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Sustainable Coloration Technologies

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***Abstract:** The textile industry is witnessing significant transformations in dyeing methods due to technological advancements. Innovations in dyeing techniques have not only revolutionized the way fabrics are colored but also paved the way for more sustainable and efficient practices. This article explores the innovations and advancements in dyeing methods brought about by technology, the impact of these advancements on the industry, and the implications for the future of textile dyeing processes. The successful substitution of hazardous chemicals with more sustainable alternatives like salt-free dyeing, urea replacement, use of natural dyes, and low-temperature soaping enhances efficiency, reduces waste, minimizes environmental impact, and promotes sustainable practices having eco-friendly solutions. These methods reduce water consumption and chemical waste, making them more sustainable alternatives to conventional dyeing processes.*

***Keywords:** Microwave, Plasma, Sonication, Supercritical CO2, Salt-free*

I. INTRODUCTION

One of the major industries contributing to environmental dangers worldwide is the textile sector, which produces 60 billion kg of fabric each year and consumes up to 9 trillion gallons of water. During coloration, large volumes of unfixed dye are released into water bodies; 10–15% of the dye is lost as wastewater and finds its way into the environment. The level of competition in the textile industry has also led to a rise in the use of synthetic dye combinations, which has increased the volume of effluent in dye wastewater. Due to its excellent thermal photostability and resistance to biodegradation, the dye can withstand prolonged exposure to the environment. Discharging colorless sewage into rivers and saltwater poses a significant threat to all living things, including humans [1].

A number of the conventional techniques have a significant water, energy, and chemical consumption. In the contemporary era, there is a heightened global consciousness regarding environmental contamination, climate variations, global warming, carbon emissions, and sustainability [2].

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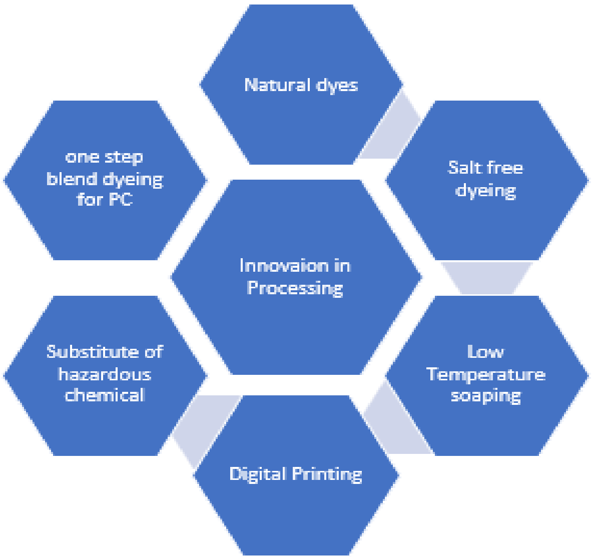
Technologies for sustainable processing reduce harmful chemicals, are safer to create, more effective, clean, affordable, and recyclable in some situations. Numerous researchers have worked to provide environmentally friendly chemicals, dyes, and auxiliaries to achieve sustainable chemical techniques for textile wet processing. This paved the way for the textile industries to achieve sustainability.

This study looks at strategies to improve the sustainability of the dyeing process, such as creating reactive dyes, changing the dyeing equipment and procedures, chemically altering cotton fiber before dyeing, and incorporating organic molecules that decompose quickly into dyebath formulations.

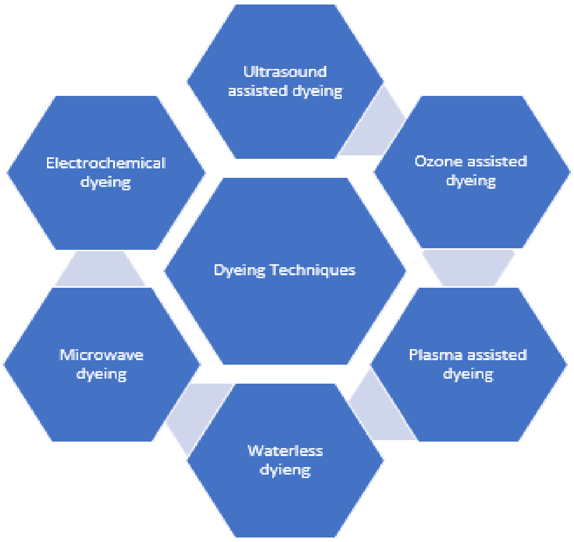
The paper discusses various dyeing processes' sustainability techniques, such as modification of chemical pretreatments, altering or modifying dyeing processes, and equipment to improve sustainability in reactive dyeing through multiple approaches, microwave-assisted dyeing, supercritical carbon dioxide dyeing, plasma-induced coloration, and nano dyeing process, plasma-induced colouration, supercritical carbon dioxide dyeing microwave-assisted dyeing, and ultrasonic dyeing.

A. Recent Developments in Sustainable Dyeing Technologies

Colouring of textiles can be more sustainable by innovations at two levels.



[Fig.1: Advancement by Adopting Sustainable Processes] [1]



[Fig.2: Innovations by Technology Advancement] [2]

Considering environmental factors, sustainable dyeing techniques bring revolutionary changes to the textile sector. Current developments in several dyeing methods highlight the industry's dedication to environmentally responsible operations.

B. Use of Natural Dyes

The excessive use of synthetic dyes produces large amounts of hazardous waste, and unfixed colourants are released during production and application, disrupting the environmental equilibrium. Growing ecological concern necessitates the reemergence of natural colorants due to their widespread availability and range of tones. Researchers are currently focusing on developing sustainable and eco-friendly [3]. Natural dyes can create innovative qualities in addition to delicate, muted colors. These features could include deodorizing, antioxidant, antibacterial, antifeedant, and UV protection in active textile substrates. In today's market, creating colourful textile items using natural colourants may increase consumer interest. Finding substitute natural degradable dyes has emerged as one of the industry's top initiatives. Thus far, various plants and agricultural waste materials have demonstrated encouraging outcomes in textile colouring that are becoming more environmentally friendly and sustainable [4]. Colorants derived from plants, insects, fungi, invertebrates, or minerals are natural dyes. Vegetable dyes, mostly derived from different plant parts such as roots, stems, seeds, bark, leaves, and wood, comprise most of the natural dyes. Insects, fungi, snails, and other biological sources are also used as a source of colouring matter for textiles. Mineral dyes are made from natural earth pigments that have tinctorial qualities because of the oxides or the Manganese oxides that are hydrated. Mineral dyes include manganese brown, Prussian blue, iron buff, nankin yellow, and chrome yellow [5].

C. Salt-free Dyeing

Since reactive colorants have great overall fastness properties and are safe for the environment, they are frequently employed for cotton dyeing. However, using reactive colorants requires a very high concentration of salt. The salinity in the drain water stream rises due to the salt discharged during the dyeing of cotton, and the results affect the ecology and environment [6]. Recent research has focused on chemically modifying cotton fiber to introduce cationic charges to accomplish the ideal reactive dyeing results. Anionic dyes' affinity for cotton was greatly increased by adding cationic groups to cotton fibers, which eliminated the need for salt when dyeing cotton garments and increased the potency of reactive dyes. A well-researched technique for salt-free dyeing involves chemically altering cellulosic fibers by cationizing them with a cationic reagent. Salt-free dyeing methods have been explored extensively in textile research to reduce environmental impact and improve dyeing efficiency. Various approaches have been investigated, such as cationization of cellulose fibers [7]. Cotton fabric alteration using cationic copolymers soluble in water modification of cotton fabrics with water-soluble cationic copolymers [8], and pretreatment of fibers with an alcohol-water-NaOH system [9]. These methods aim to enhance the reactivity of fibers and reduce the consumption of chemicals like salt during dyeing. Studies have shown that optimizing cationisation processes can lead to successful salt-free reactive dyeing [10]. Additionally, using cationic copolymers on cotton fabrics has demonstrated effective dyeing under eco-friendly conditions without salt [11].

D. Low-temperature Soaping

These products offer energy-efficient and effective cleaning processes for dyed fabrics. These agents can operate at lower temperatures, reducing water consumption and energy usage. They are designed to remove undyed dyes, improve colour fastness, and reduce COD and BOD levels in wastewater, promoting a cleaner and more sustainable dyeing process [12]. The composition of these agents varies, including components like biological enzymes, chitosan-beta-cyclodextrin, sodium salt of polyacrylic acid, and organic peroxy acid, each contributing to the

|agent's cleaning efficiency and environmental benefits. Low-temperature soaping agents significantly advance textile dyeing technology, offering operational and environmental advantages.

E. Digital Printing

Offers significant advantages over conventional printing methods. It enables the production of high-value-added and high-quality printed textile products [13] , meets diverse customer demands without increasing costs or waste [14], and overcomes limitations of traditional screen printing, such as limited design accuracy and colour inconsistency [15]. Digital printing in textiles significantly reduces water consumption through various innovative approaches. Research has shown that using self-dispersing pigment inks eliminates the need for pretreatment and post-washing processes, reducing chemical waste and simplifying the printing procedure, thus minimizing water usage [16]. The innovation history of digital textile printing shows advancements in machine features, automation, accuracy, and production speed, enhancing print speed, design, and efficiency [17]. Digital textile printing, based on inkjet technology, allows for versatile design printing on various fabrics, with inks tailored to specific fiber types like cotton, silk, or polyester [18]. This technology streamlines production, minimizes wastage, ensures consistency in patterns and colors, and can be particularly beneficial for exclusive boutique designs targeting high-end customers.

F. Substitute of Hazardous Chemicals

The chemicals employed in the textile industries impact the environment. The primary environmental problems linked to the textile industry stem from discharges into bodies of water. Ecology is a new metric that is becoming more and more important today. The two main global environmental issues connected to the textile sector are the use of hazardous chemicals, particularly during processing, and water pollution from untreated wastewater discharge. Wet processors can reduce the volume and toxicity of discharges by using alternative, "greener" chemicals and processing processes [19].

Below are some substitutes where basic chemicals used in textile processing are substituted by a greener alternative.

i. *Substitute for Urea*

In cotton fabric printing, urea is a necessary disaggregating and color solubilization agent. However, because printing effluent contains a high amount of ammonia and nitrogen, The discharge of water containing ammonia is the primary source of the eutrophication issue, particularly in lakes and tourist regions. The application of urea results in ammonia nitrogen emissions that have a detrimental impact on environmental quality and human well-being. Reactive dyes are printed on cotton fabrics using caprolactam, PEG 400, and PEG 600 as partial or full alternatives for urea. It has been noted that various reactive dyes, such as caprolactam, can substitute urea. PEG 400 and PEG 600 can do so to a degree of around 50% of the ideal urea concentration needed for fixation [20].

ii. *Substitute for Reducing Agent for Sulfur –*

Sulfur dyes are mostly used to colour textiles made of cellulosic materials. Although sodium sulfide is a common reducing agent for sulfur dyeing and is inexpensive, it is persistent and not biodegradable. It produces difficult-to-treat wastewaters that are bad for the environment and leave hazardous residues in finished fabrics. Traditional Reducing agents, like sodium sulfide, can be substituted with sugar-based chemicals, such as glucose, which are eco-friendly alternatives with similar colour strength and fastness properties [21]. By replacing sodium sulfide with these green alternatives, the industry can reduce its environmental impact and move towards more eco-friendly practices in textile dyeing. Innovative green alternatives to replace other reducing agents, like hydrose, in textiles, include using natural substances like Thiourea dioxide, and ferrous sulphate, which are Furthermore, the use of natural plant-based indigo dyeing processes, like banana paste and banana peel paste, has shown promise as green alternatives to sodium hydrosulfite, contributing to sustainable and environmentally friendly textile production [22].

iii. *Substitute for Soda Ash in Reactive Dyeing -*

Textile dyeing, the shift towards sustainable chemicals is crucial to mitigate the environmental impact caused by traditional processes involving salt, soda ash (soda), caustic soda, and other hazardous chemicals. Researchers have explored eco-friendly alternatives that have a low impact on the environment. One such alternative is using mixed alkali, combining soda ash and sodium hydroxide, which has shown promising results in fixing deep shades of reactive dyes on cotton fabrics, improving fastness properties, and reducing process costs [23]. Research is being done on substituting soda ash with alkali, which has multiple poes and a large surface area, so it can be used in tiny concentrations and lower the effluent load by lowering the TDS.

iv. *Substitute for Hydros in Reduction Clearing of Polyester-*

Reduction clearing is frequently used as an after-treatment to clean the surface of dyed polyester of residual contaminants and deposits of disperse dye. Alternative methods are attracting interest from the industry due to some of the financial and environmental drawbacks of classic reduction clearance [24]. Organic reducing agents, such as formamidine sulphinic acid (thiourea dioxide), hydroxyacetone, and glucose, have been used as eco-friendly alternatives. Products like sodium hydroxymethane sulfonate (Rongalit® C, Superlite® C), optionally in mixtures with sodium hydroxymethanesulfonate or dithionite-formaldehyde condensates, exert reducing power under acidic conditions. It improves productivity and saves water and energy because it can perform reduction clearing without changing the liquid after dyeing and does not require a neutralization process [25].

G. One-Step One-Bath Dyeing with Disperse Reactive for PC Blend

Polyester/cotton blended fabrics are traditionally dyed using a two-bath or one-bath two-step dyeing process, utilizing reactive and disperse dyes separately. The one-bath, one-step dyeing process of polyester/cotton blends with disperse/Reactive dyes has advantages over the conventional dyeing processes in reducing the dyeing cycle as well as energy consumption [26]. A traditional area of study has surfaced modification of polymeric fibers without affecting the bulk properties [27]. Because several functional groups, such as hydroxyl, ester, carboxyl, and carbonate groups, attach to the surface of textile fibers rather than just one desired functional group, surface modification improves and increases dyeability.

Chemically altering cellulose fibers at the surface without significantly altering their original morphology and crystallinity is possible through esterification reactions, which alter the surface characteristics by modifying the chemistry of the fiber surface except reducing the cellulose fibers' inherent hydrophilicity. Another method is a one-bath super dark dying method using polyester-cotton fabric dyeing with WW series of disperse dyes and C series of Reactive dyes [28]. The main advantage of the one-bath, one-step dyeing process for polyester-cotton (PC) blends is the significant reduction in water, energy, and chemical consumption compared to traditional two-bath dyeing methods. This innovative approach involves dyeing the fabric in a single bath with either disperse dye after surface modification of cotton or a combination of Reactive and Acid dye. This leads to improved production efficiency and lower environmental impact [29]. Studies have shown that the one-step one-bath dyed PC blends exhibit good color strength, fastness properties, tear strength, and abrasion resistance, making them a sustainable and cost-effective option for textile dyeing processes. Additionally, the one-bath one-step dyeing method enhances the overall quality of the fabric while streamlining the dyeing cycle and reducing production costs associated with energy consumption and chemical usage.

II. INNOVATIONS AND TECHNOLOGICAL ADVANCEMENT

Innovations in dyeing methods have been driven by the textile industry's need for sustainable practices due to water consumption and environmental concerns [29]. Traditional dyeing processes contribute significantly to water pollution, prompting the development of eco-friendly techniques like supercritical CO2 dyeing, plasma dyeing, electrochemical dyeing, foam dyeing, microwave dyeing, ozone dyeing, air dyeing technology, which eliminate water usage and reduce chemical concentrations, energy consumption, and processing time compared to conventional methods. These advancements not only address environmental concerns but also aim to improve efficiency and cost-effectiveness in textile dyeing processes, showcasing the industry's commitment to sustainable innovation.

A. Supercritical CO2 dyeing

Supercritical CO2 dyeing is an innovative and sustainable method that offers numerous environmental benefits compared to traditional dyeing processes. Research has shown that supercritical fluid dyeing (SFD) using CO2 can significantly reduce water consumption, energy expenditure, and chemical usage in the textile industry [30]. Studies have demonstrated that the solubility of various dyes in supercritical CO2 can be influenced by pressure, temperature, and dye polarity, providing a basis for advancing this technology [31]. Supercritical waterless dyeing technology requires just supercritical fluid for circulation and dyeing. Once this is achieved, the process can be completed without generating wastewater by lowering the temperature and pressure. A supercritical fluid possesses both the liquid quality of dissolving materials into their constituent parts and the gaseous property of penetrating anything. In addition, near the critical point, minor changes in pressure or temperature result in huge changes in density, allowing many aspects of a supercritical fluid to be "fine-tuned".

The most widely utilized supercritical fluid is carbon dioxide. Since carbon dioxide is inexpensive, easily obtainable, non-toxic, and non-flammable, it is employed as a supercritical fluid. The physical characteristics above 31.06 degrees Celsius and 72.8 atmospheres of pressure lie in between those of a liquid and a gas. In carbon dioxide dyeing, carbon dioxide automatically separates from textiles and leftover dyes, which are reusable. Most significantly, the dyeing cycle is shortened from several hours to 15 to 60 minutes as operation procedures are decreased; energy is also conserved as a result of the lower operational temperature. Furthermore, the use of special reactive dyes in supercritical CO2 systems has shown improved dye uptake and fixation on fabrics, enhancing color fastness and efficiency. The development of reactive disperse dyes specifically designed for supercritical CO2 dyeing has resulted in excellent color strength and dye fixation on both synthetic and natural fabrics, highlighting the potential for eco-friendly textile dyeing processes._Supercritical CO2 dyeing offers numerous benefits that make it a promising alternative to traditional dyeing methods. The process is environmentally friendly, leading to zero pollution, energy savings, and reduced emissions [32]. It allows for increased color strength, uniformity, and fastness in fabrics, without the need for auxiliaries like dispersing agents or surfactants, resulting in a more sustainable textile future. Additionally, supercritical CO2 dyeing enables the reuse of non-adsorbed dyes, captures atmospheric CO2, and offers a water-free and effluent-free process, contributing to environmental preservation and financial gains [33].The technology also shows potential for circular manufacturing and recycling frameworks, simplifying processing, reducing water usage, and promoting the use of sustainable materials like cellulose diacetate. Furthermore, the solubility of dyes in supercritical CO2 can be accurately measured, providing a basis for the advancement and widespread adoption of this innovative dyeing technique.

B. Plasma Dyeing

Plasma dyeing technology is an eco-friendly method that utilizes plasma treatment to enhance the dyeing process of textiles. This innovative approach involves modifying the surface of fabrics without altering their bulk properties, improving dye uptake and coloration while addressing environmental concerns associated with traditional dyeing methods [34]. Plasma treatment creates active sites on fabric surfaces, allowing for better interaction with dyes and facilitating the application of nanomaterials as a pretreatment step. Studies have shown that plasma treatment can significantly improve the dyeability of various fabrics like cotton, wool, and polyester, offering a sustainable alternative to conventional dyeing processes [35]. By adjusting parameters such as gas type, pressure, power, and duration, plasma technology can be tailored to achieve specific modifications on textile surfaces, making it a versatile and efficient tool for enhancing dyeing and finishing processes in the textile industry [36]. The primary applications of plasma technology are in the induction of surface alterations as well as the improvement of textile material properties for increased dyeing rates, colour improvement, coated dye adhesion, and diffusion. After the textile material is colored into the chamber, plasma is activated. After being created, the particles interact with the textile material's surface. The material's surface forms a thin film the thickness of a nanometer and is a functional group organized [37]. The benefits of plasma dyeing are that the color obtained is vivid and long-lasting, with minimal chemical and water outflow. This technique modifies the fiber's outside rather than the material's interior. The impact on the environment is minimal. At the same time, it has some negative aspects also. When this treatment is in operation, it releases hazardous gasses like nitrogen oxides and ozone. The plasma device is expensive and needs a knowledgeable and skilled operator [38].

C. Electrochemical Dyeing

Vat and sulfur dyes are insoluble in water; however, when reduced, they become soluble in water and prefer cellulose materials. Following the dyeing process, these dyes undergo in-situ oxidation to revert to their original pigment structure, which is insoluble in water. In aqueous solutions, sodium sulfide and sodium dithionite (hydrosulfite) are the most often utilized reducing agents when combined with alkali. These sulfur-based reducing agents used for reduction are corrosive, and poisonous, and raise the effluent burden. Furthermore, coloring baths and rinse water disposal are costly, and these often-used reduction agents cannot be recycled. Electrochemistry is a prominent alternative where an electric current transmits electrons from the electrode to the dye, a potentially effective substitute for dye reduction. The development of electrochemical reduction has been studied, encompassing both direct and indirect forms of reduction.

A novel electrochemical reduction technique called electrocatalytic hydrogenation uses dye at the electrode surface to react with in-situ hydrogen produced during water electrolysis. These methods offer numerous advantages for the environment and the economy and are more promising for textile dyeing by reducing chemical consumption and effluent load [39]. The electrochemical reduction of textile dyes can be divided into direct and indirect reduction. Direct electrochemical dyeing involves dyeing the fabric by applying electrical potential directly to the textile substrate, while indirect electrochemical dyeing utilizes an electrolysis system with specific solutes to enhance the dyeing process. Indirect electrochemical dyeing methods often involve the use of complex systems like iron-hydroxyl-aluminum binuclear complexes [40], iron-triethanolamine-calcium gluconate complexes, and iron ion-inositol hexaphosphoric acid chelating systems [41]. These systems improve the reduction potential, reduce dyeing time, and enhance dyeing depth, addressing poor dye reduction rates and color fastness [42]. Indirect electrochemical dyeing methods offer a greener approach by reducing the need for excess chemicals and minimizing environmental pollution, making them a promising alternative in the textile industry.

D. Ozone Technology for Dyeing

Ozone technology offers a sustainable alternative in the textile industry, allowing for chemical substitution, waste reduction, and energy conservation in various denim applications. It is a promising solution for a more environmentally friendly denim production process [43]. Ozone technology is increasingly utilized in denim applications due to its exceptional oxidation potential and eco-friendly nature. Research has shown that ozone can be applied to denim fabric before weaving or during laundry processes to achieve a local bleaching effect [44]. Studies have demonstrated that ozone treatment on denim fabric leads to fading of indigo dye, with the extent of fading influenced by ozone concentration, moisture content, and exposure time. Furthermore, ozone gas has been found to affect the color fading and strength performance of indigo-dyed yarns, showcasing its potential for denim fading processes [45].

E. Ultrasonic Dyeing

Ultrasonic dyeing is a promising technique that offers numerous benefits in the textile industry, particularly in terms of sustainability and efficiency. Research has shown that ultrasound-assisted dyeing can lead to enhanced colour yield, improved fastness properties, reduced energy consumption, and minimized wastewater pollution [46]. Ultrasonic sound is defined as sound that has a frequency higher than 20 kHz, which is above the range of human hearing. This type of sound can produce ultrasonic waves and cavitation in liquids, which can have dramatic effects [47]. Ultrasonic waves generate many tiny vacuum bubbles, which burst in the high-pressure cycle, producing localized shock waves at high temperatures and pressures as well as strong shear forces that can break up clumped particles and cause material disintegration, mixing, and milling. Reagents fragment into reactive free radicals by cavitation, which then catalyze a reaction.

Other mechanical impacts of ultrasound on the reaction include enlarging the space between the reactants, quickening the dissolving process, and/or rejuvenating the surface of a catalyst or solid reactant. By utilizing ultrasound energy during the dyeing process, various studies have demonstrated significant improvements in dye penetration, dyeing depths, and dyeing uniformity, resulting in good dyeing properties that reduce the need for high temperatures, toxic chemicals, and excessive water usage, making it an environmentally friendly alternative that aligns with the growing demand for sustainable practices in textile dyeing processes [48]. The textile sector is lagging in implementing sonochemical processes, largely due to a lack of compelling data on the energy, water, and chemical savings associated with using ultrasound in actual industrial production machines.

F. Microwave-assisted Dyeing

Microwave dyeing technology offers numerous benefits in the textile industry, including reduced processing time, energy efficiency, and enhanced colorant extraction from natural sources. Studies have shown that microwave irradiation can be effectively utilized for dye extraction, pretreatment of textile fibers, and colouration processes, both with synthetic and natural dyes [49]. Researchers have achieved sustainable and eco-friendly outcomes by employing microwave radiation with improved color strength and fastness properties [50]. Since microwave photons' energy is very small compared to chemical bonds' energy, microwaves have no direct effect on a compound's molecular structure or atoms' electronic configuration [51]. Different materials are impacted differently by microwave radiation; some absorb, some transmit, and some reflect the microwaves. Microwave heating is a viable substitute for traditional heating methods for quick, efficient, and consistent heating. The instantaneous and uniform heating that results from microwave energy's ability to penetrate all material particles readily removes any potential issues that may arise from traditional heating [52]. By reducing energy consumption, accelerating heating processes, and improving dye exhaustion rates, microwave irradiation is valuable for achieving time, energy, and environmental pollution reduction goals in textile coloration processes.

G. Foam Dyeing

Foam dyeing in the textile industry is gaining traction as a sustainable substitute for conventional dyeing techniques because of its ability to significant water, chemical, and energy savings [53]. Research has focused on optimizing foam generation and application for various dyes and finishes, with alkane sulfonate sodium salt-based foaming agents showing promising results in dyeing and finishing properties. The main dyeing element in this process is foam, using air instead of water to carry the chemistry or dye onto the fabric. Foam dyeing processes offer advantages such as enhanced quality of the final product and reduced environmental impact by minimizing effluent generation [54]. By transitioning from conventional water-assisted systems to foam-assisted systems, textile manufacturers can address consumer awareness, comply with environmental regulations, and mitigate water scarcity and high energy costs. The foam dyeing technique not only improves cost-effectiveness, productivity, and sustainability but also presents opportunities for further research and development in the field of textile dyeing and finishing [55].

H. Air Dyeing

Air dyeing technology, also known as air dye, is a waterless textile dyeing method that offers significant environmental benefits over conventional dyeing processes [56]. Air-dye technology manages the application of colour to textiles without the use of water or with a liquor ratio of around 90% less than the conventional Dyeing techniques. Air-dye uses up to 95% less water and up to 86% less energy contributing 84% less to global warming [57]. Airflow is a crucial component of this technology since it is an ideal transport medium. The jet dyeing machines employ air, not coloured liquid, to carry pieces of goods, which significantly lowers the number of chemicals and water used. To achieve consistent and reliable dying, the moisture-saturated airflow ensures that the temperature is distributed evenly inside the machine and on the fabric. Moreover, the cloth may be rapidly accelerated to high speeds because it is lighter than conventional machinery due to the minimal amount of liquor in the dyeing boiler. As a result, there is little chance of draft or strain, which is wonderful for dyeing goods with less damage. Thanks to the two-sided air dyeing process, the resulting fabric has a smooth, opulent hand feel [58]. Air dying is a cutting-edge dying technique with negligible environmental impact [59]. Air dyeing has gained popularity due to its advantages, such as emitting less waste, consuming less energy, and having a shorter operating time than traditional methods [60].

III. CONCLUSION

A paradigm shift in dying techniques is required as the textile industry moves toward sustainability. There are many advantages to using sustainable dyeing methods, such as less water use and fewer chemical contaminants. However, issues still need to be resolved, including cost-effectiveness, energy consumption optimization, and colour fastness improvement. Recent advancements in the discipline suggest that the textile industry will become more environmentally friendly. To bring about a new era of responsible textile production, producers, academics, and legislators must work together to accelerate the use of these sustainable dyeing technologies. In conclusion, the textile industry offers a wide range of environmentally friendly dyeing techniques that can lessen their negative effects on ecosystems and pollution.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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