Solubility measurements of flame retardants and application of the process to cotton, *Journal of CO2 Utilization*, **37** 222-229 (2020).
10. Abate, M.T., Zhou, Y., Guan, J., Chen, G., Ferri, A. and Nierstrasz, V. Colouration and bio-activation of polyester fabric with curcumin in supercritical co2: Part ii – effect of dye concentration on the colour and functional properties, *The Journal of Supercritical Fluids*, **157** (2020).
11. Mohamed, A.L. Changing the properties of natural fibres by coating and of synthetic fibres by infiltration, RWTH Aachen University, p. 251 (2011).
12. Mohamed, A.L., Er-Rafik, M. and Moller, M. Supercritical carbon dioxide assisted silicon based finishing of cellulosic fabric: A novel approach, *Carbohydrate Polymers*, **98**(1) 1095–1107 (2013).
13. Ragab, M.M., Hassabo, A.G. and Othman, H.A. An overview of natural dyes extraction techniques for valuable utilization on textile fabrics, *J. Text. Color. Polym. Sci.*, **19**(2) 137-153 (2022).
14. Hassabo, A.G., Zayed, M., Bakr, M., Abd El-Aziz, E. and Othman, H. Applications of supercritical carbon dioxide in textile finishing: A review, *J. Text. Color. Polym. Sci.*, **19**(2) 179-187 (2022).
15. Abd-Elaal, L.S., El-Wekil, A.N., Marey, A.G., Allam, L.N. and Hassabo, A.G. Supercritical carbon dioxide as an impregnation medium for producing functional materials in textile finishing, *J. Text. Color. Polym. Sci.*, - (2024).

16. Kumar, D., Ambadas Garje, Desai, K. and Gupta, D. Dyeing without water, *Journal of the TEXTILE Association*, (2010).

17. Jaxel, J., Amer, H., Bacher, M., Roller, A., Guggenberger, M., Zwirchmayr, N.S., Hansmann, C. and Liebner, F. Facile synthesis of 1-butylamino- and 1,4-bis(butylamino)-2-alkyl-9,10-anthraquinone dyes for improved supercritical carbon dioxide dyeing, *Dyes and Pigments*, **173** (2020).

18. Zheng, H., Su, Y., Zheng, L. and Ke, H. Numerical simulation of co2 and dye separation for supercritical fluid in separator, *Separation and Purification Technology*, **236** (2020).

19. Liu, M., Zhao, H., Wu, J., Xiong, X. and Zheng, L. Eco-friendly curcumin-based dyes for supercritical carbon dioxide natural fabric dyeing, *Journal of Cleaner Production*, **197** 1262-1267 (2018).

20. Zheng, H., Zhang, J., Liu, M., Yan, J., Zhao, H. and Zheng, L. Co 2 utilization for the dyeing of yak hair: Fracture behaviour in supercritical state, *Journal of CO2 Utilization*, **18** 117-124 (2017).

21. Penthala, R., Kumar, R.S., Heo, G., Kim, H., Lee, I.Y., Ko, E.H. and Son, Y.-A. Synthesis and efficient dyeing of anthraquinone derivatives on polyester fabric with supercritical carbon dioxide, *Dyes and Pigments*, **166** 330-339 (2019).

22. Atav, R. The use of new technologies in dyeing of proteinous fibers, in: M. Günay (Ed.), Eco-friendly textile dyeing and finishing, (2013).

23. Lewis, D.M. Coloration in the next century. Review of progress in coloration and related topics, **29** 23-28 (1999).

24. Rani, K.V., Chandwani, N., Kikani, P., Nema, S.K., Sarma, A.K. and Sarma, B. Optimization and surface modification of silk fabric using dbd air plasma for improving wicking properties, *The Journal of The Textile Institute*, **109**(3) 368-375 (2017).

25. HAJI, A. Eco-friendly dyeing and antibacterial treatment of cotton, *CELLULOSE CHEMISTRY AND TECHNOLOGY*, **47** 303-308 (2013).

26. DAVE, H., DESAI, L.L.B., S.K.NEMA, N.C.A. and KIKANI, P. Surface modification of polyester fabric by non- thermal plasma treatment and its effect on coloration using natural dye, *Journal of Polymer Materials*, 292-303 (2013).

27. Hamdy, D.M., Othman, H.A. and Hassabo, A.G. A recent uses of plasma in the textile printing *J. Text. Color. Polym. Sci.*, **19**(1) 1-10 (2022).

28. Gaafar, Z.S., Roshdy, Y.A.E.-m., El-Shamy, M.N., Mohamed, H.A. and Hassabo, A.G. Antimicrobial processing techniques for fabric enhancement, *J. Text. Color. Polym. Sci.*, - (2024).

29. Zakaria, N., Shahin, A., Othman, H. and Hassabo, A.G. Enhancing the properties of textile fabrics using plasma technology, *Egy. J. Chem.*, **67**(13) 171-177 (2024).

30. Hassabo, A.G., Gouda, N.Z., Khaleed, N., Shaker, S., Abd El-Salam, N.A., Mohamed, N.A. and Othman, H. Enzymes in digital printing of polyamide fabric, *J. Text. Color. Polym. Sci.*, **21**(1) 149-160 (2024).

31. Hassabo, A.G., Khaleed, N., Shaker, S., Abd El-Salam, N.A., Mohamed, N.A., Gouda, N.Z. and Othman, H. Impact of various treatments on printing wool techniques, *J. Text. Color. Polym. Sci.*, **21**(1) 75-86 (2024).

32. Mamdouh, F., Othman, H. and Hassabo, A.G. Improving the performance properties of polyester fabrics through treatments with natural polymers, *J. Text. Color. Polym. Sci.*, - (2024).

33. Abdel-Aziz, E., Bakr, M., Zayed, M., Othman, H. and Hassabo, A.G. Microencapsulation and its application in textile wet processing: A review, *J. Text. Color. Polym. Sci.*, **19**(2) 189-202 (2022).

34. El-Sayed, E. and Hassabo, A.G. Recent advances in the application of plasma in textile finishing, *J. Text. Color. Polym. Sci.*, **18**(1) 33-43 (2021).

35. Hassabo, A.G., Zayed, M., Bakr, M. and Othman, H.A. Review on some fabric pretreatment via plasma to improve their printability using various types of colorants and dyes, *Materials International*, **4**(3) 1-16 (2023).

36. Dave, H., Ledwani, L. and Nema, S.K. Nonthermal plasma: A promising green technology to improve environmental performance of textile industries, The impact and prospects of green chemistry for textile technologypp. 199-249, (2019).

37. Ahmed, N.S.E. and El-Shishtawy, R.M. The use of new technologies in coloration of textile fibers, *Journal of Materials Science*, **45**(5) 1143-1153 (2009).

38. McCoustra, M.R.S. and Mather, R.R. Plasma modification of textiles: Understanding the mechanisms involved, *Textile Progress*, **50**(4) 185-229 (2019).

39. Herbert, T. Atmospheric-pressure cold plasma processing technology, Plasma technologies for textilespp. 79-128, (2007).

40. Samanta, K., Jassa, M. and Agrawal, A.K. Atmospheric pressure glow discharge plasma and its applications in textile, *Indian Journal of Fibre & Textile Research*, **31** 83-98 (2006).

41. Kan, C.W. and M., Y.C.W. Plasma technology in wool, *Textile Progress*, **39**(3) 121-187. (2007).

42. Büyükakıncı, B.Y. Usage of microwave energy in turkish textile production sector, *Energy Procedia*, **14** 424-431 (2012).

43. Katović, D. Microwaves in textile finishing, yes or no, *Journal of Textile Science & Engineering*, **01**(01) (2012).

44. Elmaaty, T.A. and El-Aziz, E.A. Supercritical carbon dioxide as a green media in textile dyeing: A review, *Textile Research Journal*, **88**(10) 1184-1212 (2017).

45. Miah, L., Ferdous, N. and Azad, D.M.M. Textiles material dyeing with supercritical carbon dioxide (co 2) without using water, *Chemistry and Materials Research*, **3** 38-40 (2013).

46. GregorIan, R.S., Bafford, R.A. and Namboodri, C.G. The utilization of foams in the wet processing of textiles, Energy conservation in textile and polymer processingpp. 155-173, (1979).

47. M.Capponi, A.Flister, R.Hasler, C.Oschatz, G.Robert, T.Robinson, H.P.Stakelbeck, P.Tschudin and J.P.Vierlina Foam technology in textile pro cessing, *Progress in Color, Colorants and Coatings*, **12**(48) (1982).

48. Elbadawi, A.M. and Pearson, J.S. Foam technology in textile finishing, *Textile Progress*, **33**(4) 1-31 (2003).

49. Abate, M.T. and Tadesse, M.G. Airflow, foam, and supercritical carbon dioxide dyeing technologies, Innovative and emerging technologies for textile dyeing and finishingpp. 137-164, (2021).

50. Hoque, E., Acharya, S., Shamshina, J. and Abidi, N. Review of foam applications on cotton textiles, *Textile Research Journal*, **93**(1-2) 486-501 (2022).

51. Denkov, N.D. Mechanisms of foam destruction by oil-based antifoams, *Langmuir*, **20** 9463-9505 (2004).

52. Yu, H., Wang, Y., Zhong, Y., Mao, Z. and Tan, S. Foam properties and application in dyeing cotton fabrics with reactive dyes, *Coloration Technology*, **130**(4) 266-272 (2014).

53. Ge, F., Zhang, J., Liu, J., Fei, L. and Wang, C. A novel crease-resistant and hydrophobic dual-function foam coating for silk fabric by the one-step method, *Textile Research Journal*, **90**(13-14) 1495-1506 (2019).

54. Namboodri, C.G. and Duke, M.W. Foam finishing of cotton-containing textiles, *Textile Research Journal*, **49** 156-162 (1979).

55. Bhavsar, P.S., Zoccola, M., Patrucco, A., Montarsolo, A., Mossotti, R., Giansetti, M., Rovero, G., Maier, S.S., Muresan, A. and Tonin, C. Superheated water hydrolyzed keratin: A new application as a foaming agent in foam dyeing of cotton and wool fabrics, *ACS Sustainable Chemistry & Engineering*, **5**(10) 9150-9159 (2017).

56. Chen, S., Fei, L., Ge, F., Liu, J., Yin, Y. and Wang, C. A versatile and recycled pigment foam coloring approach for natural and synthetic fibers with nearly-zero pollutant discharge, *Journal of Cleaner Production*, **243** (2020).

57. Wang, Q., Zhou, W., Du, S., Xiao, P., Zhao, Y.n., Yang, X., Zhang, M., Chang, Y. and Cui, S. Application of foam dyeing technology on ultra-fine polyamide filament fabrics with acid dye, *Textile Research Journal*, **89**(23-24) 4808-4816 (2019).

58. Mohsin, M. and Sardar, S. Multi-criteria decision analysis for textile pad-dyeing and foam-dyeing based on cost, performance, productivity and sustainability, *Cellulose*, **26**(6) 4143-4157 (2019).

59. Ma, B., Wang, K., Lu, M., Zhang, L., Zhang, L., Zhang, J., Cheng, X. and Wang, Z. Transient features and growth behavior of artificial cracks during the initial damage period, *Appl Opt*, **56**(4) C123-C130 (2017).

60. Tyler, D.J. Textile digital printing technologies, *Textile Progress*, **37**(4) 1-65 (2005).

61. Abate, o.T., Seipel, S., Yu, J., Viková, M., Vik, M., Ferri, A., Guan, J., Chen, G. and Nierstrasz, V. Supercritical co2 dyeing of polyester fabric with photochromic dyes to fabricate uv sensing smart textiles, *Dyes and Pigments*, **183** (2020).

62. Vouters, M., Rumeau, P., Tierce, P. and Costes, S. Ultrasounds: An industrial solution to optimise costs, environmental requests and quality for textile finishing, *Ultrason Sonochem*, **11**(1) 33-8 (2004).

63. Schönberger, H. and Schäfer, T. Best available techniques in textile industry, (2003).

64. Montero, G.A., Smith, C.B., Hendrix, W.A. and Butcher, D.L. Supercritical fluid technology in textile processing: An overview, *Ind. Eng. Chem. Res*, **39** 4806-4812 (2000).

65. Roessler, A. Direct electrochemical reduction of vat dyes in a fixed bed of graphite granules, *Dyes and Pigments*, **63**(1) 29-37 (2004).

66. Matsuoa, T. Innovations in textile machine and instrument, *Indian Journal of Fibre & Textile Research*, 288-303 (2008).

67. Haji, A. and Naebe, M. Cleaner dyeing of textiles using plasma treatment and natural dyes: A review, *Journal of Cleaner Production*, **265** (2020).

68. Bhat, N.V., Kale, M.J. and V.Gor, A. Microwave radiations for heat-setting of polyester fibers, *Journal of Engineered Fibers and Fabrics*, **4**(4) (2009).

69. Gong, D., Jing, X., Zhao, Y., Zheng, H. and Zheng, L. One-step supercritical co2 color matching of polyester with dye mixtures, *Journal of CO2 Utilization*, **44** (2021).

70. Mohsin, M., Sardar, S., Akhtar, K.S., Anam, W., Ijaz, S., Afraz, N. and Jamil, A. Performance enhancement

of water and energy efficient foam dyeing and finishing through different foaming agents, *Journal of Natural Fibers*, **20**(1) (2023).

71. Lämmermann, D. and Aktiengesellschaft, H. Formaldehyde-free easy care finishing of cellulose-containing textile material., *Patent 5352242-A, USA,*, (1994).

72. Dehabadi, V.A., Buschmann, H.-J. and Gutmann, J.S. Durable press finishing of cotton fabrics: An overview, *Textile Research Journal*, **83**(18) 1974-1995 (2013).

73. Li, K., Zhang, J. and Gong, J. Wrinkle-resistant finish of foam technology for cotton fabric, *Journal of Industrial Textiles*, **43**(4) 525-535 (2013).

74. Rowland, S., Bertoniere, N.R. and KIing, W.D. Durable press performance and reagent distribution from foam application of dmdheu, 197-204 (1983).

75. Gregorian, R.S., Young, C.G.N.a.R.E. and Baitinger, W.F. Foam application of phosphonium salt flame retardants, *Textile Research Journal*, **53** 148-152 (1983).

76. Hasanbeigi, A. and Price, L. A technical review of emerging technologies for energy and water efficiency and pollution reduction in the textile industry, *Journal of Cleaner Production* **95**(7) (2015).

77. Mohsin, M. and Sardar, S. Development of sustainable and cost efficient textile foam-finishing and its comparison with conventional padding, *Cellulose*, **7** 4091-4107 (2020).