Green Chemistry

CRITICAL REVIEW

View Article Online
View Journal

Cite this: DOI: 10.1039/d5gc06662j

Color stripping of dyed textile waste

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The increasing accumulation of post-consumer textile waste (PCTW), driven by fast fashion trends and growing consumer demands, poses significant threats to environmental safety. This waste is difficult to recycle due to the persistent nature of synthetic dyes, which hinder fiber regeneration and reuse. Color stripping (CS), the process of removing dyes from fabrics, holds potential as an important solution to enhance the possibility of textile reusing/recycling. Chemical approaches, including oxidative and reductive methods, are widely applied for CS, but concerns about fiber degradation and the toxicity of effluents produced during the process remain substantial. Biological methods using fungal enzymes offer eco-friendly alternatives, but they are often limited by much slower reaction rates and higher costs. Advanced oxidation processes (AOPs) and solvent-based techniques show promising potential for more efficient dye removal. This review provides an in-depth discussion of the recent advancements in CS technologies for dyed PCTW, focusing on the performance and influencing parameters of CS efficiency, such as time, temperature, pH, bleaching agent concentration, and dye types. Despite the progress in CS technologies, significant challenges remain, particularly in terms of optimizing efficiency and sustainability. This review also highlights future directions for developing more sustainable and efficient dye removal strategies, which are crucial for achieving closed-loop circularity in the textile industry and minimizing the environmental impact of textile waste.

Received 9th December 2025,
Accepted 21st May 2026

DOI: 10.1039/d5gc06662j

rsc.li/greenchem

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1. Color stripping, the process of removing dyes from fabrics, has strong potential to improve textile reuse and recycling. In this work, we evaluate the environmental impacts of the recent advances in dye-removal technologies and assess the feasibility of future developments.
2. Textile waste is challenging to recycle because synthetic dyes are difficult to break down and they interfere with fiber recovery. This work contributes meaningfully to the recycling field by advancing circularity and increasing the availability of clean, safe, and sustainable textile materials through effective dye-removal methods.
3. Developing more sustainable and efficient dye-removal strategies is essential for achieving real closed-loop circularity in the textile industry and reducing the environmental footprint associated with textile waste.

1. Introduction

Coloration is one of the most important and value-adding processes in textile manufacturing. Dyes and pigments impart aesthetic appeal and commercial value to textiles, making color an inseparable part of consumer expectations across apparel, home textiles, and technical fabrics.[1] The global textile dye market is valued at over USD 14 billion in 2026 and is projected to grow steadily.[2] Textile dyeing, however, is also one of the most resource-intensive and environmentally burdensome stages of the textile production chain, consuming large volumes of water, energy, and auxiliary chemicals while generating highly colored and chemically complex effluents.[3] Conventional dyeing of cotton with reactive dyes, for instance, requires substantial electrolyte additions and operates at high liquor-to-goods ratios, resulting in wastewater with high salt loads, unfixed dye residues (typically 30%–40% of the applied dye), and elevated chemical oxygen demand. These environmental pressures have driven growing interest in green dyeing technologies. Ethanol–water binary solvent systems have been demonstrated as effective media for reactive dyeing of cotton, substantially reducing salt consumption and improving dye fixation efficiency compared with conventional aqueous dyeing.[4] Supercritical CO_2 dyeing of polyester eliminates water entirely from the dyeing bath, recovering the fluid and dye in a closed-loop process.[5] Enzymatic pre-treatments and bio-based mordants have enabled low-impact natural dyeing systems on protein fibers.[6] Waterless plasma and ultrasonic-assisted dyeing technologies reduce both water and energy demands while maintaining acceptable color yield and fastness.[7] Understanding this broader context of the importance of dyeing and the ongoing efforts to make it greener is essential

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for appreciating why color stripping of post-consumer textile waste represents a critical complementary challenge: the dyes that are so deliberately and resource intensively applied must, at end of life, be efficiently removed to enable fiber reuse and circularity.

The textile industry generates approximately 92 million tons of waste each year, largely due to the influence of fast fashion, which accelerates the disposal of garments. In the European Union (EU), people used to buy 17 kg of textiles per person in 2019, but by 2022, that number has increased to 19 kg per person on average. Around 12 kg of clothes are thrown away every year in the EU and only 1% of used clothes are recycled into new clothes.[8–11] This considerable waste generates huge environmental and societal issues, including pollution from textile dyes, heightened landfill utilisation, and health hazards in manufacturing stage.[12–14] Moreover, textile waste often contains synthetic dyes and chemical finishes, posing a considerable barrier to direct reuse and recycling. The presence of such contaminants complicates efforts to close the loop in the textile lifecycle.[15,16] It has been revealed that color stripping (CS) is a potential pre-treatment process to address the environmental challenges caused by dyed post-consumer textile waste (PCTW).[10,17,18] Hence, CS can facilitate the recycling, reusing, and re-dyeing.[19]

CS involves the removal or significant reduction of dyes from fabrics and enhances the suitability to produce regenerated fibers, new fabric blends, and re-dyed garments. During CS, PCTW presents distinct challenges compared to industrial pre-consumer waste due to their heterogeneity in dye types, fiber blends, finishes, and the wear-related damage accumulated during their use phase. Various types of dyes, including reactive,[20] disperse,[21,22] vat,[23] sulfur,[24] acid,[25] and direct[25] dyes are utilized for textile coloration according to the type of fiber, whether natural or synthetic. Each of these dye types forms unique chemical bonds, and some interact *via* van der Waals forces and ionic interactions with the fiber and need specialized stripping techniques to remove the specific type of dye.[26–29] Furthermore, PCTW is frequently composed of blended fibers, such as cotton/polyester, polyester/linen, cotton/nylon, polyester/wool, cotton/wool, jute/cotton, wool/silk, cotton/elastane, and polyester/viscose, which further complicates the CS process.[30,31]

Various CS methods have been developed to address the complexities of color removal from PCTW. Chemical stripping (oxidative and reductive) is the widely employed approach, and commonly used agents in this process include hydrogen peroxide, ozone, sodium hydrosulfite, sodium chlorite, sodium hypochlorite and potassium permanganate. Oxidative and reductive color stripping agents break the dye chromophore under controlled temperature and pH conditions, and it is necessary to optimize the processing conditions for both high CS efficiency and minimum damage to the fiber.[32–36] In contrast, biological methods, such as enzymatic and microbial degradation, offer an environmentally sustainable alternative to chemical stripping. Enzymes, particularly those derived from fungi like *Ganoderma lucidum*, have demonstrated effective CS of reactive dyes from cotton dyed waste.[37–39] Advanced oxidation processes (AOPs), including UV/H_2O_2 and TiO_2-based photocatalysis, are also gaining recognition due to their high reactivity and ability to decompose dye molecules. This method is particularly effective for CS of multiple dyes.[40–43] Solvent-based methods using dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) have also proven successful in removing dyes from synthetic fabrics without causing excessive fiber damage. When combined with the microwave-assisted technique, the solvent-based method can further enhance CS.[24,44,45]

Although many researchers have studied color removal from the textile wastewater, very few research studies have focused on color stripping from dyed post-consumer textile waste. In recent years, however, it has gained increased attention, as it is now identified as one of the main challenges for improving the efficiency of textile recycling. In addition, there is a lack of comprehensive reviews published in the literature on CS of dyed PCTW. This review explores the recent advances of color stripping technologies for dyed post-consumer textile waste. It aims to provide a detailed evaluation of the effectiveness, limitations, and ecological implications of various color stripping methods. This review provides the CS performance analysis of each technique and factors affecting the color stripping efficiency. The current challenges of existing technologies and future prospects are also briefly discussed.

2. Evaluation of color-stripped textiles

The effectiveness of color stripping must be assessed not only in terms of color removal but also in relation to the structural and mechanical integrity of the treated fabric. Quantitative evaluation relies on colorimetric methods for measuring color change, whiteness, and shade correction. To understand the effects of color stripping on the physico-chemical properties of textiles, complementary analyses of fabric structure, strength, and chemistry are required. Together, these methods allow a comprehensive evaluation of both the efficiency of color stripping and the preservation of fabric properties.

The stripping percentage of the striped fabric was assessed using the K/S value, calculated through eqn (1) and (2).[46] This equation, based on the Kubelka–Munk theory, relates the fabric's reflectance (R) to its absorption (K) and scattering (S) properties at a specific wavelength as follows:

$$\frac{K}{S}=\frac{(1-R)^2}{2R}, \tag{1}$$

$$\text{Stripping}=\frac{\frac{K}{S}(\text{unstripped fabric})-\frac{K}{S}(\text{stripped fabric})}{\frac{K}{S}(\text{unstripped fabric})}\times 100. \tag{2}$$

The CIE $L^*a^*b^*$ color space is a widely adopted system in the textile industry for the objective evaluation of color. It characterizes the color of a sample by assigning numerical values to three parameters: L^* (lightness), a^* (green–red axis), and b^* (blue–yellow axis), thereby enabling precise color assessment and comparison.[47] The L^* value in the CIELAB color space is the most important parameter for evaluating color stripping. It ranges from 0 (black) to 100 (white). As more color is removed, the L^* value increases, indicating a lighter and cleaner material. Therefore, L^* directly reflects the effectiveness of the stripping process. By measuring the L^* value before and after color stripping, the degree of color removal can be quantified (eqn (3)). A higher ΔL^* indicates greater stripping efficiency.

$$\Delta L^* = L^*_{\text{after CS}} - L^*_{\text{before CS}}. \tag{3}$$

The whiteness index of the color-stripped fabrics can be calculated using eqn (4),[48] which is derived from the CIE $L^*a^*b^*$ values as follows:

$$\text{Whiteness index} = 100 - \sqrt{(100 - L^*)^2 + (a^*)^2 + (b^*)^2}. \tag{4}$$

The whiteness level of the stripped fabric can be quantitatively evaluated using the CIE whiteness index, in accordance with the AATCC 110-2005 standard. Measurements are conducted at four distinct positions on each sample, and the results are averaged to obtain representative values.

Elemental analysis technique can be applied to color-stripped fabrics using a CHNSO Elemental analyzer to confirm the efficiency of the stripping process by verifying whether nitrogen (such as azo dyes) or sulfur (such as sulfur dyes)-containing dye molecules have been completely removed.[49]

To assess the impact of the stripping process on the fabric surface, surface morphology (SEM) can be examined both before and after treatment, allowing for the identification of any physical damage incurred during the stripping process. Fourier transform infrared (FT-IR) spectroscopy analysis can be employed to monitor the presence or removal of dye molecules by comparing the spectral characteristics of the fabric samples before and after stripping.[41] X-ray diffraction (XRD) analysis can be performed to investigate the structural properties of the fibers, specifically to distinguish between amorphous and crystalline regions.[50] The degree of crystallinity (X_c) can be calculated based on integrated intensities of the crystalline phase (I_c) and amorphous phase (I_a) using eqn (5) from the XRD data to quantify the changes in the fiber structure associated with the stripping treatment as follows:

$$X_c = \frac{I_c}{I_a + I_c} \times 100. \tag{5}$$

The tensile strength of the fabric before and after color stripping can be measured using a fabric strength tester in accordance with the ASTM D5035-1995 standard, which specifies the strip test method for evaluating the fabric tensile properties. The fabric weight loss resulting from the stripping process can be determined using eqn (6), which quantifies the percentage reduction in fabric mass before and after color stripping as follows:

$$\text{Weight loss} = \frac{\text{dry weight before CS} - \text{dry weight after CS}}{\text{dry weight before CS}} \times 100. \tag{6}$$

The degree of polymerization (DP) can be calculated to evaluate the changes induced by CS treatments. The DP of the cellulosic fabrics can be determined using a copper ethylenediamine (CED) solution, following the ISO 5351:2010 standard method.[50] The quality of the stripped fabric can be evaluated by assessing its pilling resistance, and it can be measured in accordance with the ASTM (1999) standard test method. The resistance to pilling was graded on a standardized arbitrary scale ranging from 5 to 1, where a rating of 5 indicates no pilling and a rating of 1 denotes very severe pilling.[37]

3. Methods of color stripping of dyed textile waste

Color stripping of dyed textile waste can be done using various methods including chemical methods (oxidative stripping, reductive stripping, and alkaline and acidic treatments), biological methods (microbial and enzymatic stripping) and advanced oxidation processes (Fenton reaction, UV/H_2O_2, and photocatalysis). The choice of color stripping technique is influenced by multiple factors, including the chemical nature of the dye, the type and sensitivity of the fabric, and environmental considerations such as effluent management and chemical sustainability. Various color stripping processes and their advantages–disadvantages are stated in Table 1.

3.1. Chemical methods

Chemical bleaching is a widely adopted technique in textile manufacturing and recycling and various chemicals are utilized in this process, depending on the type of dye and textile substrate. A common method involves the use of acidic or alkaline solutions to degrade dye molecules, thereby enabling their removal from the fabric. Alternatively, oxidative agents that promote oxygen-based chemical reactions are frequently employed due to their effectiveness in breaking down complex dye structures. The performance of oxidation processes can be further enhanced through the application of auxiliary technologies such as microwave irradiation and ultrasonic treatment, which increase reaction efficiency and accelerate the stripping process. Reductive methods represent another key strategy, in which reducing agents disrupt the molecular bonds within dye compounds, allowing the color to be stripped from the textile.

3.1.1. Acidic color stripping. Acidic color stripping method involves the application of strong acids to alter the chemical integrity of dye molecules or disrupt the interaction between dyes and textile fibers, thereby facilitating the removal of unwanted coloration. At the core of the acid stripping process is the use of mineral acids, most notably hydrochloric acid

Table 1 Various color stripping process with their advantages and disadvantages

Stripping method	Dye type	Common agents used	Advantages	Disadvantages
Oxidative	Vat, sulfur, and reactive	H_2O_2, NaClO, $NaClO_2$, O_3, and $KMnO_4$	↓ Less time	↑ High risk of fiber damage ↑ Chemical-intensive
Reductive	Vat, sulfur, and disperse	$Na_2S_2O_4$ and $CH_4N_2O_2S$	↓ Less fiber damage	↑ Generation of toxic aromatic amines
Biological	Reactive	*Ganoderma lucidum*	♣ Environmentally friendly ↓ Less risk of fiber degradation	↑ Higher cost ↑ Slower processing time
AOP	Reactive	UV/H_2O_2, TiO_2/UV, and Fe^{2+}/H_2O_2	√ High efficiency ♣ Environmentally friendly	↑ Higher cost ↑ Recovery is challenging
Solvent	Direct, reactive, sulfur, and disperse	DMSO, DMF, and tetramethylurea	↓ Less fiber damage √ Solvent recovered and reused	↑ Health and environmental risks ↑ Cost-intensive

(HCl) and sulfuric acid (H_2SO_4), which effectively lower the pH of the treatment medium. This acidification leads to the protonation of functional groups on both the dye molecules and the fiber surface. As a result, key interactions such as electrostatic attraction and covalent bonding between the dye and the fiber are significantly weakened, allowing for partial removal of the dye from the fabric.

Experimental studies have demonstrated the variable effectiveness of acid stripping on different dye–fiber systems. For instance, when reactive-dyed cotton fabrics were treated with a 4% HCl solution at a pH of approximately 2, using a material-to-liquor ratio of 1 : 15, only a marginal reduction in color strength (measured *via* K/S values) was observed. This suggests that the chromophoric structures of reactive dyes are relatively stable under acidic conditions. However, the stripping efficiency varied by dye type; Reactive Blue Black 5 and Reactive Turquoise CLB exhibited stripping efficiencies of 3.68% and 7.66%, respectively.[51] These results indicate that acid stripping primarily weakens dye–fiber bonding rather than completely removing the dye, especially in the case of cotton substrates. Further investigations have expanded on acid stripping by assessing the stripping efficiency of H_2SO_4 on cotton fabrics dyed with various dyes, including C.I. Reactive Blue 19, C.I. Reactive Black 5, C.I. Reactive Red 228, and Vat Blue 1. The observed stripping efficiencies were 8.29%, 7.41%, 3.46%, and 10.19%, respectively, using 10 mL L^{-1} sulfuric acid at 60 °C for 1 hour maintaining a liquor-to-fabric ratio of 30 : 1.[23]

3.1.2. Alkaline color stripping. Alkaline color stripping process typically involves the use of alkaline agents such as sodium hydroxide (NaOH) and sodium carbonate (Na_2CO_3). Under the high-pH conditions, hydroxide ions can hydrolyze the covalent bonds formed between reactive dyes and cellulose fibers. This disruption enables the dye molecules to detach from the fiber matrix. Furthermore, the alkaline environment causes the cellulose fibers to swell, which enhances dye diffusion and promotes more effective desorption from the fiber interior.

A study investigating the efficiency of alkaline treatment for reactive dyed cotton fabrics demonstrated reductions in color strength, as measured by eqn (2). Specifically, stripping efficiencies of 74.23% and 43.02% were recorded for Reactive Blue Black 5 and Reactive Turquoise CLB, respectively. In this experiment, cotton fabrics dyed with these reactive dyes were immersed in a sodium hydroxide solution at a concentration of 80 g L^{-1} (pH approximately 12) for 60 minutes at 90 °C. After the alkaline treatment, the samples were thoroughly rinsed with water and air-dried.[51] The observed reduction in color strength indicated that, although reactive dyes form stable covalent bonds with cellulose, these bonds are susceptible to degradation in highly alkaline environments. Another study evaluated the stripping efficiency of three commercial reactive dyes (Procion Red MX-5B, Procion Yellow MX-G, and Procion Blue MX-G) applied to woven cotton fabrics using Na_2CO_3. Initially, the dyed samples underwent a simple rinse in tap water, followed by a wash-off process using a sodium carbonate solution (5 g L^{-1}) at 95 °C for 30 minutes with a liquor ratio of 30 : 1. The stripping efficiency was found to be 21.61% for Procion Red MX-5B, 21.92% for Procion Yellow MX-G and 25.76% for Procion Blue MX-G.[52]

3.1.3. Oxidative color stripping. Oxidative color stripping is a process that utilizes oxidizing agents to remove dyes from dyed textiles. Common oxidants used include ozone (O_3), hydrogen peroxide (H_2O_2), sodium hypochlorite (NaClO), sodium chlorite ($NaClO_2$), and potassium permanganate ($KMnO_4$).

Ozone is a highly reactive oxidant widely used for eco-friendly color stripping. It disrupts conjugated double bonds in dye molecules, causing color removal. Its efficacy depends on the dye structure, pH, dosage, and exposure time. For instance, Reactive Blue 21 showed maximum color stripping ($L^* = 79.43$) at pH 3, 7 g h^{-1} ozone, and 40 minutes exposure. Increasing the ozone dosage and contact time enhanced lightness (L^*) for color-stripped fabrics dyed with Reactive Black 5 and Reactive Yellow 84.[53] Hydrogen peroxide offers a safer alternative for stripping cotton fabrics dyed with reactive or direct dyes. Under alkaline and heated conditions, it generates hydroxyl radicals ($^{\bullet}OH$), which cleave dye chromophores. In one study, a system using 40 g L^{-1} H_2O_2, 20 g L^{-1} NaOH, and 10 g L^{-1} TAED at 70 °C and pH 10 achieved 96.4% color stripping of dark-colored reactive-dyed cotton waste.[50] Sodium hypochlorite is an effective but aggressive oxidant. It improves whiteness with increased concentration and treatment duration. For example, a study observed significant increases in lightness (ΔL^*) in dyed cotton fabrics, especially in darker shades (3.0% dye based on the weight of fabric) such as Avitera Brilliant Yellow SE and Light Red SE.[54] Potassium permanganate rapidly oxidizes dye chromophores, achieving up to 99.4% color removal in 90 minutes. However, it severely compromises fabric integrity. A 5% $KMnO_4$ treatment with 5% H_2SO_4 at 40 °C and pH 5 reduced the tensile strength and polymerization by over 50% within the first 15 minutes.[50] Sodium chlorite is used for color stripping with less impact on fabric structure. In one study, 5.25 g L^{-1} $NaClO_2$ applied at 20 °C for 8 hours, in the presence of phosphonates, achieved a whiteness index of 72.6, comparable to untreated control fabrics (W.I. = 74.2) while maintaining superior tensile strength and reduced structural damage.[55]

3.1.4. Reductive color stripping.

Reductive color stripping is a chemical process used to remove dyes from colored textiles. It works by breaking down the chromophoric structures in dye molecules using strong reducing agents, mostly sodium hydrosulfite ($Na_2S_2O_4$), sodium hydroxymethane sulfinate (CH_3NaO_3S) and thiourea dioxide ($CH_4N_2O_2S$). These chemicals are applied under controlled alkaline conditions and at elevated temperatures to ensure effective color stripping.[43,56,57]

A detailed study involving waste cotton fabrics dyed with vinyl sulfone-based reactive dyes demonstrated that treatment with 25 g L^{-1} sodium hydrosulfite at 90 °C and pH 9 could achieve up to 90.9% color removal after 90 minutes. However, this process led to a reduction in fabric tensile strength, from 479.1 N to 387.4 N.[50] Alternative reducing agents, such as sodium hydroxymethane sulfinate, have also shown promise. At 20 g L^{-1}, it achieved nearly 84% stripping for Reactive Red 23, which is comparable to the 88.5% obtained with sodium hydrosulfite.[58] Thiourea dioxide, also known as formamidine sulfinic acid, functions well under similar alkaline, high-temperature conditions. In one study, the fabrics dyed with various reactive dyes were treated with 5 g L^{-1} thiourea dioxide and 5 g L^{-1} sodium hydroxide at 100 °C. The stripping efficiencies varied by dye, ranging from 76.77% to 96.45%.[59]

3.1.5. Sequential color stripping.

Sequential color stripping strategy is importantly required because reactive dyes form a strong bond with the cellulosic fibers and show high resistance to bleaching. A single stripping process, such as acid, alkali, oxidation or reduction, is normally insufficient to break the dye–fiber bonds. The sequential stripping treatment process includes acid/alkali hydrolysis, oxidation and then reduction, and each step targets different parts of the dye–fiber system. Alkalis break the dye–fiber covalent bonds, oxidation breaks the chromophoric groups and reduction removes the residual fragments. This multi-step treatment process ensures the complete color removal.

Across the recent literature, sequential color stripping appears as a potential route for color stripping from dyed textile materials. Redox-based ($Na_2S_2O_4$–H_2O_2) treatment processes efficiently removed the dark reactive color from cotton waste.[50] A sequential redox CS mechanism in which dark-colored waste is first treated with sodium dithionite ($Na_2S_2O_4$) to reduce and break down the reactive dye molecules and then with hydrogen peroxide (H_2O_2) to oxidise and remove the remaining dye residues is stated in Fig. 1.

A solvent-assisted method using a DMSO–water mixture, combined with alkali and sodium dithionite, can increase the dye solubilization. The method is effective for mixed dyed post-consumer textile waste containing direct, reactive and vat

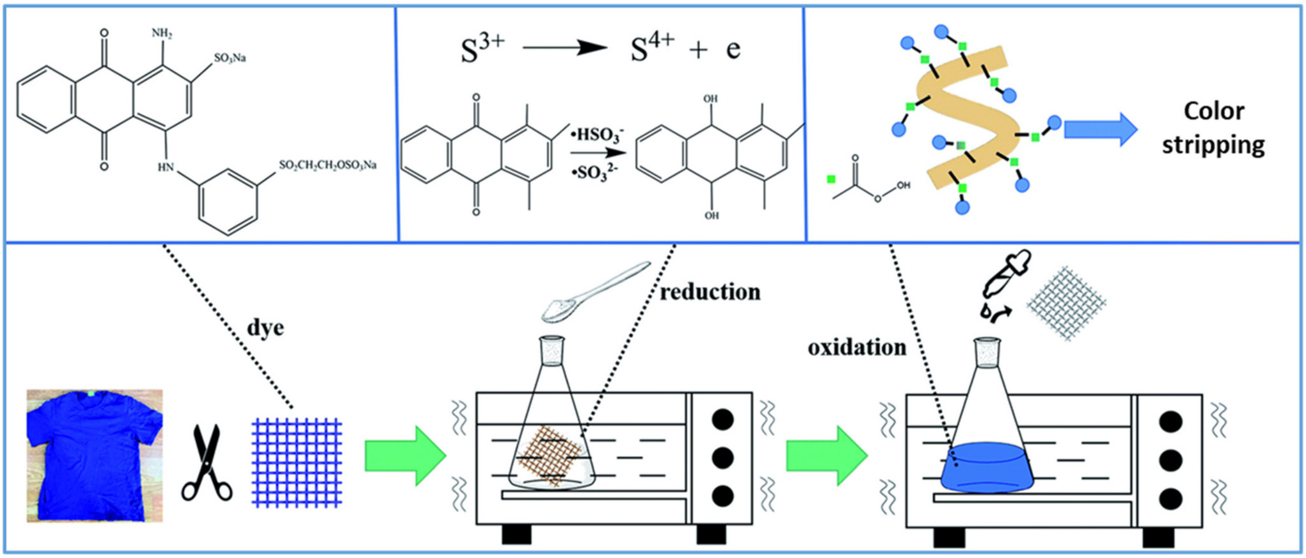

Fig. 1 Proposed combined CS mechanism of the reductive ($Na_2S_2O_4$) and oxidative (H_2O_2) processes. Reproduced from ref. 50 with permission from the Royal Society of Chemistry, copyright 2022.

dyes.[24] Microwave-assisted sequential (acid/alkali hydrolysis → oxidation → reduction) process also increases the color stripping efficiency for Reactive blue black 5 and Reactive Turquoise CLB.[51] Sodium dithionite and thiourea dioxide are employed in the CS of recycled dark-colored yarns.[60] The stripping of knitted cotton fabrics dyed with C.I. Reactive Yellow 145 was conducted using sodium hydrosulfite and sodium hypochlorite. The effectiveness of the stripping process was evaluated based on the whiteness index of the treated fabrics. The results indicated that the whiteness improved, confirming effective removal of the dye.[61]

3.1.6. Microwave-assisted CS.

Microwave-assisted CS utilizes microwave radiation to facilitate the removal of dyes from textiles. Microwaves generate rapid and uniform heating, which enhances the penetration and reaction rates of stripping agents within the fabric. This approach reduces the processing time, energy consumption, and the need for harsh chemicals, thereby minimizing damage to the fabric and environmental impact.[62,63] This process works on chemical-treated dyed fabrics under microwave irradiation. For instance, sodium citrate can act as a microwave absorber, enhancing heat generation during the process. In one study, pretreatment with sodium citrate followed by microwave irradiation achieved a CS efficiency of 94.8% in a $Na_2S_2O_4$ process and 96.2% in a meta-treatment, compared to 75.7% efficiency using conventional methods.[62] Sequential treatments combining alkali, oxidation, and reduction steps under microwave irradiation have also been explored. Such methods have achieved stripping efficiencies of up to 98% for certain dyes within 120 seconds, significantly outperforming conventional methods that may require up to 60 minutes.[64] Microwave absorber interaction with electromagnetic radiation and its role in the microwave-assisted CS of cotton fabrics dyed with Reactive Yellow C4GL are illustrated in Fig. 2.

3.1.7. Advanced oxidation process.

Advanced oxidation process (AOP) is an effective chemical method used to remove color from dyed fabrics. It works by generating highly reactive hydroxyl radicals ($^{\bullet}OH$) on-site, which have a strong redox potential of +2.8 V. These radicals react with dye chromophores in a non-selective manner, quickly breaking them down and causing color stripping and degradation of the dye molecules.[40–42]

Hydroxyl radicals ($^{\bullet}OH$) are produced in the Fenton reaction (eqn (7)), which can break down dye molecules.[42] In addition, ultraviolet (UV) light can split hydrogen peroxide (H_2O_2) to form radicals (eqn (8)), helping to remove the dye color.[40,41,43]

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^-, \quad (7)$$

$$H_2O_2 + h\nu \rightarrow 2\ {}^{\bullet}OH. \quad (8)$$

A study showed that the $Ti/TiO_2–RuO_2–IrO_2$ anode can be used in an electrochemical process for CS from dyed cotton. The study demonstrated that Reactive Black 5 was effectively removed and various levels of CS performance were achieved in different media, including water, pyridine, and phenol solutions.[47] The influence of current density on the CS efficiency of dyed cotton was investigated using Na_2SO_4 and NaCl. When Na_2SO_4 was used, an increase in current density from 5 mA cm^{-2} to 15 mA cm^{-2} led to a significant improvement in CS performance. Specifically, the CS increased from 7.5% to

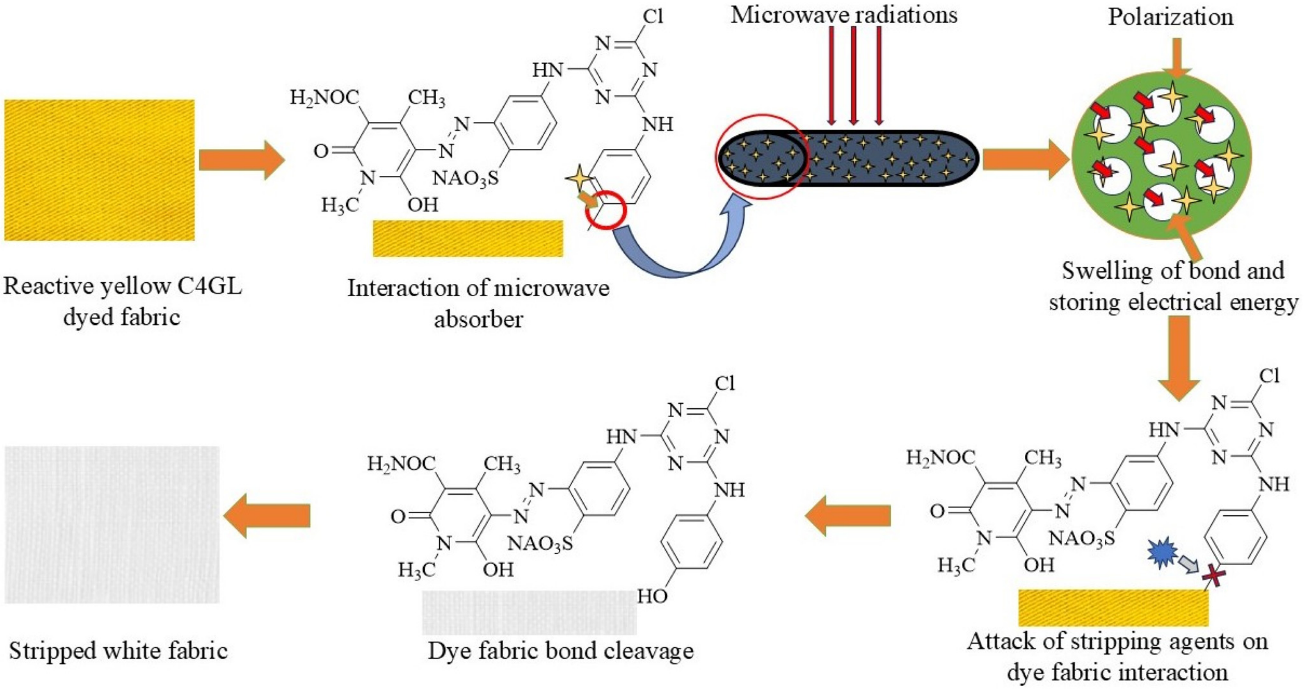

Fig. 2 Microwave absorber interactions with electromagnetic radiation and their role in the microwave-assisted CS of cotton fabric dyed with Reactive Yellow C4GL. Reproduced from ref. 64 with permission from Elsevier, copyright 2024.

25.4% in water, from 6.7% to 29.3% in a 100 mg L^{-1} pyridine solution, and from 6.8% to 27.3% in a phenol solution. In contrast, when NaCl was employed as the electrolyte, the CS increased from 86.3% to 96.1% in water, from 85.3% to 94.4% in a pyridine solution, and from 62.7% to 67.5% in a phenol solution. This notable enhancement is attributed to the generation of active chlorine species—such as Cl_2 and HOCl—on the Ti/TiO_2–RuO_2–IrO_2 anode in the presence of chloride ions. These reactive chlorines participate in indirect oxidation reactions and boost dye degradation and CS performance (eqn (9) and (10)).

A UV/$K_2S_2O_4$ system was developed for stripping reactive dyes from cotton fabrics at room temperature using a dipping process. Under UV irradiation, potassium persulphate generates highly reactive species that selectively degrades the fixed dyes on the cotton substrate. The process achieved over 90% color removal within 30 minutes.[41] The schematic mechanism of UV/$K_2S_2O_4$ photocatalytic CS is presented in Fig. 3.

$$2Cl^- \rightarrow Cl_2 + 2e^-, \tag{9}$$

$$Cl_2 + H_2O \rightarrow HClO + H^+ + Cl^-. \tag{10}$$

3.2. Solvent-extract color stripping

Solvent-based color stripping is an effective technique for removing dyes from textiles, especially when the dye and fiber have complex interactions. Dimethyl formamide is commonly used to remove disperse and direct dyes from PET/cotton-blended fabrics. In this process, the fabric is first soaked in a swelling solution, and then treated with a stripping solution containing DMF at 140 °C for 30 minutes.[44] Another study focused on stripping dyes from cellulosic textiles, such as cotton, that were dyed with direct, reactive, vat, and sulphur dyes. The process used a mixture of solvent and water, with optimized conditions of 20 g L^{-1} sodium hydroxide and 20 g L^{-1} sodium hydrosulphite at 90 °C for 20 minutes, combined with a 50/50 water/DMSO ratio.[24] The research also showed that 100% of disperse dyes, acid dyes, and direct dyes were successfully removed from PET, nylon 6,6, and cotton fabrics using various solvents.[25] Dimethylformamide along with water in 1 : 1 ratios can be used for the CS of reactive dyes (C.I. Reactive Blue 19–73.5%, C.I. Reactive Yellow 3–5.9%, C.I. Reactive Orange 5–4.5%, and C.I. Reactive Red 195–3.9%) and acid dyes (C.I. Acid Blue 25–87.5%, C.I. Acid Yellow 151–82.7% and C.I. Acid Red 131–79.3%).[65] Dimethyl sulfoxide (DMSO) can be used to remove the color from disperse-dyed polyester and reactive-dyed cotton. Moreover, it can be used in polyester–cotton blend textile without separating blend components.[9] DMSO removed disperse dyes from polyester significantly after several treatment cycles. However, DMSO is less effective for removing reactive dyes from cotton.

3.3. Biological color stripping

Biological color stripping method can remove dyes from fabrics using microorganisms. This approach offers a sustain-

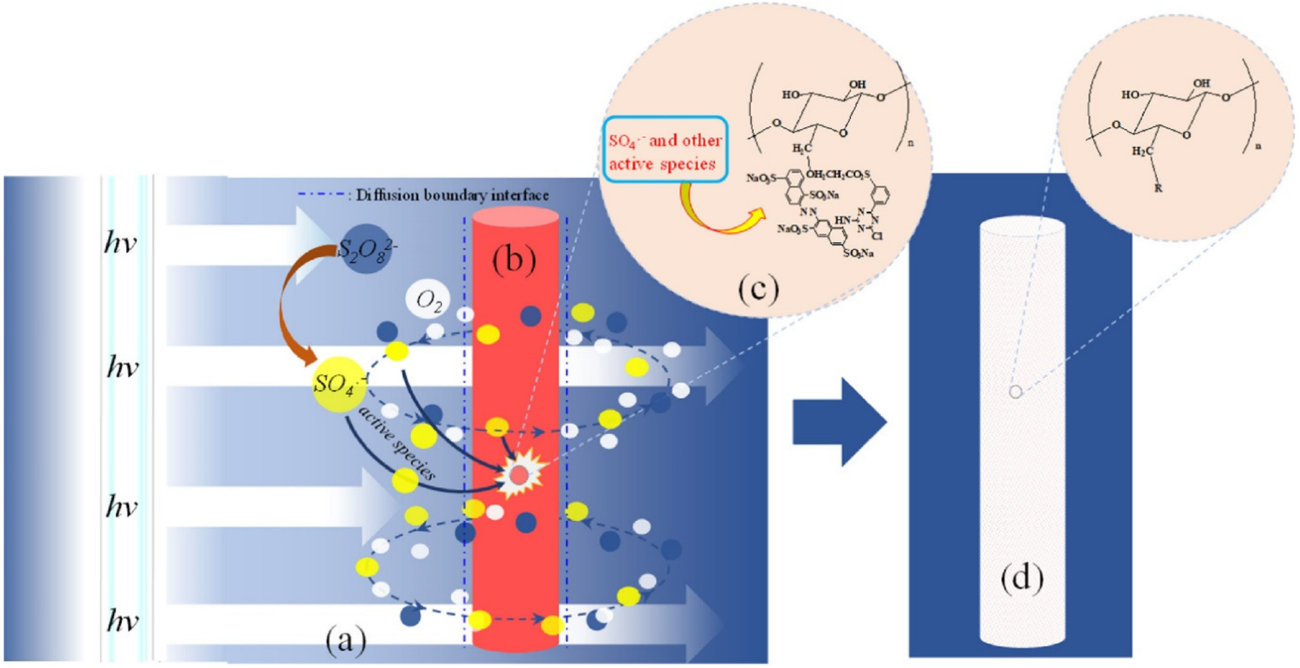

Fig. 3 Schematic of the CS mechanism of the UV/$K_2S_2O_8$ system for reactive-dyed cotton fabric, initiated under UV irradiation at ambient temperature. The mechanism comprises several sequential steps: (a) the generation of reactive oxidative species (*e.g.*, sulfate and hydroxyl radicals) through the UV activation of $K_2S_2O_8$, followed by their transmission, surface adsorption, and diffusion into the dyed cotton substrate; (b) cotton substrate dyed with the Reactive M-3BE dye; (c) the oxidative attack by the generated radicals on dye molecules covalently bonded to the cellulose chains, leading to the cleavage of chromophoric groups; and (d) the resulting cotton substrate after CS, indicating successful CS by the proposed photocatalytic process. Reproduced from ref. 41 with permission from Elsevier, copyright 2021.

able alternative to traditional chemical processes, minimizing environmental impact and preserving fabric strength.[37] The fungal enzyme extracts from *Ganoderma lucidum* IBL-05 can be utilized to strip color from cotton fabrics dyed with C.I. Reactive Black 5. Under optimized conditions (pH 4.5, 30 °C, 10 day incubation), a 70.81% CS has been achieved.[38] The CS of cotton fabric dyed with Reactive Blue 21 can be enhanced by fungal strains of *Ganoderma lucidum*.[39]

4. Performance of color stripping of dyed textile waste

Color stripping performance of colored textile waste depends on the types of dye (direct, reactive, vat, disperse, acidic, and basic) used, nature of textile material (natural and synthetic fibers), stripping methods and processing parameters. The success of color stripping procedures is measured by the amount of color removal, process efficiency, quality of stripped textile materials, impact on the environment and wastewater generation. The performance of various color stripping methods with different textile fibers is mentioned in Tables 2–4.

4.1. Color stripping of the direct-dyed textile

Direct dyes are a class of water-soluble dyes. In today's textile industry, direct dyes continue to hold a small market share, especially for the dyeing of cotton fabrics, household textiles, and low-cost apparel.[66,67] Their appeal lies in their simple application, low processing cost, and the ability to produce bright, vivid colors without the need for additional chemicals like mordants. However, their moderate wash fastness (2–3 out of 5) remains a major disadvantage. To address this, many manufacturers either apply fixing agents after dyeing or shift toward reactive dyes when better fastness is needed.[68] Nevertheless, direct dyes are still favored for cost-sensitive products, short-life textiles, and applications where fast production is prioritized over long-term color retention. The performance of various color stripping methods for direct dyed cotton fibers is mentioned in Table 2.

The process of removing direct dyes from the fabric involves boiling it in an alkaline sodium hydrosulfite solution, bleaching it with sodium hypochlorite or immersing it in a 1–2% sodium chlorite solution with a pH of 3–4. The pH is adjusted using formic/acetic acid.[37] CI Direct Red 72 was removed from cotton fabrics by using DMSO. The dyeing process was carried out at 95 °C for 1 hour. The 100% direct dyes were removed from cotton after three cycles of dye removal process using DMSO at 110 °C.[25] Direct dyes are attached to cellulose molecules through weak intermolecular interactions, primarily hydrogen bonds and van der Waals forces. As a result, they can be removed by solvent extraction much more efficiently compared to dyes that form strong covalent bonds with the fiber like reactive dyes. A 50/50 mixture of DMF/water and DMSO/water at 90 °C for 30 minutes effectively removed Direct Blue NB 2B dye from bleached, mercerized, woven cotton fabrics (175 g m^{-2}).[24]

4.2. Color stripping of the reactive-dyed textile

Reactive dyes are coloured organic compounds that have reactive groups, like chlorotriazine or vinyl sulphone, that can bond with hydroxyl groups in cellulose fibres or amino groups in protein fibres like wool and silk. Because of the strong covalent bond, reactive dyes show excellent fastness properties.[69] However, they also have some problems. The efficiency of fixation is usually 60–70% of the dye that is put on the fibre sticks to it. Moreover, the dyeing process needs a lot of electrolytes (like salts) to help the dye get into the fabric, which uses a lot of water and energy.[70,71] The performance of various color stripping methods for reactive dyed cotton fibers is mentioned in Table 2.

The capacity of reactive dyes to form covalent bonds with the molecules of the fabric allows them to produce vivid and colorfast hues, making them extensively utilized in the textile industry. A study found that *Ganoderma lucidum* IBL-05 was used for biological stripping of reactive dyed cotton fabric. For chemical stripping, the fabric was treated at 80 °C for 30 minutes with 20 g L^{-1} NaOH and 15 g L^{-1} $Na_2S_2O_4$. Biological stripping removed 89.64% of color at 2% shade, while chemical stripping removed 63.09%. Enzymatic treatment was milder and did not reduce the fabric weight, whereas chemical treatment caused fabric damage and weight loss. Additionally, enzymatic processing has shown better mechanical strength.[37] Another study found that fungal enzymes from solid-state fermentation removed 70.81% of C.I. Reactive Black 5 dye from the woven cotton fabric under stripping conditions of pH 4.5, 30 °C, and 10 days.[38] A 50/50 mixture of DMF/water and DMSO/water at 90 °C for 30 minutes did not effectively remove Procion Turquoise HEA (reactive dye) from cotton fabrics. However, adding NaOH (30 g L^{-1}) and $Na_2S_2O_4$ (30 g L^{-1}) improved the stripping efficiency.[24] Using 20 g L^{-1} CH_3NaO_3S for CI Reactive Red 23 achieves an 83.6% color removal, which is similar to the 88.5% removal obtained with 20 g L^{-1} $Na_2S_2O_4$ on 100% cotton single jersey fabric. Similarly, for CI Reactive Red 239, 40 g L^{-1} CH_3NaO_3S results in 80.7% color removal, comparable to the 82.9% achieved with 20 g L^{-1} $Na_2S_2O_4$. In contrast, using 40 g L^{-1} $K_2S_2O_8$ for CI Reactive Blue 21 enhances color removal to 94.03%, surpassing the 75.96% obtained with 40 g L^{-1} $Na_2S_2O_4$. Likewise, for CI Reactive Blue 19, 40 g L^{-1} $K_2S_2O_8$ improves color removal to 75.90%, compared to 64.35% with 40 g L^{-1} $Na_2S_2O_4$.[58]

The study demonstrated that *Ganoderma lucidum* is an eco-friendly and cost-effective medium for stripping Reactive Blue 21 dye from cotton fabrics, with the mutant strain UV-60 achieving 89% color stripping under optimal conditions.[39] Ozone treatment was used to decolorize Reactive Blue 21 (phthalocyanine), Reactive Black 5 (diazo), and Reactive Yellow 84 (monoazo) from cotton fabrics. The color stripping efficiency varied by chromophore type, with the highest color removal for Reactive Blue 21 under the conditions of pH 3, 7 g

Table 2 Performance of various color stripping methods for dyed cotton fabrics

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
C.I. Direct Red 72	Solvent extraction	DMSO	pH 10; M : L = 1 : 5 at 100 °C for 30 min; cycle: 3	100%	L^* = NR WL% = NR TSL% = NR	25
Direct Blue NB 2B	Reductive stripping	NaOH and $Na_2S_2O_4$	[NaOH] = 10 g L^{-1}; [$Na_2S_2O_4$] = 10 g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	96.91%	L^* = 71.20 WL% = NR TSL% = NR	24
Direct Blue NB 2B	Solvent extraction	H_2O and DMSO	[Solvent] : water 50 : 50 DMSO; [NaOH] = 30 g L^{-1}; [$Na_2S_2O_4$] = 30 g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	97.50%	L^* = 74.33 WL% = NR TSL% = NR	
CI Direct Red 72 CI Reactive Blue 19 CI Reactive Red 120	Solvent extraction	NMMO and H_2O	[Solvent] : NMMO 65 : 35 H_2O; [NaOH]: 0.5%; M : L = 1 : 5 at 95 °C for 30 min	99% 99% 99%	L^* = NR WL% = NR TSL% = NS	77 and 78
C.I. Reactive Black 5	Enzymatic treatment	*Ganoderma lucidum IBL-05*	[Enzyme dose]: 20 mL; pH 4.5 at 30 °C for 10 days	70.81%	L^* = NR WL% = NR TSL% = NR	38
Procion Turquoise HEA	Reductive stripping	NaOH and $Na_2S_2O_4$	[NaOH] = 10 g L^{-1}; [$Na_2S_2O_4$] = 10 g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	94.95%	L^* = 73.30 WL% = NR TSL% = NR	24
Procion Turquoise HEA	Solvent extraction	H_2O and DMSO	[Solvent] : water 50 : 50 DMSO; [NaOH] = 30 g L^{-1}; [$Na_2S_2O_4$] = 30 g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	96.32%	L^* = 75.82 WL% = NR TSL% = NR	
CI Reactive Red 23 CI Reactive Red 239	Reductive stripping	CH_3NaO_3S	[CH_3NaO_3S]: 40 g L^{-1}; pH 4; M : L = 1 : 10 at 80 °C for 15 min	83.6% 80.7%		58
CI Reactive Red 23 CI Reactive Red 239 CI Reactive Blue 21 CI Reactive Blue 19	Reductive stripping	$Na_2S_2O_4$	[$Na_2S_2O_4$]: 40 g L^{-1}; pH 14; M : L = 1 : 10 at 80 °C for 15 min	88.5% 82.9% 75.96% 64.35%	L^* = NR WL% = NR TSL% = NR	
CI Reactive Blue 21 CI Reactive Blue 19	Oxidative stripping	$K_2S_2O_8$	[$K_2S_2O_8$]: 40 g L^{-1}; pH 10–10.5; M : L = 1 : 10 at 80 °C for 15 min	94.03% 75.90%		
Reactive Black 5	Microwave-assisted reductive	1. H_2SO_4 2. $Na_2S_2O_4$	1. [H_2SO_4] = 1%; M : L = 1 : 30 for 30 s 2. [$Na_2S_2O_4$] = 30 g L^{-1}; [NaOH] = 40 g L^{-1}; M : L = 1 : 30 for 90 s	94.21%	L^* = NR WL% = NR TSL% = 28.84	46
Reactive Black 5	Microwave-assisted oxidative	1. H_2SO_4 2. H_2O_2	1. [H_2SO_4] = 3%; M : L = 1 : 30 for 30 s 2. [H_2O_2] = 1 M; [NaOH] = 1.2 g L^{-1}; [Na_2CO_3]: 1.8 g L^{-1}; [Na_2SiO_3]: 7 g L^{-1}; M : L = 1 : 30 for 120 s	65%	L^* = NR WL% = NR TSL% = 5.76	
Reactive Black 5	Microwave-assisted reductive	1. NaOH 2. $Na_2S_2O_4$	1. [NaOH] = 50 g L^{-1}; M : L = 1 : 30 for 30 s 2. [$Na_2S_2O_4$] = 30 g L^{-1}; [NaOH] = 40 g L^{-1}; M : L = 1 : 30 for 120 s	97%	L^* = NR WL% = NR TSL% = 25	
Reactive Black 5	Microwave-assisted reductive	1. NaOH 2. H_2O_2	1. [NaOH] = 50 g L^{-1}; M : L = 1 : 30 for 30 s 2. [H_2O_2] = 1 M; [NaOH] = 1.2 g L^{-1}; [Na_2CO_3]: 1.8 g L^{-1}; [Na_2SiO_3]: 7 g L^{-1}; M : L = 1 : 30 for 120 s	86%	L^* = NR WL% = NR TSL% = 3.85	
Reactive Blue 21	Enzymatic treatment	*Ganoderma lucidum*	[Mutant]: *G. lucidum;* pH 4 at 35 °C for 15 days	89%	L^* = NR WL% = NR TSL% = 0	39

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
Solar Golden Yellow R	Reductive treatment	$Na_2S_2O_4$ and NaOH	$[Na_2S_2O_4]$ = 15 g L^{-1}; [NaOH] = 20 g L^{-1}; M : L = 1 : 10 at 80 °C for 15 min	68.27%	L^* = NR WL% = 3.76 TSL% = 6.15	79
Solar Golden Yellow R	Enzymatic treatment	*Ganoderma lucidum*	[Mutant]: *G. lucidum*; pH: 4.5 at 30 °C for 9 days	61.29%	L^* = NR WL% = 1.51 TSL% = 2.32	
C.I. Reactive Red 24	Reductive treatment	$CH_4N_2O_2S$	$[CH_4N_2O_2S]$ = 4 g L^{-1}; M : L = 1 : 50 at 70 °C for 40 min	90%	L^* = NR WL% = NR TSL% = 2.8	80
CI Reactive Yellow 37	Reductive stripping	TUDO	[TUDO] = 5 g L^{-1}; M : L = 1 : 15 at 100 °C for 60 min	84.96%		59
CI Reactive Blue 19				76.77%		
CI Reactive Blue 21				91.93%		
CI Reactive Red 120				82.28%		
CI Reactive Blue 71				93.12%		
CI Reactive Red 223				96.45%		
CI Reactive Blue 221				95.96%	L^* = NR	
CI Reactive Yellow 37	Oxidative stripping	O_3	$[O_3]$ = 105 mg L^{-1} at room temperature for 45 min	89.91%	WL% = NR	
CI Reactive Blue 19				91.47%	TSL% = NR	
CI Reactive Blue 21				93.28%		
CI Reactive Red 120				88.76%		
CI Reactive Blue 71				93.12%		
CI Reactive Red 223				88.89%		
CI Reactive Blue 221				94.65%		
C.I. Reactive Black 5	Oxidative stripping	O_3	$[O_3]$ = 85 (g m^{-3} TPN); pH 3 at room temperature for 30 min	97.45%	L^* = NR WL% = NR TSL% = NR	81
C.I. Reactive Black 5	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4]$ = 10 mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min	100%		23
C. I. Reactive Blue 19		2. NaOH	2. [NaOH] = 23%; M : L = 1 : 30 at 100 °C for 10 min	82%		
C. I. Reactive Red 228		3. H_2O_2	3. $[H_2O_2]$ = 1 mol L^{-1}; [NaOH] = 1.2 g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	100%	L^* = NR	
C.I. Reactive Black 5	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4]$ = 10 mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min	100%	WL% = NR	
C. I. Reactive Blue 19		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4]$ = 30 g L^{-1}; [NaOH] = 40 g L^{-1}; [PVP]: 2.5 g L^{-1}; [ND]: 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	100%	TSL% = NR	
C. I. Reactive Red 228		3. H_2O_2	3. $[H_2O_2]$ = 1 mol L^{-1}; [NaOH] = 1.2 g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	100%		
C. I. Reactive Yellow 176	Alkaline treatment	NaOH	[NaOH] = 80 g L^{-1}; M : L = 1 : 100 at 90 °C for 90 min	86%	L^* = NR	48
C. I. Reactive Red 24	Sequential treatment	1. NaOH	1. [NaOH] = 80 g L^{-1}; M : L = 1 : 100 at 90 °C for 90 min	98.5%	WL% = NR	
C. I. Reactive Blue 19		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4]$ = 1.2 g L^{-1}; M : L = 1 : 100 at 90 °C for 90 min	97.3%	TSL% = NR	
Reactive Blue Black 5	Microwave assisted	1. NaOH	1. [NaOH] = 80 g L^{-1}; pH 12; M : L = 1 : 15 for 120 s	97.48%		51
Reactive Turquoise CLB	sequential treatment	2. H_2O_2	2. $[H_2O_2]$ = NR; M : L = 1 : 15 for 120 s	91.35%	L^* = NR	
Reactive Blue Black 5	Sequential treatment	1. NaOH	1. [NaOH] = 80 g L^{-1}; pH 12; M : L = 1 : 15 at 90 °C for 60 min	94.17%	WL% = NR	
Reactive Turquoise CLB		2. H_2O_2	2. $[H_2O_2]$ = NR; M : L = 1 : 15 at 90 °C for 60 min	87.67%	TSL% = NR	

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
Reactive Blue Black 5	Microwave assisted sequential treatment	1. NaOH 2. H_2O_2 3. $Na_2S_2O_4$	1. [NaOH] = 80 g L^{-1}; pH 12; M : L = 1 : 15 for 120 s 2. [H_2O_2] = NR; M : L = 1 : 15 for 120 s 3. [$Na_2S_2O_4$] = NR; M : L = 1 : 15 for 120 s	98.52%	*L** = NR WL% = 2.7 TSL% = 6.45	51
Reactive Turquoise CLB				97.7%	*L** = NR WL% = 3.6 TSL% = 32.25	
Reactive Blue Black 5	Sequential treatment	1. NaOH 2. H_2O_2 3. $Na_2S_2O_4$	1. [NaOH] = 80 g L^{-1}; pH 12; M : L = 1 : 15 at 90 °C for 60 min 2. [H_2O_2] = NR; M : L = 1 : 15 at 90 °C for 60 min 3. [$Na_2S_2O_4$] = NR; M : L = 1 : 15 at 90 °C for 60 min	96.44%	*L** = NR WL% = 4.1 TSL% = 14.52	
Reactive Turquoise CLB				88.4%	*L** = NR WL% = 4.7 TSL% = 37.09	
Reactive Blue Black 5	Microwave assisted	1. HCl	1. [HCl] = 4%; pH 2; M : L = 1 : 15 for 60 s	42.33%		
Reactive Turquoise CLB	sequential treatment	2. H_2O_2	2. [H_2O_2] = NR; M : L = 1 : 15 for 120 s	88.6%	*L** = NR	
Reactive Blue Black 5	Sequential treatment	1. HCl	1. [HCl] = 4%; pH 2; M : L = 1 : 15 at 90 °C for 60 min	76.07%	WL% = NR	
Reactive Turquoise CLB		2. H_2O_2	2. [H_2O_2] = NR; M : L = 1 : 15 at 90 °C for 60 min	85.25%	TSL% = NR	
Reactive Blue Black 5	Microwave assisted sequential treatment	1. HCl 2. H_2O_2 3. $Na_2S_2O_4$	1. [HCl] = 4%; pH 2; M : L = 1 : 15 for 60 s 2. [H_2O_2] = NR; M : L = 1 : 15 for 120 s 3. [$Na_2S_2O_4$] = NR; M : L = 1 : 15 for 120 s	97.79%	*L** = NR WL% = 1.9 TSL% = 8.06	
Reactive Turquoise CLB				94.69%	*L** = NR WL% = 3.1 TSL% = 33.87	
Reactive Blue Black 5	Sequential treatment	1. HCl 2. H_2O_2 3. $Na_2S_2O_4$	1. [HCl] = 4%; pH 2; M : L = 1 : 15 at 90 °C for 60 min 2. [H_2O_2] = NR; M : L = 1 : 15 at 90 °C for 60 min 3. [$Na_2S_2O_4$] = NR; M : L = 1 : 15 at 90 °C for 60 min	92.94%	*L** = NR WL% = 3.4 TSL% = 16.13	
Reactive Turquoise CLB				88.21%	*L** = NR WL% = 4.5 TSL% = 48.39	
CI Reactive Red 195	UV assisted treatment	$K_2S_2O_8$	[$K_2S_2O_8$] = 1 g L^{-1}; pH 2; M : L = 1 : 30 at 20 °C for 30 min	95.7%	TSL% = 19.3	41
CI Reactive Blue 160				90.7%	TSL% = 12.9	
CI Reactive Red 141				95.0%	TSL% = 18.1	
CI Reactive Yellow 84				90.0%	TSL% = 13.0	
CI Reactive Blue 194				95.4%	TSL% = 15.5	
CI Reactive Yellow 145				86.4%	TSL% = 6.7	
CI Reactive Blue 221				92.2%	TSL% = 17.4	
CI Reactive Blue 5				83.9%	TSL% = 12.4	
CI Reactive Brown 9				97.6%	TSL% = 13.4	
CI Reactive Blue 19				89.7%	TSL% = 8.2	
CI Reactive Green 19				96.2%	TSL% = 14.8 [*L** and WL% = NR]	
CI Reactive Black 5	Oxidative stripping	O_3	[O_3] = 85 (g m^{-3} TPN); pH 3 at room temperature for 30 min	97.45%	*L** = NR WL% = NR TSL% = 28	72
Reactive Black B	Enzymatic treatment	*Ganoderma lucidum* IBL-05	[Mutant]: *G. lucidum*; dose: 100 mL; pH 4 at 35 °C for 15 days	89.64%	*L** = NR WL% = 1.45 BSL% = 6.42	37
Reactive Black B	Reductive stripping	$Na_2S_2O_4$	[$Na_2S_2O_4$] = 15 g L^{-1}; [NaOH] = 20 g L^{-1}; M : L = 1 : 20 at 80 °C for 30 min	63.09%	*L** = NR WL% = 3.13 BSL% = 11.05	

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
Mix of vinyl sulfone reactive dyes	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4] = 25$ g L^{-1}; pH 9; M : L = 1 : 30 at 90 °C for 90 min	90.9%	L^* = NR WL% = 0.9 TSL% = 19.11	50
Mix of vinyl sulfone reactive dyes	Oxidative stripping	H_2O_2	$[H_2O_2] = 40$ g L^{-1}; [NaOH] = 20 g L^{-1}; [TAED]: 20 g L^{-1}; pH 10; M : L = 1 : 30 at 70 °C for 90 min	96.4%	L^* = NR WL% = 2.0 TSL% = 26.46	
Mix of vinyl sulfone reactive dyes	Oxidative stripping	$KMnO_4$	$[KMnO_4]$ = 5%; $[H_2SO_4]$ = 5%; pH 5; M : L = 1 : 30 at 40 °C for 90 min	99.4%	L^* = NR WL% = 5.7 TSL% = 49.57	
Mix of vinyl sulfone reactive dyes	Sequential stripping	1. $Na_2S_2O_4$ 2. H_2O_2	1. $[Na_2S_2O_4] = 25$ g L^{-1}; pH 9; M : L = 1 : 30 at 90 °C for 90 min 2. $[H_2O_2] = 40$ g L^{-1}; [NaOH] = 20 g L^{-1}; [TAED]: 20 g L^{-1}; pH 10; M : L = 1 : 30 at 70 °C for 90 min	97.8%	L^* = NR WL% = 1.2 TSL% = 23.91	
Reactive Yellow C4GL	Alkali treatment	NaOH	[NaOH] = 10 g L^{-1}; M : L = 1 : 30 at 90 °C for 60 min	90.46%	L^* = NR WL% = 1.5 TSL% = 12.38	64
Reactive Yellow C4GL	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4] = 2.5$ g L^{-1}; [NaOH] = 2.5 g L^{-1}; M : L = 1 : 30 at 90 °C for 60 min	96.90%	L^* = NR WL% = 3.0 TSL% = 10.48	
C.I. Reactive Black 5 C.I. Reactive Blue 19 C.I. Reactive Red 228	Sequential treatment	1. H_2SO_4 2. NaOH	1. $[H_2SO_4] = 10$ mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min 2. [NaOH] = 23%; M : L = 1 : 30 at 100 °C for 10 min	98.99% 57.64% 98.46%	L^* = 81 L^* = 32 L^* = 84 [WL% and TSL% = NR]	
C.I. Reactive Black 5 C.I. Reactive Blue 19 C.I. Reactive Red 228	Sequential treatment	1. H_2SO_4 2. NaOH 3. H_2O_2	1. $[H_2SO_4] = 10$ mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min 2. [NaOH] = 23%; M : L = 1 : 30 at 100 °C for 10 min 3. $[H_2O_2] = 1$ mol L^{-1}; [NaOH] = 1.2 g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	99.87% 81.66% 99.62%	L^* = 92 L^* = 43 L^* = 90 [WL% and TSL% = NR]	76
CI Reactive Blue 19 CI Reactive Red 2 CI Reactive Yellow 145	Substantial swelling	1. NaOH 2. $C_5H_{11}NO_2 : H_2O$	1. [NaOH] = 0.5%; M : L = 1 : 10 at 90 °C for 30 min 2. $C_5H_{11}NO_2$ 1 : 5 H_2O at 90 °C for 10 min	96% 96% 96%	L^* = NR WL% = NR TSL% = NR	73
Novacron Red TS-3B Novacron Yellow TS-3R Novacron Blue TS-3G	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4] = 10$ g L^{-1}; [NaOH] = 10 g L^{-1}; M : L = 1 : 15 at 100 °C for 30 min	93.80%	L^* = NR WL% = 5.99 TSL% = 10.0	56
Drimarene Yellow CL2R, Drimarene Red CL5B, and Drimarene Blue HFRL	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4] = 5$ g L^{-1}; [NaOH] = 5 g L^{-1}; M : L = 1 : 40 at 100 °C for 20 min	92.87%	L^* = NR WL% = 0.9 TSL% = 0.9	74
Reactive Red X-3B	Photocatalytic stripping	Nano-TiO_2/UV	$[TiO_2] = 50.0$ mg L^{-1}; pH 8; M : L = 1 : 30 at 20 °C for 90 min	97%	L^* = NR WL% = NR TSL% = 4	40
CI Reactive Blue 19	Solvent extraction	DMSO	[Solvent] : water 30 : 70 DMSO; [NaOH] = 0.6%; M : L = 1 : 10 at 90 °C for 10 min; [cycle]: 3	99.9%	L^* = NR WL% = NR TSL% = NR	82

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
CBY SP + CY SP	Oxidative stripping	O_3	$[O_3]$ = 85 g m^{-3}; pH 7 at room temperature for 60 min	88.64%		75
CB SP + NY S3 + JN CE				86.06%		
NR S3 + NY S3				91.94%		
BB BR + SYE + SRE				96.62%	L^* = NR	
CBY SP + CY SP	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4]$ = 5 g L^{-1}; [NaOH] = 5 g L^{-1}; M : L = 1 : 6 at 80 °C for 30 min	92.79%	WL% = NR	
CB SP + NY S3 + JN CE				31.19%	TSL% = NR	
NR S3 + NY S3				58.24%		
BB BR + SYE + SRE				56.07%		
Evercion Blue H-ER	UV assisted reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4]$ = 0.6 g L^{-1}; pH 6; M : L = 1 : 30 at 20 °C for 60 min	82.2%	TSL% = 4.3	43
Evercion Red H-E7B				89.8%	TSL% = 11.3	
Evercion Yellow H-E4R				43.1%	TSL% = 3.6	
Evercion Yellow 3RF				68%	TSL% = 5	
Evercion Navy ED				89.9%	TSL% = 9.3	
Evercion Blue BF				90.3%	TSL% = 10	
Evercion Blue BRF				81.5%	TSL% = 6.6	
Megafix Orange B-2RLN				91.5%	TSL% = 13	
Megafix Black B-GFF				88.6%	TSL% = 12.1	
Megafix Brown B-R				90.5%	TSL% = 11.5	
Megafix Black B-ED				81%	TSL% = 11	
Megafix Blue B-RV				91.6%	TSL% = 6.4	
Megafix Green B-4BL				56.4%	TSL% = 5.1	
Megafix Blue K-GR				84.9%	TSL% = 1.3	
Reactive Red M-3BE				93.26%	TSL% = 11.99 [L^* and WL% = NR]	
Reactive Turquoise CLB	Microwave assisted alkali treatment	NaOH	[NaOH] = 50 g L^{-1}; M : L = 1 : 30 for 120 s	88.4%	L^* = NR WL% = 3.4 TSL% = 15	62
Reactive Turquoise CLB	Microwave assisted reductive treatment	NaOH and $Na_2S_2O_4$	$[NaOH + Na_2S_2O_4]$ = 1 : 1.75; $[C_6H_5Na_3O_7]$ = 50 g L^{-1}; M : L = 1 : 30 for 150 s	94.1%	L^* = NR WL% = 2.9 TSL% = 20	
Reactive Turquoise CLB	Alkali treatment	NaOH	[NaOH] = 50 g L^{-1}; M : L = 1 : 30 at 80 °C for 45 min	75.7%	L^* = NR WL% = 4.5 TSL% = 10	
Reactive Turquoise CLB	Reductive treatment	NaOH and $Na_2S_2O_4$	$[NaOH + Na_2S_2O_4]$ = 1 : 1.75; $[C_6H_5Na_3O_7]$ = 50 g L^{-1}; M : L = 1 : 30 at 80 °C for 150 s	80.8%	L^* = NR WL% = 4.2 TSL% = 22	
C.I. Reactive Blue 19	Solvent stripping	DMF and H_2O	[Solvent] : C_2H_6O 1 : 1 $C_2H_4O_2$ boil for 4 min; NH_3 = 1% boil for 4 min; [Solvent] : DMF 1 : 1 H_2O boil for 4 min, DMF boil for 4 min	73.5%	L^* = NR	65
C.I. Reactive Red 195				3.9%	WL% = NR	
C.I. Reactive Yellow 3				5.9%	TSL% = NR	
C.I. Reactive Orange 5				4.5%		
C.I Reactive Red 195	Reductive stripping	Reducing agent D p	[Reducing agent D p] = 12 g L^{-1}; pH 13.40–13.70; M : L = 1 : 10 at 98 °C for 60 min	85.90%	L^* = NR WL% = 3 TSL% = 8	83
C.I Reactive Red 195	Reductive stripping	Molasses	[Molasses] = 18 g L^{-1}; pH 13.40–13.70; M : L = 1 : 10 at 98 °C for 60 min	69.37	L^* = NR WL% = 6 TSL% = 5	
C.I Reactive Red 195	Reductive stripping	$Na_2S_2O_4$	$[Na_2S_2O_4]$ = 3 g L^{-1}; pH 13.40–13.70; M : L = 1 : 10 at 98 °C for 60 min	95.55	L^* = NR WL% = 12 TSL% = 12	

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
Novatic Brown R MD	Reductive stripping	NaOH and $Na_2S_2O_4$	$[NaOH] = 10$ g L^{-1}; $[Na_2S_2O_4] = 10$ g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	27.80%	$L^* = 71.20$ WL% = NR TSL% = NR	24
Novatic Brown R MD	Solvent extraction	H_2O and DMSO	[Solvent] : water 50 : 50 DMSO; $[NaOH] = 30$ g L^{-1}; $[Na_2S_2O_4] = 30$ g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	93.26%	$L^* = 75.00$ WL% = NR TSL% = NR	
CI Vat Black 27	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4] = 10$ mL L^{-1} (96% vol.); M : L = 1 : 30 at 60 °C for 60 min	99%		84
CI Vat Blue 4		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 40$ g L^{-1}; PVP = 2.5 g L^{-1}; nonionic detergent = 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	96%		
CI Vat Blue 1				98%	$L^* =$ NR	
CI Vat Black 27	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4] = 10$ mL L^{-1} (96% vol.); M : L = 1 : 30 at 60 °C for 60 min	99%	WL% = NR	
CI Vat Blue 4		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 40$ g L^{-1}; PVP = 2.5 g L^{-1}; nonionic detergent = 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	97%	TSL% = NR	
CI Vat Blue 1		3. H_2O_2	3. $[H_2O_2] = 1$ mol L^{-1}; $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	99%		
Mix of indigo dyes	Oxidative stripping	HRP and H_2O_2	[HRP] = 150 u mL^{-1}; $[H_2O_2] = 2.5$ mL L^{-1}; pH 5 at 35 °C for 60 min	85.2%	$L^* =$ NR WL% = NR TSL% = 2.5	85
CI Vat Blue 1 CI Vat Orange 1	Solvent extraction	NMMO and H_2O	[Solvent] : NMMO 70 : 30 H_2O; M : L = 1 : 20 at 110 °C for 60 min	100% 100%	$L^* =$ NR WL% = NR TSL% = NR	86
Mix of indigo dyes	Solvent extraction	DMF	[Solvent] = DMF; M : L = 1 : 20 at 80 °C for 40 min	95.7%	$L^* =$ NR WL% = NR TSL% = NR	87
C. I. Vat Blue 1	Sequential treatment	1. H_2SO_4 2. NaOH 3. H_2O_2	1. $[H_2SO_4] = 10$ mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min 2. [NaOH] = 23%; M : L = 1 : 30 at 100 °C for 10 min 3. $[H_2O_2] = 1$ mol L^{-1}; $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	82%	$L^* =$ NR WL% = NR TSL% = NR	23
C. I. Vat Blue 1	Sequential treatment	1. H_2SO_4 2. $Na_2S_2O_4$ 3. H_2O_2	1. $[H_2SO_4] = 10$ mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min 2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 40$ g L^{-1}; [PVP]: 2.5 g L^{-1}; [ND]: 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min 3. $[H_2O_2] = 1$ mol L^{-1}; $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	100%	$L^* =$ NR WL% = NR TSL% = NR	23
Sulphur Black	Reductive stripping	NaOH and $Na_2S_2O_4$	$[NaOH] = 10$ g L^{-1}; $[Na_2S_2O_4] = 10$ g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	1%	$L^* = 28.60$ WL% = NR TSL% = NR	24
Sulphur Black	Solvent extraction	H_2O and DMSO	[Solvent] : water 50 : 50 DMSO; $[NaOH] = 30$ g L^{-1}; $[Na_2S_2O_4] = 30$ g L^{-1}; M : L = 1 : 15 at 90 °C for 30 min	91.31%	$L^* = 58.10$ WL% = NR TSL% = NR	

Table 2 *(Contd.)*

Dye	Stripping method	Main chemicals/micro-organism used	Stripping conditions	Color stripping (%) eqn (2)	Notes	Ref.
CI Sulphur Black 1	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4] = 10$ mL L^{-1} (96% vol.); M : L = 1 : 30 at 60 °C for 60 min	95%		84
CI Sulphur Blue 7		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 40$ g L^{-1}; PVP = 2.5 g L^{-1}; nonionic detergent = 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	97%	L^* = NR	
CI Sulphur Black 1	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4] = 10$ mL L^{-1} (96% vol.); M : L = 1 : 30 at 60 °C for 60 min		WL% = NR	
CI Sulphur Blue 7		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 40$ g L^{-1}; PVP = 2.5 g L^{-1}; nonionic detergent = 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	99%	TSL% = NR	
		3. H_2O_2	3. $[H_2O_2] = 1$ mol L^{-1}; $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	98%		
CI Sulfur Black 1	Solvent extraction	NMMO and H_2O	[Solvent] : NMMO 70 : 30 H_2O; [NaOH]: 1%; M : L = 1 : 5 at 95 °C for 30 min	98%	L^* = NR WL% = NR TSL% = NS	77
Reactive Red CL4BN	Microwave assisted sequential treatment	1. HCl	1. [HCl] = 4%; pH 2; M : L = 1 : 15 for 120 s	97.44%	L^* = 87.02 and 87.05	88
Reactive Black PLS		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 20$ g L^{-1}; M : L = 1 : 15 for 120 s	97.85%	WL% = 1% and 1.25%	
		3. H_2O_2	3. $[H_2O_2] = 97.8$ mL (35% vol.); $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 15 for 120 s		TSL% = NR	
Reactive Red CL4BN	Microwave assisted sequential treatment	1. NaOH	1. [NaOH] = 8%; pH 12; M : L = 1 : 15 for 120 s	97.46%	L^* = 88.3 and 88.30	
Reactive Black PLS		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 20$ g L^{-1}; M : L = 1 : 15 for 120 s	98.41%	WL% = 0.25% and 0.1%	
		3. H_2O_2	3. $[H_2O_2] = 97.8$ mL (35% vol.); $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 15 for 120 s		TSL% = NR	
Reactive Red CL4BN	Sequential treatment	1. HCl	1. [HCl] = 4%; pH 2; M : L = 1 : 15 at 90 °C for 2 min	96.68%	L^* = 87.37 and 86.97	88
Reactive Black PLS		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 20$ g L^{-1}; M : L = 1 : 15 for 15 min	97.86%	WL% = 1.75% and 1.75%	
		3. H_2O_2	3. $[H_2O_2] = 97.8$ mL (35% vol.); $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 15 at 90 °C for 60 min		TSL% = NR	
Reactive Red CL4BN	Sequential treatment	1. NaOH	1. [NaOH] = 8%; pH 12; M : L = 1 : 15 at 90 °C for 30 min	97.68%	L^* = 88.9 and 88.24	
Reactive Black PLS		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4] = 30$ g L^{-1}; $[NaOH] = 20$ g L^{-1}; M : L = 1 : 15 for 15 min	98.45%	WL% = 2.75% and 2.5%	
		3. H_2O_2	3. $[H_2O_2] = 97.8$ mL (35% vol.); $[NaOH] = 1.2$ g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 15 at 90 °C for 60 min		TSL% = NR	
Polycarboxylic acid Black	Alkali treatment	NaOH	[NaOH] = 5%; M : L = 1 : 10 at 90 °C for 240 min	82.18%	L^* = NR WL% = NR TSL% = NR	4 and 89

Abbreviations: NR = data not reported; NS: no significant difference; AC: activated carbon; EG: ethylene glycol; PET: polyethylene terephthalate; DMSO: dimethyl sulfoxide; DMF: dimethylformamide; TS: tensile strength; BS: bursting strength; ZAD: zinc acetate dehydrate; UV: ultraviolet; EC: ethylene carbonate; TMU: tetramethylurea; TUDO: thiourea dioxide; NP: nanoparticle; TPN: tropospheric pressure and normal temperature; CDP: conventional discharge printing; SFS: sodium formaldehyde sulfoxylate; CBY SP: colorsol brilliant yellow SP; CY SP: colorsol yellow SP; CB SP: colorsol black SP; NY S3: Novacron Yellow S-3RN; JN CE: Jakazol Navy CE; NR S3: Novacron Ruby S3B; BB BR: Bergazol Brilliant Blue R; SYE: Sunfix Yellow EX; SRE: Sunfix Red EX; DB 2: Disperse Blue 2BLN; DB D: Direct Blue D-RGL; DB S: Disperse Brown S-BRL; and DB B: Direct Brown BRL.

Table 3 Performance of various color stripping methods for different synthetic fabrics

Fiber type	Dye	Stripping method	Main chemicals/ micro-organism used	Stripping condition	Color stripping (%) eqn (2)	Notes	Ref.
Polyester	C.I. Disperse Blue 56	Solvent extraction	EC and TMU	[Solvent] : EC 7 : 3 TMU; pH 10; M : L = 1 : 5 at 120 °C for 30 min; [cycle]: 3	100%	L^* = NR WL% = NR TSL% = NR	25
Nylon 6,6	CI Acid Blue 40	Solvent extraction	DMSO and H_2O	[Solvent] : DMSO 95 : 5 H_2O; pH 10; M : L = 1 : 5 at 100 °C for 30 min; [cycle]: 3	100%		
Polyester	CI Disperse Orange 30 CI Disperse Blue 60	Oxidative stripping	O_3	[O_3] = 130 mg L^{-1} min^{-1}; pH 3 at room temperature for 120 min	54% 47%	TSL% = 20 TSL% = 20 L^* and WL% = NR	21
Polyester/ cotton	DB 2 + DB D	Solvent extraction	DMF	[Solvent] = DMF 11 : 2 surface-active agent ASE: 1 emulsifier OP at 140 °C for 30 min	97%	TSL% = 12	44
	DB S + DB B				84%	TSL% = 12 L^* and WL% = NR	
Polyester	C.I. Disperse Red 74, and C.I. Disperse Yellow 23	Solvent extraction	DMF	[Solvent] = DMF; M : L = 1 : 20 at 120 °C for 60 min	97%	L^* = NR WL% = NR TSL% = NR	107
Polyester	Disperse dye	Solvent extraction	EG	[EG]: 100 mL at 110 °C for 30 min	97.7%	L^* = 98.2 WL% = NR TSL% = NR	108
Polyester	CI Disperse Blue 79	Solvent extraction	Benzyl alcohol	[Solvent] = benzyl alcohol; M : L = 1 : 10 at 130 °C for 30 min; cycle: 3	99%	L^* = NR WL% = NR TSL% = NR	109
Polyester	Disperse Orange 30 Disperse Blue 79 Disperse Yellow 42 Disperse Yellow 86 Disperse Red 60 Disperse Blue 56 Basic Yellow 28	Solvent extraction	CH_3NaO_3S	[CH_3NaO_3S] = 10 g L^{-1}; M : L = 1 : 50 at 100 °C for 30 min	99.24% 98.64% 98.81% 97.92% 99.58% 98.75% 94.69%	L^* = NR WL% = NR TSL% = NR	110
Polyester	C.I. Disperse Blue 56	Solvent extraction	DMSO	[Solvent] : DMSO; M : L = 1 : 10 at 150 °C for 10 min	99.9%	L^* = NR WL% = NR TSL% = NR	82
Polyester	C.I. Disperse Red 60	Adsorbent treatment	AC-HNO_3	[HNO_3] = 10 M mol L^{-1} at 90 °C for Time: 10 min	97.6%	L^* = NR WL% = NR TSL% = NR	111
Polyester	C.I. Disperse Red 177	Solvent extraction	DMSO	[Solvent] = DMSO; M : L = 1 : 100 at 130 °C for 30 min	100%	L^* = NR WL% = NR TSL% = NR	112
Polyester	Disperse dye (NR)	Solvent extraction	EG/ZAD and chitosan/Fe_3O_4 NP	[Chitosan/Fe_3O_4] = 0.04 g; [H_2O_2] = 10 mL; voltage = 15 V; [$NaBF_4$] = 10.0 mM at 110 °C for 6 h	87.24%	L^* = NR WL% = NR TSL% = NR	113
Polyester	C.I. Disperse Red 60	Electrochemical treatment	EG/ZAD and electro-Fenton/Fe_3O_4 NP	[Fe_3O_4] = 0.6 g L^{-1}; current density = 90 mA cm^{-2}; pH 4.6 for 3 h	97.2%	L^* = NR WL% = NR TSL% = NR	114
Polyester	CI Disperse orange 30, CI Disperse blue79, CI Disperse red 60, and CI Disperse blue 56	Electrochemical treatment	EG and electro-Fenton/Zn-MNPs	[Zn-MNPs] = 0.35 wt%; [H_2O_2] = 2.6 wt%; current density = 0.19 A cm^{-2} at 160 °C for 2 h	97.5%	L^* = NR WL% = NR TSL% = NR	115
Polyester	C.I. Disperse Blue 14	Electrochemical treatment	EG/zinc acetate and AC	[BHET] = 10 g; [EA] = 100 g at 65 °C for 3 h	99.9%	L^* = NR WL% = NR TSL% = NR	116

Table 3 *(Contd.)*

Fiber type	Dye	Stripping method	Main chemicals/ micro-organism used	Stripping condition	Color stripping (%) eqn (2)	Notes	Ref.
Polyester/ cotton	Remazol Brilliant blue R, Remazol Yellow RR, and Remazol Red RR	Alkaline hydrolysis	NaOH and H_2O	M : L = 5 : 10 at 121 °C for 90 min	100%	L^* = NR WL% = NR TSL% = NR	117
Nylon 6,6	CI Acid Blue 40 and Acid Yellow 49	Solvent extraction	$C_4H_{10}O_2$	[Solvent] = $C_4H_{10}O_2$; M : L = 1 : 3 at 150 °C for 5 min	100%	L^* = NR WL% = NR TSL% = NR	118

Table 4 Performance of various color stripping methods for different printed cotton fabrics

Dye	Stripping method	Main chemicals/ micro-organism used	Stripping condition	Color stripping performance (%) eqn (2)	Notes	Ref.
CI Pigment Blue 15	Oxidative stripping	O_3	$[O_3]$ = 100 g Nm^{-3} pH 3 at room temperature for 120 s	94.92%	L^* = 65.37 WL% = NR TSL% = 34	104
CI Reactive Blue 221	CDP	Na_2CO_3	$[Na_2CO_3]$ = 2 g L^{-1}; [Detergent] = 2 g L^{-1} at 95 °C for 52 min	82.3%	L^* = NR	106
CI Reactive Yellow 145				93.6%	WL% = NR	
CI Reactive Red 223				94.3%	TSL% = NR	
Printofix Black T-M	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4]$ = 10 mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min	95.81%	L^* = NR	84
Printofix Blue T-P		2. NaOH	2. [NaOH] = 23%; M : L = 1 : 30 at 100 °C for 10 min	98.81%	WL% = NR	
Printofix Red T-N01		3. H_2O_2	3. $[H_2O_2]$ = 1 mol L^{-1}; [NaOH] = 1.2 g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	98.19%	TSL% = NR	
Printofix Black T-M	Sequential treatment	1. H_2SO_4	1. $[H_2SO_4]$ = 10 mL L^{-1}; M : L = 1 : 30 at 60 °C for 60 min	67.66%		
Printofix Blue T-P		2. $Na_2S_2O_4$	2. $[Na_2S_2O_4]$ = 30 g L^{-1}; [NaOH] = 40 g L^{-1}; [PVP]: 2.5 g L^{-1}; [ND]: 2 mL L^{-1}; M : L = 1 : 30 at 100 °C for 60 min	88.09%		
Printofix Red T-N01		3. H_2O_2	3. $[H_2O_2]$ = 1 mol L^{-1}; [NaOH] = 1.2 g L^{-1}; $[Na_2CO_3]$: 1.8 g L^{-1}; $[Na_2SiO_3]$: 7 g L^{-1}; M : L = 1 : 30 at 85 °C for 60 min	99.88%		

h^{-1} ozone dose, and 40 min exposure time, followed by diazo and monoazo dyes.[53]

In a study, the color stripping percentages have been calculated for cotton-dyed fabrics for various reactive dyes (CI Reactive Yellow 37, CI Reactive Blue 19, CI Reactive Blue 21, CI Reactive Red 120, CI Reactive Blue 71, CI Reactive Red 223, and CI Reactive Blue 221) using two different stripping methods: TUDO stripping and ozone stripping. The results indicate that ozone stripping is generally more effective in removing the color from the fabric compared to TUDO stripping. For instance, CI Reactive Yellow 37 shows an increase in stripping efficiency from 84.96% with TUDO to 89.91% with ozone, and CI Reactive Blue 19 improves significantly from 76.77% to 91.47%. Similarly, CI Reactive Blue 21, CI Reactive Red 120, and CI Reactive Red 223 also exhibit higher stripping percentages with ozone treatment. The only exception is CI Reactive Blue 221, which shows a slight decrease in stripping efficiency with ozone (94.65%) compared to TUDO (95.96%).[59] Microwave-assisted sequential stripping was developed as an alternative to conventional stripping for cotton dyed with Reactive Blue Black 5 and Turquoise CLB. The alkali → oxidation → reduction method achieved 98% and 97% stripping efficiency in 120 seconds, while the acid → oxidation → reduction method achieved 97% and 94% at the same time, for Reactive Blue Black 5 and Turquoise CLB.[51]

The UV/$K_2S_2O_8$ treatment efficiently improved color stripping, achieving a stripping ratio above 90% within 30 minutes for various reactive-dyed cotton fabrics.[41] Cotton fabric dyed with C.I. Reactive Black 5 dye achieved 97.45% color stripping using O3 under conditions of pH 3, an ozone concentration of 85 g m^{-3}, and a 30 minute treatment time.[72] A study developed an efficient $Na_2S_2O_4$–H_2O_2 system for decolorizing vinyl sulfone-based reactive dark-colored waste cotton fabric, achieving a CIE whiteness index of 74.1, 97.8% decoloration, 24.0% tensile strength loss, and 1.2% weight loss. This combination produced a reasonably white fabric with minimal tensile strength reduction, following the order: $Na_2S_2O_4 > Na_2S_2O_4–H_2O_2 > H_2O_2 > KMnO_4$.[50] Fig. 4 illustrates the effects of chemical CS duration and treatment type on dyed cotton fabric. Digital photographs of fabrics treated with sodium dithionite for varying durations, along with corresponding CS rates and their respective CIE whiteness index values, digital photographs of fabrics subjected to hydrogen peroxide treatment for different durations, along with corresponding CS rates and their respective CIE whiteness index values, digital photographs of fabrics treated with potassium permanganate for varying durations, along with corresponding CS rates and their respective CIE whiteness index values, digital photographs of fabrics subjected to sequential $Na_2S_2O_4$–H_2O_2 treatment for different durations, along with corresponding CS rates and their respective CIE whiteness index values of the samples shown are presented. The dyed cotton was initially pre-cleaned to remove soluble dirt and soil and then air-dried to prepare it for the subsequent CS process. CS was conducted in a 100 mL Erlenmeyer flask, which was placed on a reciprocating shaker and heated for a defined duration. During the treatment, fabric samples were fully immersed in the respective CS solutions. After the CS treatment period, the samples were thoroughly rinsed with hot and then cold water until the pH reached neutrality (pH 7), followed by drying at room temperature (25 °C). Four different CS procedures were employed. In the sodium dithionite ($Na_2S_2O_4$) process, samples were treated

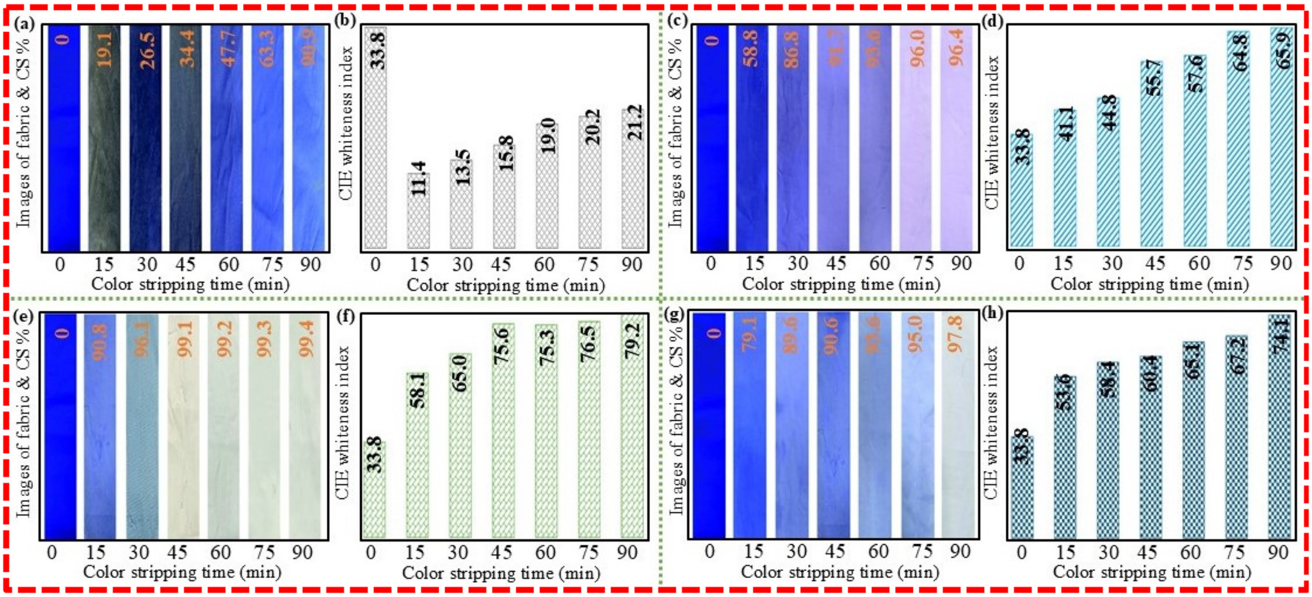

Fig. 4 Effects of chemical CS duration and treatment type on dyed cotton fabric. Digital photographs of fabrics treated with (a) sodium dithionite, (c) hydrogen peroxide, (e) potassium permanganate and (g) $Na_2S_2O_4$–H_2O_2 for varying durations, along with their corresponding CS rates. (b, d, f and h) Respective CIE whiteness index values of the samples shown in (a), (c), (e) and (g). Adapted from ref. 50 with permission from the Royal Society of Chemistry, copyright 2022.

at 90 °C and pH 9 using a solution containing 25 g L^{-1} $Na_2S_2O_4$. For the hydrogen peroxide (H_2O_2), a mixture of 40 g L^{-1} H_2O_2, 20 g L^{-1} sodium hydroxide (NaOH), and 10 g L^{-1} tetraacetylethylenediamine (TAED) was used at 70 °C and pH 10. The potassium permanganate ($KMnO_4$) process was performed in two steps: the first step involved treating the fabric with 5% owf $KMnO_4$ and 5% owf sulfuric acid (H_2SO_4) at 40 °C and pH 5, followed by a second step using 8 g L^{-1} oxalic acid ($H_2C_2O_4$) and 5% owf H_2SO_4 at the same temperature and pH. In the sequential $Na_2S_2O_4$–H_2O_2 procedure, dyed cotton was first immersed in a $Na_2S_2O_4$ solution (25 g L^{-1}) at 90 °C with vigorous shaking. A total of six samples were prepared, and one sample was withdrawn every 7.5 minutes, rinsed to neutral pH, and then transferred to a second bath containing 40 g L^{-1} H_2O_2, 20 g L^{-1} NaOH, and 10 g L^{-1} TAED at 70 °C. Again, samples were collected every 7.5 minutes, rinsed first with hot water (60 °C), then with cold water until the pH became neutral, and dried at 25 °C for 24 hours.[50]

A clean technology was developed to recycle reactive-dyed cotton and dyes by controlled dye hydrolysis. Dye hydrolysis broke covalent bonds between dyes and cellulose, while fiber swelling in *N*-methylmorpholine *N*-oxide (NMMO)/water minimized dye-cellulose interactions. Reactive Blue 19, Reactive Red 2 and Reactive Yellow 145 were removed and almost white fabric was achieved by this process.[73] Fig. 5 demonstrates the CS of reactive dyes from cotton fabrics using NMMO–water systems under various treatment conditions. The effect of NaOH addition on the cleavage of dye–cotton bonds and CS efficiency is evaluated. The process was conducted at 100 °C for 30 minutes using an NMMO–water system containing 35 wt% water and NaOH as a cleavage agent. There is excellent influence of temperature and multiple swelling cycles on the CS efficiency. For each temperature tested, the NaOH concentration was maintained at 0.5 wt%, and the water content in the NMMO–water system was fixed at 35 wt%. Each swelling cycle was carried out for 30 minutes. The weight ratio of the NMMO–water system to cotton was 5 : 1 for the first cycle and 3 : 1 for the second and third cycles. Reactive Blue 19 was used as the reference dye to evaluate dye–cotton separation. The results indicate that the effect of CS cycles on CS efficiency for various reactive dyes, including Reactive Blue 19, Reactive Red 2, and Reactive Yellow 145, are different. The process was conducted at 90 °C. Prior to NaOH treatment, cotton was subjected to dips and nips to enable calcium ion exchange, facilitating the hydrolysis of dye–cotton bonds.

The stripping efficiency of mixed-colored cotton fabrics (Novacron Red TS-3B, Novacron Yellow TS-3R, and Novacron Blue TS-3G) increased with higher concentrations of hydrose and caustic soda. At 100 °C, using 10 g L^{-1} hydrose and 10 g L^{-1} caustic soda, the stripping was 92.84% for a 2.5% shade and 93.80% for a 5% shade.[56] A study found that using 5 g L^{-1} hydrose and 5 g L^{-1} caustic soda at 100 °C achieved a 92.87% stripping efficiency for a 0.3% light shade of single jersey cotton fabric dyed with Drimarene Yellow CL2R, Drimarene Red CL5B, and Drimarene Blue HFRL reactive dyes.[74] Commercially available reactive dyes were applied to cotton

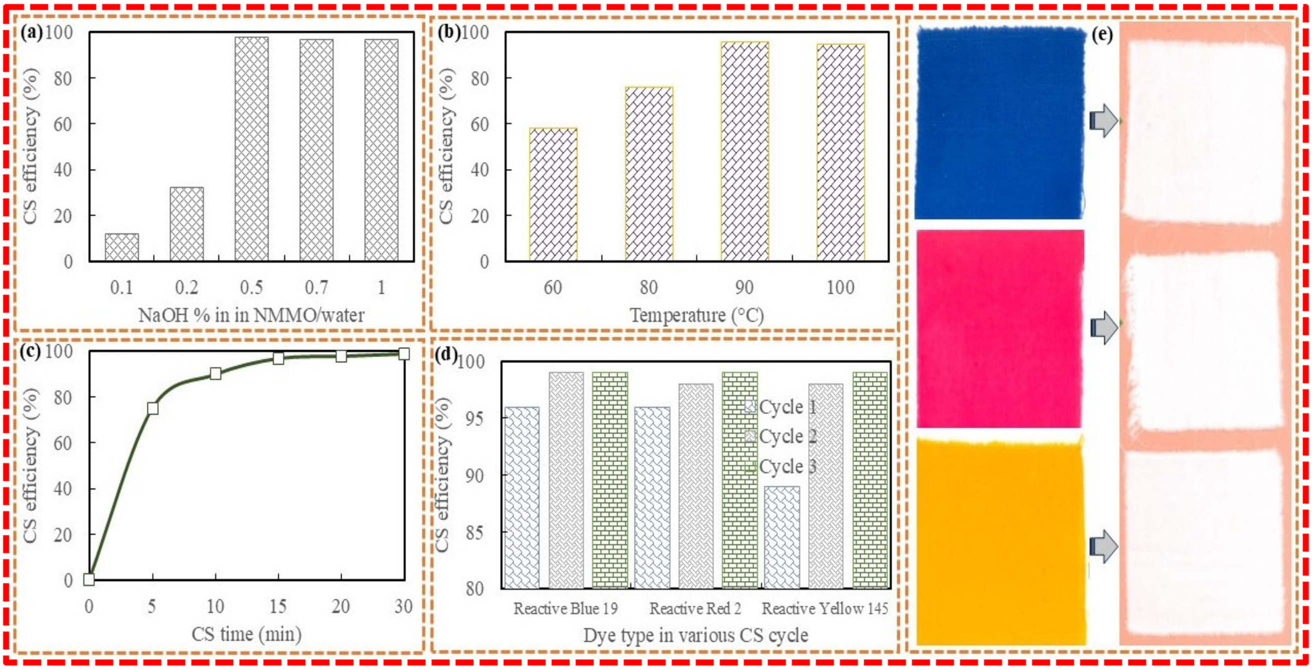

Fig. 5 CS efficiency of reactive dyes from cotton fabric using NMMO–water systems under various treatment conditions. (a) Effect of NaOH addition on the cleavage of dye–cotton bonds and CS efficiency. (b) Influence of temperature and multiple swelling cycles on the CS efficiency. (c) Relationship between the CS time and CS efficiency. (d) Effect of CS cycles on the CS efficiency for various reactive dyes, including Reactive Blue 19, Reactive Red 2, and Reactive Yellow 145. (e) Digital images showing cotton fabrics before and after CS treatments, illustrating the visual changes in CS.[73] Adapted from ref. 73 with permission from Elsevier, copyright 2023.

fabric and stripped under optimized conditions using the UV/$Na_2S_2O_4$ system (pH 6.0, 0.6 g L^{-1} sodium hydrosulfite, 20 °C, 60 minutes, 1 : 30 bath ratio). Most Evercion reactive dyes showed over 80% color stripping, with tensile strength retention above 90%. Evercion Yellow H-E4R and Everzol Yellow 3RF had lower stripping efficiencies of 43.1% and 68.0%, accordingly.[43] After 60 minutes of ozonation, yellow- and black-dyed fabrics showed color fading of 88.64% and 86.06%. In contrast, red and blue fabrics achieved 91.94% and 96.62% color fading in just 30 minutes.[75]

Microwave-assisted alkali hydrolysis pre- and meta-treatments of Reactive Turquoise CLB-dyed cotton fabrics achieved stripping efficiencies of 88.4% and 84.9%, compared to 80.2% and 75.7% without an absorber and using conventional methods. Similarly, microwave-assisted reduction pre- and meta-treatments with a microwave absorber (M.W.A.) achieved 94.1% and 95.2% stripping efficiencies, while conventional methods and treatments without an absorber achieved 85.3% and 80.8%, respectively. The fabric weight loss after stripping with microwave-assisted alkali hydrolysis and reduction with M.W.A. was 3.4% and 2.9%, whereas conventional methods resulted in 4.5% and 4.2% weight loss.[62] Photocatalytic (nano-TiO_2/UV) color stripping of Reactive Red X-3B dyed cotton using a nano-TiO_2/UV system achieved 80% to 97% efficiency with treatment times from 30 to 90 minutes at pH 8.0, 50 mg L^{-1} nano-TiO_2, and 20 °C.[40] Fig. 6 shows the evaluation of the photocatalytic CS performance and mechanical retention of Reactive Red X-3B dyed cotton fabric under varying treatment conditions using nano-TiO_2 as a photocatalyst (50 mg L^{-1}) in an aqueous solution with an initial pH of 8.

The sequential CS of reactive-dyed cotton fabric (dyed with Levafix Yellow CA, Levafix Red CA, and Levafix Blue CA) was carried out through a two-step chemical treatment process. The first stage involved exposure to an alkaline medium (45 wt% sodium hydroxide), followed by an acidic treatment using 60 wt% acetic acid. This sequential alkaline-acid treatment resulted in a significant increase in fabric brightness, from an initial 20.9% to 83.8%.[20] A study explored the CS from

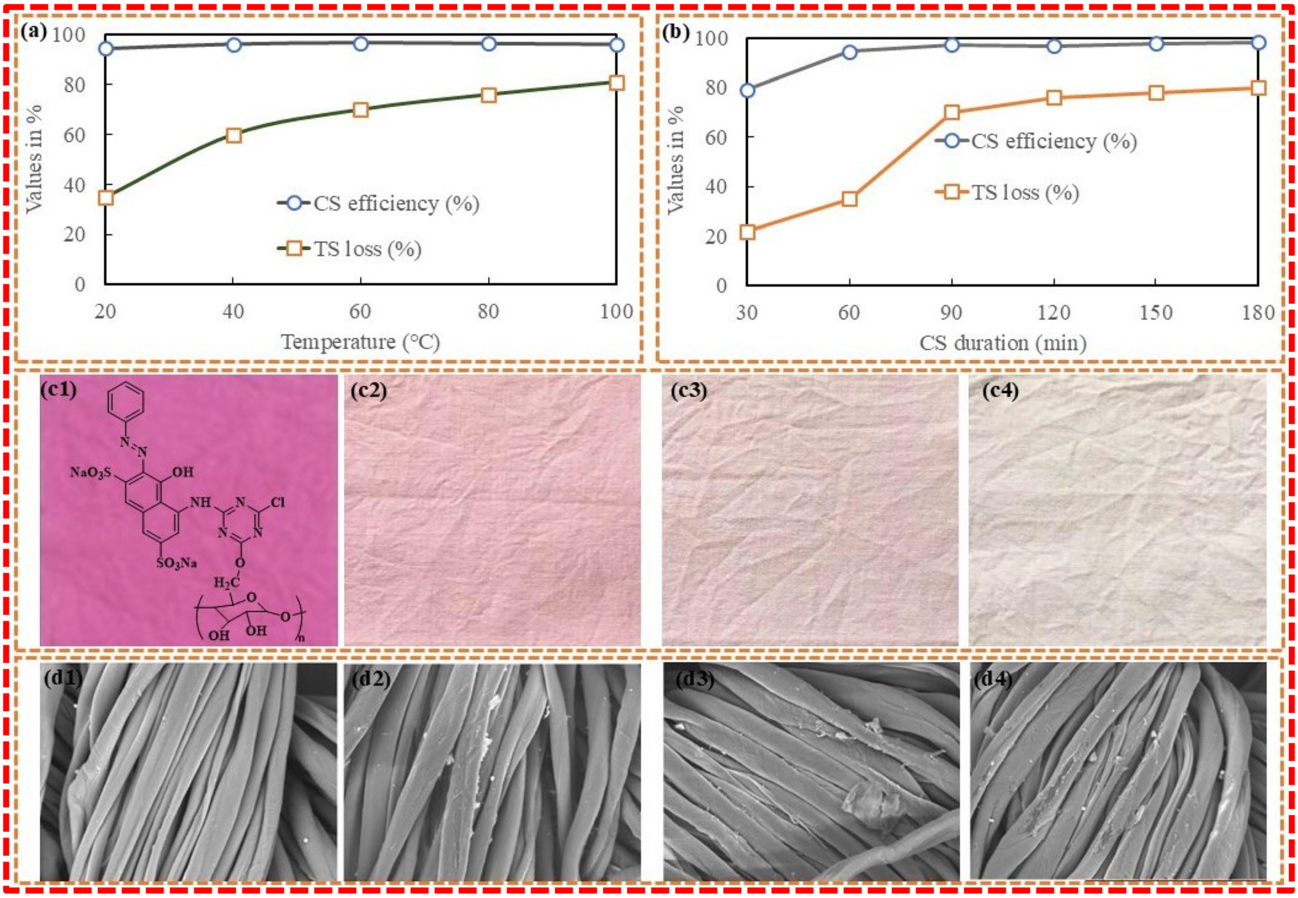

Fig. 6 Evaluation of the photocatalytic CS performance and mechanical retention of the Reactive Red X-3B-dyed cotton fabrics under varying treatment conditions using nano-TiO_2. (a) Influence of treatment temperature on the CS efficiency and tensile strength (TS) retention after 60 minutes of exposure. (b) Influence of treatment duration on the CS efficiency and TS retention at a fixed temperature of 20 °C. (c) Photographic comparison of cotton fabrics before and after nano-photocatalytic treatment: (c1) untreated dyed cotton, (c2) treated for 30 min, (c3) treated for 60 min, and (c4) treated for 90 min. (d) SEM images under 1000× magnification showing the surface morphology of (d1) untreated dyed cotton and the samples treated with nano-TiO_2 for (d2) 30 min, (d3) 60 min, and (d4) 90 min at 20 °C.[40] Adapted from ref. 40 with permission from Elsevier, copyright 2017.

cellulose fabrics dyed with Reactive Black 5 using microwave-assisted oxidative and reductive methods. The best result was found by using a microwave with 70 g L^{-1} of sodium hydroxide and sodium dithionite for 120 seconds, achieving 97.60% color removal. The treated fabric remained strong and flexible, with a maximum force of 257 N and elongation of 14.75%, close to the original fabric's 267.8 N and 16.88%.[46] In a study, a CS process involving four steps was carried out: first, the fabric was boiled for 4 minutes in a 1 : 1 volume ratio solution of glacial acetic acid and ethanol. Second, it was boiled for 4 minutes in a 1% ammonia solution. Third, the fabric was treated by boiling for 4 minutes in a 1 : 1 mixture of dimethylformamide and water. Finally, it was boiled for 4 minutes in pure DMF. The CS efficiency of various dyed cotton fabrics varied significantly depending on the dye structure and type. Among the reactive dyes, C.I. Reactive Blue 19 exhibited the highest CS of 73.5%, followed by C.I. Reactive Yellow 3 (5.9%), C.I. Reactive Orange 5 (4.5%), and C.I. Reactive Red 195 (3.9%).[65]

The color stripping of knitted cotton fabrics dyed with C.I. Reactive Yellow 145 was conducted using sodium hydrosulfite and sodium hypochlorite as the stripping agents, and the CS performance was evaluated based on the whiteness index.[61] After a series of acid (H_2SO_4), alkali (NaOH), and peroxide (H_2O_2) treatments, the color strength (*K*/*S*) of the reactive-dyed cotton fabrics was reduced. Alkali treatment had a strong effect on azo-based dyes, with C.I. Reactive Black 5 and C.I. Reactive Red 228 dropping from *K*/*S* values of 29.7 and 26.0 to 0.3 and 0.4, respectively. Hydrogen peroxide treatment further removed the dye, reducing the *K*/*S* of Reactive Black 5 to 0.04 and Reactive Red 228 to 0.1. For C.I. Reactive Blue 19, which has an anthraquinone chromophore, the alkali treatment also reduced the *K*/*S* from 22.9 to 9.7.[76] Fig. 7 shows the multiple CS approaches of dyed cotton fabrics. The visual appearance and CS efficiency of cotton fabrics dyed with C.I. Reactive Blue 19, C.I. Reactive Black 5, and C.I. Reactive Red 228 are shown following sequential treatments with acid, alkali, and peroxide. Three treatment stages were assessed: acid only, acid followed by alkali, and the complete acid/alkali/peroxide sequence. The CS efficiency for cotton fabrics dyed with Reactive Black 5 using the electrochemical method was investigated under galvanostatic conditions using different media—water, phenol, or pyridine.[47] In each experiment, 400 mL of CS solution was used without pH adjustment. A Ti/TiO_2–RuO_2–IrO_2 mesh anode covered with dyed fabrics was positioned centrally, with a cylindrical stainless-steel net cathode placed near the reactor wall. Electrodes were connected to a DC power supply to maintain a constant current, with minimal voltage adjustments. After treatment, the fabrics were thoroughly rinsed, dried, and evaluated for the CS efficiency.

The CS of cotton woven fabrics dyed with C.I. Reactive Black 5 was performed using an ozone-assisted treatment. Under specific conditions—specifically an ozone concentration of 85 g m^{-3} TPN, a pH of 3, and a treatment duration of 30 minutes—a CS efficiency of 97.45% was achieved. These results highlight the high effectiveness of ozone oxidation in degrading reactive dye chromophores under acidic conditions.[81] The effect of sequential acid/alkali/peroxide and acid/dithionite/peroxide treatments on the CS efficiency of various cotton dyed fabrics, including C. I. Reactive Black 5, C. I. Reactive Blue 19 and C. I. Reactive Red 228, has been investigated. Both treatments achieved 100% stripping efficiency for Black 5 and Red 228 dye.[23] However, for Blue 19, the acid/dithionite/peroxide treatment outperformed the acid/alkali/peroxide method. While acid/dithionite/peroxide achieved complete (100%) stripping efficiency, the acid/alkali/peroxide treatment reached only approximately 82% efficiency.[23] This suggests that the acid/dithionite/peroxide sequence is more effective.

4.3. Color stripping of the vat-dyed textile

Vat dyes are a class of insoluble dyes, such as indigo, that are converted to a water-soluble form through a vatting process, usually involving chemical reduction and alkali, to penetrate textile fibers. After dyeing, they are re-oxidized to their original insoluble state, creating a strong, water-insoluble colorant embedded within the fibers. Vat dyes generally exhibit very good chemical stability against both reduction and oxidation processes, resulting in outstanding colorfastness and durability.[90,91] The performance of various color stripping methods for vat-dyed cotton fibers is mentioned in Table 2.

The color stripping of vat dyes from cotton is performed at high temperatures. A 50/50 mixture of DMF/water and DMSO/water at 90 °C for 30 minutes was ineffective in removing Novatic Brown R MD (vat dye) from the cotton fabric, but adding NaOH (30 g L^{-1}) and $Na_2S_2O_4$ (30 g L^{-1}) enhanced the stripping efficiency.[24] The sequential acid, dithionite, and peroxide treatment removed up to 97% of CI Vat Blue 4, CI Vat Black 27, and CI Vat Blue 1 from dyed cotton, yielding a white cellulosic material.[84] In another study, the fading effect was achieved on cotton yarn dyed with CI Vat Blue 1 using ozone treatment. The results indicated that variations in yarn properties and ozone application conditions influenced the degree of fading. A lighter shade was obtained than the reference sample, and the ozonation process did not significantly reduce the yarn's strength.[92] The effect of sequential acid/alkali/peroxide and acid/dithionite/peroxide treatments on the color stripping efficiency for C.I. Vat Blue 1-dyed denim fabric was investigated. While acid/dithionite/peroxide achieved complete (100%) stripping efficiency, the acid/alkali/peroxide treatment reached only 82% efficiency.[23]

4.4. Color stripping of the sulphur-dyed textile

Sulphur dyes are a class of water-insoluble, complex organic dyes with sulphur linkages, primarily used for dyeing cotton for dark shades like black and blue. They offer excellent wash-fastness due to their insolubility post-oxidation, and generally good light-fastness (often rated 3–4 on the grayscale). However, their limited color palette, processing complexity, toxicity, and environmental concerns pose significant drawbacks.[93,94] The performance of various color stripping methods for sulphur-dyed cotton fibers is mentioned in Table 2.

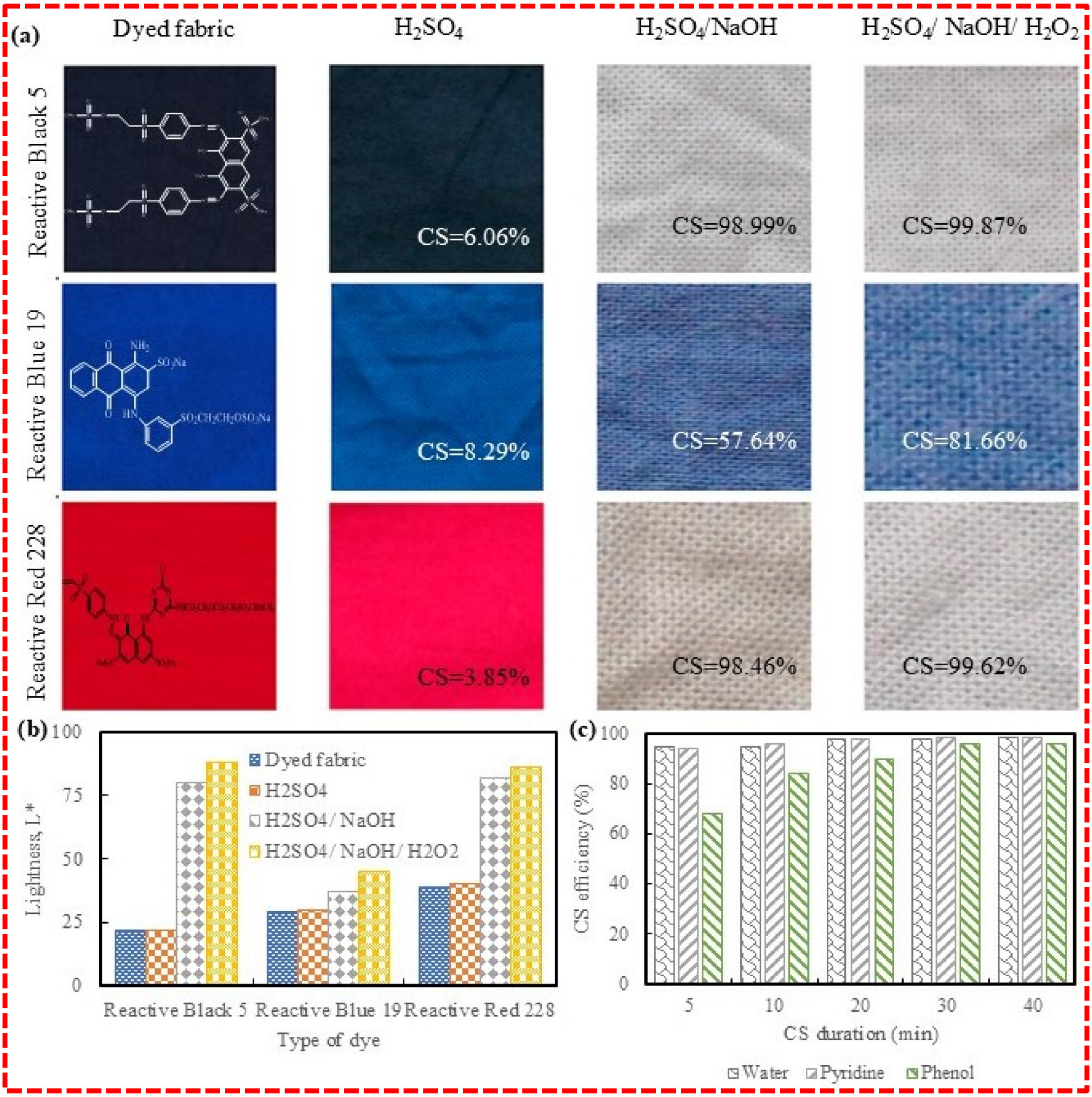

Fig. 7 Illustration of multiple CS approaches of dyed cotton fabrics. (a) Visual appearance and CS efficiency of cotton fabrics dyed with C.I. Reactive Blue 19, C.I. Reactive Black 5, and C.I. Reactive Red 228 following sequential treatments with acid, alkali, and peroxide. Three treatment stages were assessed: acid only, acid followed by alkali, and the complete acid/alkali/peroxide sequence. (b) Corresponding lightness (*L**) values of the treated fabrics. Adapted from ref. 76 with permission from Elsevier, copyright 2018. (c) CS efficiency of cotton fabrics dyed with Reactive Black 5 using the electrochemical CS method. Adapted from ref. 47 with permission from Elsevier, copyright 2018.

The process of color stripping involves removing the sulfur-based dye from the fabric that has been dyed with sulphur. Color stripping may be necessary in cases where the fabric's color needs to be changed or corrected, or where dyeing process flaws are present. Sulphur dyes are generally very stable in alkaline, reducing environments, which results in very low CS.[24] Under conditions of 10 g L^{-1} NaOH, 10 g L^{-1} $Na_2S_2O_4$, an M : L ratio of 1 : 15, and treatment at 90 °C for 30 minutes, only about 1% CS was achieved. Moreover, a 50/50 mixture of DMF/water and DMSO/water at 90 °C for 30 minutes was ineffective in removing sulfur black dye from cotton fabric, but adding NaOH (30 g L^{-1}) and $Na_2S_2O_4$ (30 g L^{-1}) enhanced the stripping efficiency.[24] In contrast, a combination of solvent extraction and a strong oxidant such as H_2O_2

can remove the dye significantly. The sequential acid, dithionite, and peroxide treatment removed up to 97% of CI Sulphur Black 1 and CI Sulphur Blue 7 from dyed cotton, producing a white cellulosic material suitable for fiber regeneration.[84]

4.5. Color stripping of acid dyed textile

Acid dyes are water-soluble, anionic colorants containing sulfonic acid groups ($-SO_3H$), which enable strong ionic interactions with positively charged sites on protein-based fibers such as wool, silk, and nylon. They typically produce vivid colors and offer excellent fastness properties.[95,96] The performance of various color stripping methods for acid dyed fibers is mentioned in Table 3.

Acid-dyed textiles are subjected to the process of color stripping, which involves removing the acid-based dye from the fabric. The process of dyeing wool, silk and nylon fibers typically involves the utilization of acid dyes. However, chemically modified cotton can be dyed with acid dye. A solvent system of DMSO/water (95 : 5 mass ratio) was used for C.I. Acid Blue 40 dye removal from Nylon 6 6. Complete dye removal (100%) was achieved after three stripping cycles using a 95% DMSO aqueous solution at 100 °C.[25] In another study, DMF along with water in 1 : 1 ratio was used for the CS of cotton fabrics, and 87.5% CS was yielded for C.I. Acid Blue 25, 82.7% for C.I. Acid Yellow 151 and 79.3% for C.I. Acid Red 131.[65] Conversely, NaOH has been demonstrated to be effective for the CS of polycarboxylic acid Black-dyed cotton fabrics. A CS efficiency of 82.18% was achieved using a 5% NaOH solution at a treatment temperature of 90 °C.[89] The high alkalinity promotes the hydrolysis and breakdown of dye–fiber bonds.

4.6. Color stripping of the disperse-dyed textile

Disperse dyes are a class of non-ionic dyes with very low water solubility used for dyeing polyester, nylon, and acrylic. Disperse dyes exhibit excellent dyeing affinity for hydrophobic fibers, resulting in vivid, long-lasting coloration with good wash, light, and sublimation fastness. However, they are constrained by limited solubility, fiber specificity, environmental and health considerations and energy-intensive requirements.[97–99] The performance of various color stripping methods for disperse dyed synthetic fibers is mentioned in Table 3.

Due to the highly crystalline and hydrophobic structure of synthetic fibers such as polyester, the diffusion of water and other chemicals into these fibers is very limited at temperatures below their glass transition temperature, which restricts the effectiveness of oxidation or reductive stripping processes under mild conditions. The solvent extraction is generally a better approach for removing dyes from polyester fibers.[100] As an example, a mixture of ethylene carbonate and tetramethylurea (7 : 3 w/w) was used to strip color from polyester fabric dyed with C.I. Disperse Blue 56. At 90 °C and a liquor ratio of 1 : 5, this process achieved 98% color removal from PET after two washing cycles. At 120 °C, complete (100%) dye removal was achieved under the same conditions after two cycles.[25] Another study found that the ozone effectively decolorized polyester fabrics dyed with C.I. Disperse Orange 30 and C.I. Disperse Blue 60. Optimal color stripping conditions were an ozone feed rate of 130 mg L^{-1} min^{-1}, 2 hour treatment time, 100% wet pick-up, and pH 3, achieving over 45% decolorization and a color difference value above 6%.[21] The PET/cotton-blended fabric dyed with disperse/direct dye shows effective color stripping when treated with DMF, achieving stripping rates above 80%, with a maximum of 97%. The optimal conditions are fabric swelling at 100 °C for 30 minutes, followed by stripping at 140 °C for 30 minutes.[44] The CS process was carried out on polyester–cotton blended fabrics to remove the synthetic reactive disperse dyes. The CS bath contained *N*-methylpyrazolidinone, sodium hydroxide, sodium hydrosulfite, and deionized water. The results showed that there was no noticeable change in the color depth of the fabric before and after CS.[101]

4.7. Color stripping of printed textiles

Pigment prints typically involve insoluble pigments affixed with binders that coat the fiber surfaces. The strong adhesion between pigment, binder, and fabric complicates complete pigment removal. Even aggressive treatments like ozone-assisted processes struggle to fully remove binder films.[102,103] The performance of various color stripping methods for different printed cotton fibers is mentioned in Table 4.

The color stripping of printed textiles is technically complex due to strong pigment–binder–fiber adhesion. A study proposed an ozone-assisted process for decolorizing pigment-printed cellulosic textiles using CI Pigment Blue 15 (copper phthalocyanine-based dye). The best color stripping results were achieved at pH 5, an ozone concentration of 100 g O_3 per Nm^3, and an exposure time of 120 minutes, with color stripping exceeding 90% under acidic conditions.[104] A study showed that using ozone gas is a viable industrial method for stripping color from fabrics misprinted with reactive dyes.

Although conventional stripping at 100 °C was more effective, ozone treatment operated at room temperature, required no heating or chemicals, and had a shorter processing time, making it a more cost-efficient alternative.[105] Conventional discharge printing with CI Reactive Blue 221 on cotton fabric achieved an 82.3% color discharge using ozone treatment. Ozone-based discharge printing is a faster process with significantly lower chemical usage.[106]

5. Factors affecting the color stripping efficiency

Several interconnected factors determine how effective color stripping is in dyed textiles, each affecting the process efficiency. In this section, we take a closer look at the key parameters that influence the color stripping from dyed textiles. Factors such as the type of dye and fiber, the choice of stripping agents, and the conditions under which the process takes place all play important roles. Exploring these aspects helps us better understand why outcomes differ across methods and provides a basis for developing more efficient and sustainable approaches to textile recycling.

5.1. Fiber type

Textile fiber production statistics indicate that polyester holds a 59% share of the global market, while cotton accounts for 19%. Together, they represent the vast majority of textile fibers, suggesting that post-consumer textile waste will likely have a similar composition.[119] As shown in Tables 2 and 3, most previous research on the color stripping of dyed textiles has therefore concentrated on these two fiber types. Cotton, a cellulosic fiber with relatively high crystallinity (60–70%) and abundant hydroxyl groups, is highly hydrophilic.[120] This structure results in significant water and dye uptake, enabling cotton to be dyed with a wide range of dye classes, including reactive, vat, sulfur, and direct dyes. Tables 2 and 3 also illustrate that various bleaching agents have been applied for stripping dyes from cotton fabrics successfully. In contrast, polyester is hydrophobic, with high crystallinity and a high glass transition temperature.[121] These properties hinder the adsorption of water, dyes, and chemicals, making polyester more resistant to conventional bleaching. Dyeing polyester typically requires elevated temperatures (>130 °C) to allow the diffusion of hydrophobic disperse dyes into its compact structure.[122] Consequently, color stripping of dyed polyester is particularly challenging under conventional bleaching conditions below 130 °C. The limited accessibility of disperse dyes within polyester's tightly packed polymeric network means that solvent-based extraction is often more effective than common bleaching agents. This comparison clearly demonstrates how fiber type strongly influences the efficiency of color stripping.

5.2. Dye class

The chemical structure of dyes plays a critical role in determining their resistance to degradation during color stripping. In an investigation on color stripping of cotton textiles, vat dyes were found to exhibit notable differences in the stripping efficiency, primarily due to variations in their molecular structure.[84] Vat Blue 1 (Indigo) was more susceptible to degradation, whereas anthraquinone-based dyes such as Vat Blue 4 and Vat Black 27 exhibited greater resistance under similar color stripping conditions. This difference is largely attributed to the larger, more condensed aromatic systems of anthraquinone dyes, which provide enhanced chemical stability against reductive and oxidative bleaching agents. In contrast, the simpler indigoid structure (Vat Blue 1) offers greater accessibility for chemical attack, leading to more effective stripping. These observations underline the importance of dye chemistry in recycling processes, as structural complexity directly influences the extent to which dyes can be degraded and removed from fibers.

In another study on the color stripping of cotton fabrics dyed with reactive dyes, it was observed that azo-based dyes such as Reactive Blue 5 were more readily removed, whereas anthraquinone-based dyes like Reactive Blue 19 exhibited much higher resistance under the same treatment conditions.[58] This difference was attributed to the higher chemical stability and stronger electron delocalization of the anthraquinone chromophore, which makes it less susceptible to degradation than the labile azo bond. These results further emphasize that the dye chemical structure, particularly the type of chromophore, plays a critical role in determining the efficiency of color stripping. The chemical structures of common direct dyes (C.I. Direct Red 72 and C.I. Direct Blue NB 2B), reactive dyes (C.I. Reactive Red 2 and C.I. Reactive Blue 19), acid dyes (C.I. Acid Red 131 and C.I. Acid Blue 40), vat dyes (C.I. Vat Blue 1 and C.I. Vat Blue 4), sulphur dyes (C.I. Sulphur Blue 7 and C.I. Sulphur Black 1) and disperse dyes (C.I. Disperse Blue 56 and C.I. Disperse Blue 60) used in the textile industry are mentioned in Fig. 8.

5.3. Stripping agents and dosage

The type (oxidative, reductive, bacteria, and enzyme) and amount of stripping agents used in the process directly impact the stripping efficiency. While higher dosages improve the stripping effectiveness, excessive amounts can weaken fibers and compromise fabric strength.[56] However, using a lower dosage is gentler on fibers but may result in incomplete color removal, and this leads to increased energy consumption and resource use. The stripping efficiency of dyed fabrics increased with the increasing concentrations of stripping agents due to chemical effectiveness.[123] Using 10 g L^{-1} hydrosulfite and 10 g L^{-1} caustic soda at 100 °C, 95.45% CS for light-shade fabrics and 79.79% for dark-shade fabrics were achieved. At 5 g L^{-1} hydrosulfite and 2.5 g L^{-1} caustic soda at 80 °C, 91.33% CS for light-shade fabrics and 69.88% for dark-shade fabrics were observed.[74] It was observed that the reactive-dyed cotton fabric showed high CS efficiency of approximately 73% even in the absence of $Na_2S_2O_4$. When a small amount of $Na_2S_2O_4$ (up to 0.5 g L^{-1}) was introduced into the stripping system, the efficiency significantly increased, exceeding 85%.[43] Tables 2–4 illustrate that various bleaching agents and their concentration have a significant impact on the stripping of dyes from textiles.

5.4. Stripping bath pH

The pH of the stripping bath significantly affects the performance of different stripping agents. Alkaline conditions (pH above 10) enhance reductive stripping, particularly for vat, disperse, and sulfur dyes. Under high pH conditions, hydroxide ions (OH^-) facilitate the breakdown of dye molecules and disrupt the fiber–dye interaction, improving color removal. Acidic conditions (pH below 5) are necessary for stripping acid dyes from protein-based fibers like wool and silk. At lower pH levels, the protonation of dye molecules reduces their affinity to the fiber, making them easier to strip away. A neutral pH is less effective for stripping but may be required for sensitive fibers to prevent damage. Maintaining an appropriate pH ensures that the stripping reaction proceeds efficiently without excessive fiber degradation. The effect of pH on dye stripping using reactive dyes shows that increasing the pH enhances the stripping efficiency, particularly under alkaline conditions. For

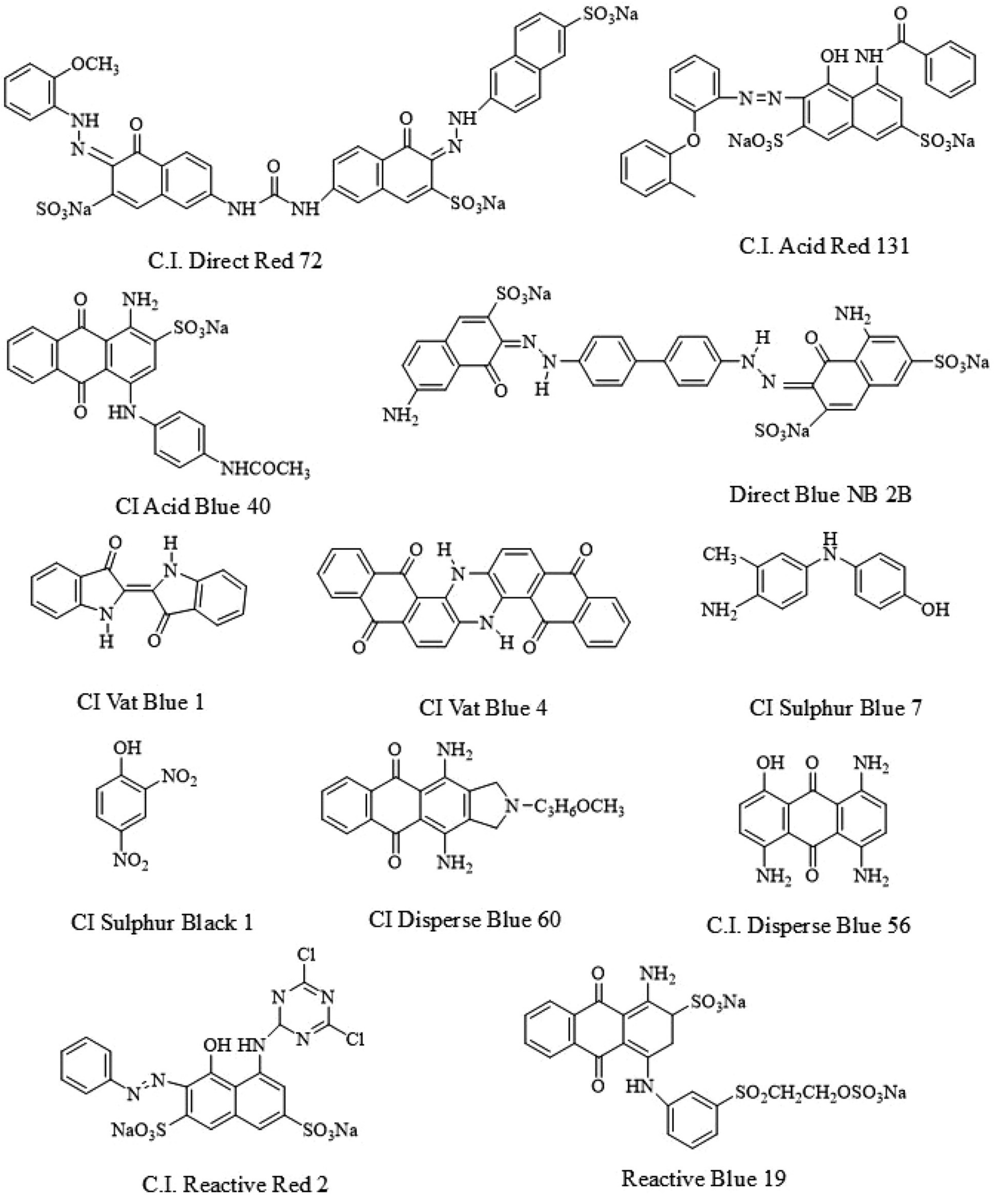

Fig. 8 Chemical structures of some common direct, acid, vat, sulphur, disperse and reactive dyes used in the textile industry.

instance, at pH 10.5 using sodium hydrosulphite and caustic soda, stripping percentages improved, achieving up to 93.8% dye removal for a 5% reactive dye shade at 100 °C.[56] The effective CS performance across a wide pH range (2.0 to 10.0) was found in a study, indicating its suitability for use under both strongly acidic and strongly alkaline conditions. The CS efficiency of reactive-dyed cotton was evaluated at different initial pH levels, adjusted using hydrochloric acid or sodium hydroxide, within the UV/$Na_2S_2O_4$ system. High stripping efficiencies exceeding 81% were achieved across the entire pH

Table 5 Various bleaching agents and their pH range and mechanistic explanation

Bleaching agent	Optimum pH range	Reason/mechanistic explanation	Ref.
Sodium dithionite ($Na_2S_2O_4$)	9–11 (alkaline)	Stable only in alkaline medium; in acidic conditions it decomposes rapidly to SO_2 and sulfites, losing reducing power. Effective for reducing vat and sulfur dyes	93
Sodium chlorite ($NaClO_2$)	3.5–5 (acidic)	Requires acidic activation (often acetic acid) to generate ClO_2, the true bleaching species. At higher pH, insufficient ClO_2 is formed	124
Sodium hypochlorite (NaClO)	10–11 (alkaline)	Stable as hypochlorite ion (OCl^-) in alkaline conditions. At lower pH, it disproportionates to Cl_2 gas and HOCl, which are unstable and hazardous	125
Hydrogen peroxide (H_2O_2)	10.5–11.5 (alkaline)	In alkaline medium, H_2O_2 forms perhydroxyl anion (HOO^-), the active bleaching species. At low pH, H_2O_2 is more stable but less reactive toward dyes	78 and 126
Ozone (O_3)	<5 (acidic)	More stable and selective in acidic conditions; at high pH, ozone decomposes rapidly to hydroxyl radicals, causing less controlled oxidation	127

range from 2.0 to 10.0, with a maximum efficiency of 85.34% observed at pH 6.0. However, a significant decrease in stripping efficiency was noted at pH values above 10.0.[43] Various bleaching agents and their pH range and mechanistic explanation are mentioned in Table 5.

5.5. Stripping duration

The duration of the stripping process is a key parameter influencing both dye removal and fiber quality. Shorter treatment times help minimize chemical damage to the fiber but may result in incomplete color removal. Therefore, optimizing treatment duration is essential to achieve an effective balance between color removal and the preservation of fiber mechanical integrity.

Fig. 9 shows the effects of various parameters including reaction duration on the efficiency of color stripping from cotton fabrics dyed with reactive dyes using a photocatalytic UV/$K_2S_2O_8$ system.[41] The stripping duration was varied between 10 and 90 minutes at ambient temperature (20 °C), with a 1.0 g L^{-1} $K_2S_2O_8$ and pH 2. The results showed a significant improvement in the color stripping as the duration increased from 10 min to 30 min, rising sharply from 49.0% to 91.7%. Further extending the duration to 90 min gradually increased the stripping ratio to 97.0% (Fig. 9d). This indicates that most reactive dye molecules were effectively decomposed within 30 min, with additional stripping time yielding marginal improvement.

A CS efficiency of 86.8% was achieved within 30 minutes using H_2O_2, which then steadily increased to 96.4% at 90 minutes. $KMnO_4$ showed the fastest response, reaching a CS efficiency of 90.8% in just 15 minutes and peaking at 99.4% after 90 minutes.[50] A significant increase in color stripping efficiency on reactive-dyed cotton was observed, rising from 53.07% to 85.34% as the stripping duration increased from 10 to 30 minutes. With further extension to 60 minutes, the efficiency continued to improve gradually, reaching 93.26%.[43]

5.6. Temperature

Temperature is another key influencing factor of CS. It was found in a study that a noticeable increase in CS efficiency from 85.34% to 93.77% was observed as the stripping temperature increased from 20 °C to 30 °C, with no significant improvement beyond 30 °C up to 80 °C. This indicates that a moderate temperature facilitates the decomposition of $Na_2S_2O_4$ into active reducing species, enhancing CS.[43] In another study, it was found that the CS efficiency of dyed cotton fabric was observed as the treatment temperature increased from 20 °C to 60 °C in the nano-TiO_2/UV system, reaching a maximum efficiency of 97.2% at 60 °C. Beyond this temperature, further increases up to 100 °C resulted in minimal changes in stripping efficiency.[40] The impact of various bleaching agents on the stripping of dyes from textiles is illustrated in Tables 2–4.

5.7. Blended fibers

Another important factor in color stripping is the presence of blended fibers, yet only limited research has addressed dye removal from fabrics composed of two or more fiber types. One study on reactive-dyed polycotton waste used a modified hydrolysis process to decolorize the cotton component while separating the polyester and recovering terephthalic acid, demonstrating a promising approach for reducing textile solid waste.[117] Another study investigated the use of Dimethyl Formamide (DMF) for stripping dyes from PET/cotton fabrics dyed with disperse/direct dyes.[44] The process involved a swelling treatment followed by stripping in a DMF-based solution. Under optimal conditions (swelling at 100 °C for 30 minutes and stripping at 140 °C for 30 minutes), dye removal exceeded 80% and reached up to 97%, while the fabric retained 90–95% of its original tensile strength. These results demonstrate that DMF is effective for correcting dyeing defects and improving material reuse. However, the study was limited to a single PET/cotton blend and disperse/direct dye system, tested only three shades, and did not evaluate other fabric properties such as whiteness and long-term durability.

5.8. Characteristics of the post-consumer textile waste

Some other characteristics of the post-consumer textile waste (PCTW) may influence the efficiency and quality of color stripping processes. Unlike textiles produced for industrial applications, consumer textiles possess diverse properties that may affect the stripping performance. Several factors have been investigated in the literature, including the influence of fiber type, dye type, stripping method, color depth, and shade complexity. However, there is limited research on how the stage at

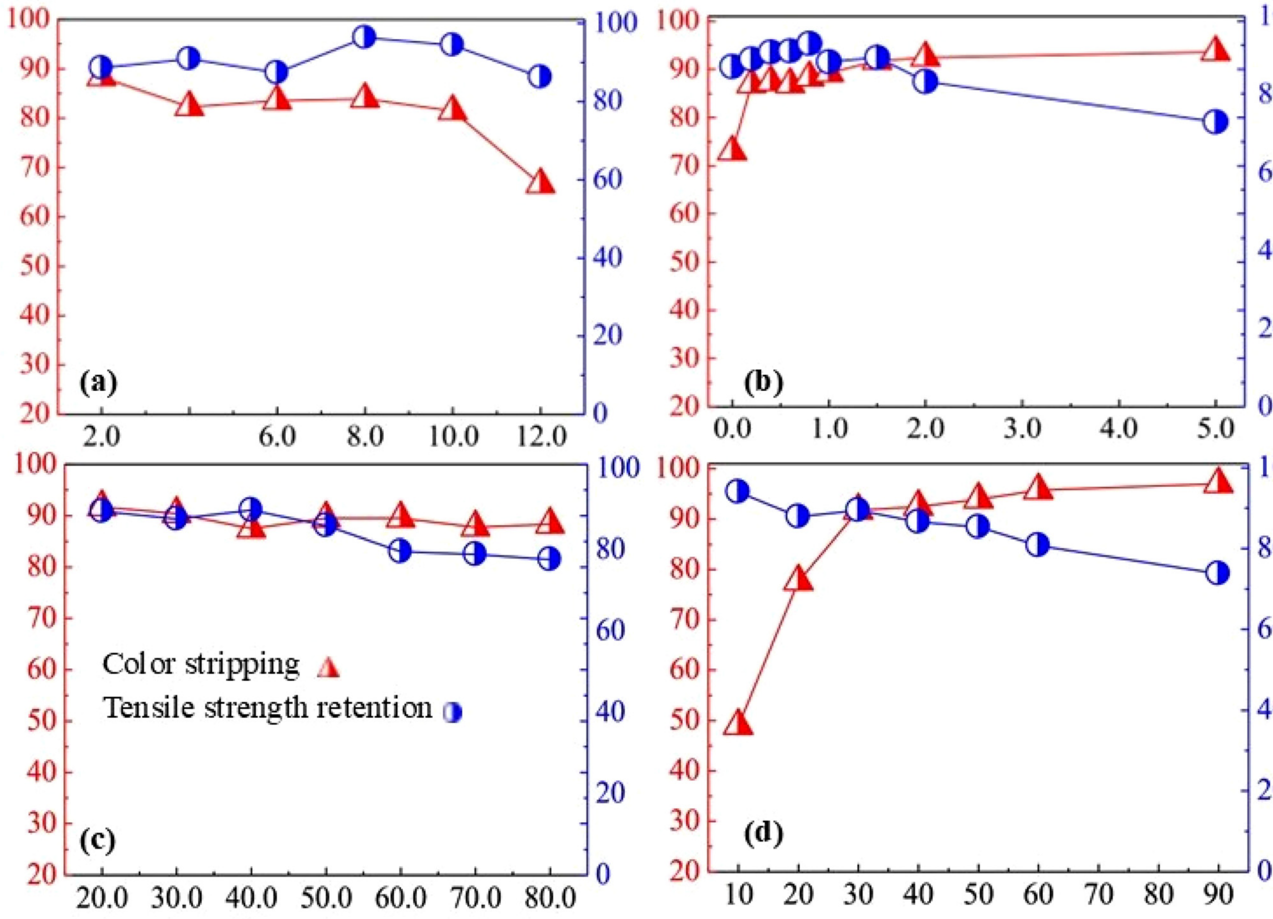

Fig. 9 Impact of the process variables pH (a), chemical dosage (b), temperature (c), and reaction time (d) on the color removal performance and tensile strength retention.[41] Adapted from ref. 41 with permission from Elsevier, copyright 2021.

which PCTW is collected and the treatments it undergoes before recycling affect the color stripping process. This represents a major gap in the current color stripping literature and highlights the need for further investigation in this area.

6. Applications of color-stripped textiles

CS enables the reuse, repurposing, and recycling of dyed textile waste. Once the color has been removed from textile materials whether through chemical, biological, or physicochemical means—the resulting decolorized fabric or fiber opens the door to a wide range of sustainable applications. These applications are aligned with the principles of the circular economy, aiming to reduce waste, minimize environmental impact, and create value from discarded materials.

6.1. Color rectification and redyeing

Shade defects, color mismatches, and undesired hues can occur during textile dyeing or printing, and partial color stripping is an effective method to correct these issues by allowing re-dyeing or re-printing with more accuracy and consistency.[28] This process is valuable in textile manufacturing, fashion production, and quality control. By enabling correction rather than replacement, color rectification not only improves product quality and consistency but also contributes to waste reduction and more sustainable production practices.

Color-stripped textiles can be redyed to increase sustainable textile reuse. The redyed textiles can be repurposed into new textile products, and this technique can reduce material waste, lower production costs, and support circular economy practices.[64] The success of redyeing depends on many factors such as the extent of color removal, fabric condition, and compatibility between the stripped fabric and the selected dye.[41] When properly managed, redyeing not only restores the aesthetic appeal of the material but also extends its life cycle.

6.2. Fiber-to-fiber recycling

In mechanical recycling, decolorized fabrics are shredded into fibers, which are then re-spun into yarns suitable for garments, home textiles, and nonwoven products. When dye residues remain, they often limit the end-use applications of the recycled yarns, as uneven coloration or off-shades restrict the possibility of producing high-quality fabrics. By contrast, clean, dye-free fibers broaden the application range, support consistent product quality, and reduce reliance on blending with virgin fibers. Color-stripped textiles provide a white or near-white feedstock that ensures uniformity in subsequent dyeing or blending processes, thereby enhancing the value and usability of recycled fibers.[64]

Moreover, producing a white recycled feedstock facilitates integration into closed-loop recycling systems, where textile waste can be continuously reprocessed into new textiles without downgrading in quality. This contributes not only to resource efficiency but also to reduced environmental impacts by lowering demand for virgin raw materials and minimizing textile waste disposal.[60] As such, effective color stripping is not merely a preparatory step but a decisive factor in scaling fiber-to-fiber recycling and realizing sustainable textile production.

Chemical recycling routes, such as the Lyocell process, offer a promising pathway for regenerating cellulose from cotton-rich textile waste.[128,129] In this approach, pre-processed textile fibers are dissolved in a suitable ionic liquid such as *N*-methylmorpholine *N*-oxide (NMMO) under controlled conditions to produce a cellulose dope that can be extruded into new Lyocell fibers.[73] However, converting dyed cotton textiles into Lyocell fibers presents two major challenges: (1) bifunctional reactive dyes can form covalent crosslinks between cellulose chains, thereby hindering efficient dissolution in ionic liquids and (2) residual dyes may partially degrade during dissolution, leading to the discoloration of the regenerated fibers. Therefore, the effectiveness of color stripping is particularly important here, as residual dyes and finishes can interfere with dissolution efficiency, dope stability, and the quality of regenerated fibers. Clean, white feedstocks enable better processing and result in regenerated fibers with uniform color, high tenacity, and improved textile performance.

7. Current challenges

The current challenges in the color stripping of dyed PCTW are multifaceted including technical, environmental, economic, and material-related factors. These challenges limit the widespread adoption and efficiency of CS processes in textile recycling and reuse.

7.1. Fiber damage and fabric quality loss

The reactive dyes form covalent bonds with the cellulose fibers, and the fiber can be damaged during the color stripping process due to the use of harsh stripping agents, and consequently, the fabric quality is affected. Cotton fabric (areal density: 166 g m^{-2}) treated with 10 g L^{-1} sodium hydrosulfite and 10 g L^{-1} caustic soda at 100 °C showed a strength loss of up to 10% for 5% shade fabric.[56] A weight reduction of up to 5.99% was observed under the same condition, indicating material degradation. Stripped fabrics exhibited lower pilling resistance than their dyed counterparts, suggesting surface fiber damage.

These results highlight the trade-off between achieving effective dye removal and maintaining fiber quality. Excessive degradation not only weakens the mechanical performance but also reduces the usability of recycled fibers in high-quality applications. Therefore, optimizing stripping conditions to minimize fiber damage while ensuring sufficient color removal is essential for enabling sustainable textile recycling pathways.

7.2. Incomplete color removal

Incomplete color removal during the CS of dyed PCTW is a significant challenge in textile recycling and reprocessing. This occurs due to various factors, including the chemical nature of dyes, their bonding with fibers, and the limitations of conventional stripping methods. Reactive dyes form covalent bonds with cellulose fibers and conventional CS agents fail to break these bonds completely.[56] Consequently, an incomplete color removal scenario was observed during the CS of the dyed PCTW. Moreover, different dyes have varying chemical structures and affinities for fibers and stripping agents may not be effective across all dye types, resulting in incomplete removal.[24] Additionally, inadequate penetration of stripping agents into the fabric can result in partial dye removal. NaOH shows partial removal of reactive dyes from cotton and remaining moieties attached to the –OH group of cellulose.[48]

7.3. Environmental and health concerns

The effluents generated during color stripping contain residual dyes and toxic chemicals like sodium hydrosulfite, hydrogen peroxide, and sodium hypochlorite. These wastewater pollutants can severely affect the environment by increasing chemical and biochemical oxygen demands (COD and BOD), leading to oxygen depletion in aquatic ecosystems and threatening aquatic life.[105] Improper disposal can also contaminate soil, reducing fertility and harming microorganisms, while volatile organic compounds (VOCs) and toxic gases, such as sulfur dioxide, released during the process contribute to air pollution, acid rain, and respiratory issues in workers.

It is important to note that the wastewater generated from color stripping does not necessarily contain higher pollutant loads than conventional textile dyeing and finishing effluents. Textile mills are typically equipped with effluent treatment plants designed to handle high COD/BOD levels, residual dyes, and bleaching agents. Therefore, when properly managed, stripping effluents can be effectively treated using the same infrastructure, without imposing disproportionate environmental burdens. The critical challenge lies less in absolute pollution load and more in ensuring appropriate pH control, oxidation–reduction balancing, and avoidance of hazardous by-products (*e.g.*, AOX or SO_2) during treatment. This perspective highlights that while color stripping introduces specific risks, they remain within the treatable range of existing industrial wastewater management systems.[130,131]

7.4. Lack of standardization

There is no standardized process for color stripping across different dye classes, fiber types, and fabric structures. Multiple color stripping techniques exist, including reductive, oxidative, biological, solvent extraction and photo-catalytic methods. Each method employs different chemicals and conditions, leading to diverse results in terms of color removal efficiency. The absence of standardized procedures means that outcomes can vary significantly between different recycling operations, affecting the quality and consistency of recycled textiles. Owing to the heterogeneous nature of the textile waste (*i.e.*, mix of different fibers and dyes), establishing a standardized CS process is challenging. As we discussed, the CS efficiency is influenced by multiple factors, and a universal solution applicable to all types of textile waste is not viable. However, it is possible to establish standardized methodologies tailored to specific dye classes and fiber types.

7.5. Efficient textile fiber fractionation

A major barrier to large-scale textile recycling is the heterogeneous composition of post-consumer textiles, which are frequently blends of polyester and cotton. Polyester and cotton together account for nearly 80% of global fiber production, and their widespread blending in fabrics (*e.g.*, poly/cotton 65 : 35) complicates end-of-life management. Since no universal color-stripping or recycling method can effectively treat natural and synthetic fibers simultaneously, separation of these two dominant fiber types becomes essential.

Separation itself poses technical and economic hurdles. Conventional manual sorting is labour-intensive and prone to error, while automated systems such as NIR (near-infrared) spectroscopy or advanced optical sorting are costly and not yet widely implemented.[132] Blended textiles pose an even greater challenge: separating polyester and cotton from intimate fiber blends requires either mechanical processes (which can damage fibers and reduce quality) or selective chemical dissolution methods, many of which remain on a pilot or laboratory scale.[133]

The absence of a universal color-stripping approach underscores the importance of polyester–cotton separation. The progress in automated sorting technologies, selective chemical fractionation, and hybrid recycling systems will be critical for overcoming this bottleneck. Achieving efficient separation not only improves color-stripping outcomes but also enhances the quality and economic viability of fiber-to-fiber recycling.

7.6. Regulatory hurdle

Regulatory implementation of color stripping for post-consumer textile waste (PCTW) faces several key challenges. A major hurdle is the classification of textiles under waste regulations, which places them under strict requirements of the European Waste Framework Directive and limits flexible industrial processing.[134]

In addition, chemical safety regulations such as REACH restrict or regulate many of the oxidizing agents, reducing agents, and solvents commonly used in color stripping, increasing compliance complexity on an industrial scale. Another challenge is the uncertain classification of treated textiles and effluents, particularly regarding hazardous substances, which may trigger additional requirements for wastewater treatment and emission control.

There is also a lack of standardized definitions and benchmarks for color stripping processes within recycling frameworks, leading to inconsistencies in regulatory classification as mechanical, chemical, or waste treatment operations.

7.7. Cost

Color stripping introduces an additional processing step in fiber-to-fiber recycling, and this inevitably increases the overall cost of recycling compared to the direct reuse of colored textiles. The costs arise primarily from the consumption of chemicals (*e.g.*, reductive or oxidative bleaching agents), additional energy inputs (heat and agitation), extended processing times, and the need for effluent treatment to handle stripping wastewater. Furthermore, harsher stripping protocols that achieve a higher dye removal efficiency often incur greater operating costs due to higher chemical concentrations and stricter process control requirements.

Thorough techno-economic assessments are required to understand the cost of the color stripping process for high-quality recycling. In particular, when the goal is to produce white feedstock suitable for re-dyeing into any color, stripping costs can significantly affect the economic viability of recycling systems.

Ultimately, while color stripping is essential for enabling closed-loop fiber-to-fiber recycling, its cost contribution remains a barrier to large-scale adoption. Addressing this challenge through process optimization and technology innovation will be key to achieving both economic and environmental sustainability in textile recycling.

8. Future prospects

8.1. Industrial feasibility and economic viability

Current chemical color stripping methods use considerable amounts of harsh chemicals, leading to significant wastewater production that requires costly treatment and raises environmental concerns. Therefore, there is a need to develop eco-friendly CS processes, especially those based on bio-based sources that are safe for both the environment and textile fibers. Non-toxic, biodegradable alternatives to traditional CS agents like sodium hydrosulfite and hypochlorite are increasingly important, as these conventional chemicals can pose risks to human health and the environment. The use of NaOH, a common reagent in pulp bleaching, represents a practical and effective approach for treating cellulosic textile waste. It can be a potential alternative solution for industrial feasibility and economic viability in the color stripping area. The chemicals should also be recovered and reused at the end of CS process to make the process more viable.

8.2. Innovation in AOPs

AOPs are comparatively effective for CS from dyed textiles. However, methods like photocatalysis can use a lot of energy, raising concerns about cost and sustainability. Some AOPs, such as Fenton-based processes, produce iron-rich sludge, which requires proper treatment before disposal. The effectiveness of AOPs also depends on the dye's chemical structure. To improve the efficiency and lower energy use, AOPs can be combined with biological or adsorption-based methods. New catalysts, such as metal–organic frameworks (MOFs) and doped semiconductors, could be potential for better performance across a range of dyes. Process optimization of the targeted CS method can further improve the treatment efficiency and reduce the operational costs.

8.3. Focus on mixed fiber and dye systems

Most CS-related research in the literature focuses on single-fiber and single-dye systems. However, PCTW may contain blended fibers (such as cotton/polyester, polyester/linen, cotton/nylon, polyester/wool, cotton/wool, jute/cotton, wool/silk, cotton/elastane, and polyester/viscose) and a mix of different dye classes. The acid treatment method targets the removal of cotton from a blend, typically by using a mild acid to break down the cellulose fibers. While effective, it comes at the cost of sacrificing the cotton portion of the mix, which is not ideal from both an environmental and a material recovery standpoint. A strong alkaline treatment can be used to break down polyester fibers, but this process also results in the loss of the polyester portion. The use of harsh chemicals in this approach is not only undesirable for material conservation but also raises concerns about its environmental footprint. Both approaches, while effective in selectively separating the fibers, involve sacrificing one part of the blend for the other, making them less desirable from a sustainability and resource efficiency perspective. To improve the overall outcome, research should focus on methods that allow the fibers to be separated more effectively without sacrificing the material value. Additionally, color stripping should be performed on the individual fiber streams (cotton and polyester separately) to achieve the best possible results in both fiber recovery and environmental sustainability.

8.4. Characteristics of the PCTW

The limited number of studies on the characteristics of post-consumer textile waste (PCTW), particularly regarding specific application-based textile, may significantly influence color stripping performance. Unlike textiles intended for industrial use, consumer textiles possess diverse properties that can affect the efficiency of the color stripping process. This represents a major gap in the current literature and highlights the need for further investigation in this area. In addition, the influence of fabric finishes and additives on color stripping should also be studied.

8.5. Color parameter analysis

In most published studies, the CS efficiency has been evaluated based on color strength values (K/S), derived from the Kubelka–Munk theory. While this method provides a numerical indication of dye removal, it often lacks practical clarity in terms of visual appearance. For instance, reported stripping efficiencies of 98–99% may still correspond to fabrics that retain visible coloration, making it challenging to interpret the actual extent of dye removal. In such cases, colorimetric parameters—particularly lightness (L^*) from the CIE $L^*a^*b^*$ color space—and the whiteness index offer valuable complementary metrics. These parameters provide a more direct correlation with the fabric's visual appearance. However, only a limited number of studies have utilized L^* values as a quantitative measure of color removal efficiency. A more comprehensive and standardized assessment of L^* values before and after stripping treatments could serve as a reliable and objective indicator of dye removal. This approach would facilitate meaningful comparisons among different CS methods (*e.g.*, reductive *vs.* oxidative, enzymatic process) and enhance the interpretability of treatment outcomes from both scientific and industrial perspectives.

8.6. Evaluation of stripped fabric properties

Preserving fabric integrity is essential for facilitating textile reuse and redyeing after CS processes. One of the most important indicators of cellulose degradation is the degree of polymerization (DP), which reflects the average length of cellulose chains. Despite its importance, DP has not been frequently addressed in the context of CS research. To ensure that chemical treatments do not irreversibly compromise the cellulose structure, advanced analytical techniques such as capillary viscometry and size exclusion chromatography (SEC) should be employed to monitor changes in DP before and after treatment. In addition to molecular integrity, physical durability must be assessed. Parameters such as weight loss and tensile strength are fundamental indicators of the mechanical robustness of fabric post-stripping. However, comprehensive mechanical evaluations are often missing in existing studies, particularly those investigating the effects of varied stripping conditions, including temperature, pH, treatment duration, and chemical concentration. To address these gaps, future research should adopt a multi-parameter evaluation framework that integrates chemical degradation indicators (*e.g.*, DP and weight loss) with mechanical performance metrics such as tensile strength, burst strength, and elongation at break. This approach would enable a more accurate understanding of the balance between effective dye removal and the preservation of fabric reusability.

8.7. Circular system integration

CS is now treated as a separate process, rather than as part of the larger circular textile system. However, integrating CS into the broader textile recycling chain is important to realize both environmental and economic benefits. CS should be linked directly with downstream processes such as fiber regeneration, re-dyeing, and remanufacturing. Once dyes are removed, fibers return to a more neutral or raw state, making them suitable for either chemical or mechanical recycling, depending on the fiber type. These regenerated fibers can then be re-dyed for reuse and upcycling. The final step could be remanufacturing the materials into new textiles with minimal additional processing. To achieve this, closed-loop systems are needed—where materials are continuously reused with minimal resource loss. It is essential to develop CS methods that preserve fiber quality for multiple reuse cycles.

8.8. Digitalization

The integration of digital tools and Artificial Intelligence (AI) can transform the traditional CS process to the emerging method. Technologies like machine learning (ML), AI, and data modeling offer solutions to improve the efficiency, reduce waste, and lower costs. These tools enable smarter decision-making by analyzing large datasets and allowing real-time adjustments, reducing reliance on trial-and-error methods. AI can predict the effectiveness of CS based on fabric and dye properties. ML models can be trained on historical data, taking into account factors such as fabric type (*e.g.*, cotton, polyester, and blends), dye class and concentration, processing conditions, and stripping agents used. AI and data analytics also enable the real-time monitoring and optimization of important process factors like pH, temperature, dwell time, and chemical dosage. By using IoT sensors and control systems, data can be continuously collected and analyzed throughout the CS process. AI models can then adjust parameters in real time to maintain the optimal efficiency and ensure consistent results.

8.9. Life cycle and environmental impact assessments

Currently, very few studies were found on the life cycle and environmental impact assessments of CS methods. A study examined the environmental impacts of using ozone treatment as an alternative to conventional chemical color stripping for reactive dyed cotton textiles.[81] Using a partial "gate-to-gate" Life Cycle Assessment (LCA), the researchers found that traditional stripping methods require large amounts of chemicals, water, and energy, leading to high environmental impacts and operating costs. In comparison, ozone treatment effectively removed color while reducing the chemical use, wastewater pollution, and overall environmental impact. However, the electricity required for ozone generation remained a significant factor.

Therefore, this is a critical research gap, and it is important to assess the life cycle impacts of different CS methods to identify the most sustainable options. Traditional color-stripping methods have significant environmental consequences. In this context, life cycle assessment (LCA) and environmental impact assessments (EIA) are essential tools for evaluating the sustainability of CS technologies. Moreover, techno-economic analysis (TEA) is required to verify the cost-effectiveness. These tools allow a thorough comparison of methods based on their impact at each stage of their lifecycle, from raw material extraction to end-of-life disposal. Comparative studies should consider factors such as carbon footprint, water usage, chemical toxicity, and end-of-life management for both stripped textiles and residual waste. This will help to take decisions in policy, industry, and consumer behavior.

8.10. Integration of existing infrastructure

The color stripping process has the potential to be integrated into existing industrial infrastructures, including textile dyeing facilities, textile recycling systems, and pulp and paper processing plants. In textile dyeing and finishing mills, color stripping could be incorporated as a pre-treatment or reprocessing step to enable the recovery and reuse of fibers or to prepare post-consumer textile waste (PCTW) for re-dyeing. Within textile recycling systems, it can serve as an intermediate purification step to improve the fiber quality by removing residual dyes and facilitating higher-value mechanical or chemical recycling routes. In pulp and paper infrastructure, especially in processes handling cotton-rich textile waste, color stripping could be adapted as part of fiber recovery and deinking-like operations, enabling more efficient utilization of cellulose-rich fractions from discarded textiles.

9. Conclusion

Color stripping treatment can tackle one of the major challenges in post-consumer textile recycling and enable circularity. Many of the color stripping formulations are based on using strong bleaching agents and oxidants. Therefore, the bleaching will also disinfect the post-consumer textile waste and provide a clean and white feedstock for reuse and recycling. The literature review reveals that various CS methods, such as chemical (acidic, alkaline, oxidative, reductive, microwave-assisted, UV-assisted, solvent-assisted, and advanced oxidation processes) and biological (enzymatic and microbial) stripping, have been explored with varying levels of effectiveness depending on the dye type, fiber blend, and process parameters. Chemical methods, particularly oxidative and reductive agents, remain the most widely applied due to their rapid results but carry risks such as fiber degradation and environmental hazards. There are a few scientific papers on using biological treatment for the color stripping of PCTW. Such treatments can be considered as greener alternatives to harsh chemical bleaching, but the results show very limited and slow color stripping, which needs further investigation. The reaction rates of this process must be significantly improved before they can become competitive on an industrial scale.

Despite substantial progress, we reported several research gaps in this study. There is a lack of comprehensive understanding regarding the synergistic effects of combined CS techniques. Additionally, limited studies assess long-term fiber performance post-stripping and evaluate the environmental footprint of stripping agents. Most of the CS studies failed to report key parameters such as weight loss, tensile strength, and L^*, as illustrated in Tables 2–4. The scalability and economic feasibility of eco-friendly alternatives also remain underexplored. Addressing these gaps is essential to transition from lab-scale experiments to industrial applications that are both sustainable and economically viable. This review has assessed the mechanisms, efficiency, and ecological impacts of current approaches and described the factors influencing performance, such as dye class, fiber type, stripping agent concentration, temperature, time, and pH. By categorizing the findings into chemical, biological, and hybrid types, the review connected each method's potential to the broader goals of textile circularity. The findings reinforce that a tailored CS strategy, responsive to the type of dye–fiber system and ecological considerations, is essential for sustainable textile waste management.

Material flow analysis (MFA) could be essential to know the flow of stripping agents, dyes, materials, energy, and water. To effectively promote circular economy and sustainability objectives, LCA, TEA, and MFA are essential in color stripping processes.

Author contributions

Md. Reazuddin Repon: conceptualization, methodology, data collection, resources, writing – original draft preparation, formal analysis, visualization. Ali Reza Tehrani-Bagha: conceptualization, methodology, data collection, formal analysis, supervision, resources, writing – reviewing and editing.

Conflicts of interest

There are no conflicts to declare.

Data availability

No new primary data were generated or analyzed in this review. The data supporting the results and analysis presented in this review article are derived from previously published works, which have been duly cited in the reference section.

Acknowledgements

This work is supported by the European Union's Horizon Europe Research and Innovation Programme under grant agreement no. 101135372 (Towards Absolute Safe and Sustainable Biobased Textile-BioSusTex) and Business Finland under agreement no. 211968 (Tackling Textile Circularity Challenges-TexirC). The authors also acknowledge the use of AI-based tools for minor language editing or grammatical correction during the preparation of this review article. However, all literature evaluation, analyses, and conclusions presented in this article are entirely the authors' own.

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