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Research article

Transforming waste cellulosic fabric dyed with Reactive Yellow C4GL into value textile by a microwave assisted energy efficient system of color stripping

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ABSTRACT

A million ton of cotton fabric is wasted during cutting process in garment industry as well as in textile dyeing industry due to faulty dyeing. Color stripping of cotton fabric has become a significant challenge in the textile industry because the harsh chemicals used in chemical stripping processes affects the quality of fabric very badly. Conventional stripping methods lead with severe effects due to prolonged treatment time and high chemical concentrations. Recently, microwave-assisted stripping techniques have been emerged as effective alternatives to improve stripping efficiency. In this research, the developed microwave assisted stripping system is improved by the application of Urea, which is utilized as a microwave absorber to further reduce stripping time, temperature, and chemical concentration kept focus on quality parameters of recycled cotton fabric. This study inspects the efficiency of microwave absorber-assisted alkali hydrolysis and reduction in terms of dye-fabric bond cleavage, chromophores removal, chemical consumption, and processing time and compared with sequential stripping, microwave assisted stripping without absorber and conventional methods. The results indicated that microwave absorber-assisted alkali hydrolysis and reduction achieved 90 % stripping efficiency by using lowest concentrations of chemicals, while sequential stripping yielded a stripping efficiency of 96 %. Similarly, microwave absorber assisted methods resulted in minor loss in tear strength and weight. These outputs highlight the superior performance of microwave absorber-assisted techniques, demonstrating their efficiency, novelty, time-saving nature, and reduced damage compared to other methods.

1. Introduction

Textile dyeing is a highly intricate process that requires precision, expertise, and meticulous attention to detail. Slight variations in

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dyeing process variables can lead to unsatisfactory or irregular color outcomes, falling short of consumer requirements. As a result, the need for color stripping or decolorization arises to correct flawed dyeing of cotton fabric, thereby upholding consumer quality expectations [1,2]. Color stripping is a technique for fixing flawed or damaged dyeing that opens the door to the possibility of recycling and reusing fabrics in a variety of tones and hues. After the color is stripped, the fabric may be dyed again in a variety of shades, giving it a new appearance that can be used in a variety of applications. These procedures enable the fabric to be recycled and put to new uses, increasing its lifecycle and lowering industry waste [3,4].

Color stripping can be performed in various ways using different chemicals: reductive color stripping uses chemicals such as Sodium Dithionite, Sodium Sulfide, and Sodium Hydrosulfide [5,6], oxidative stripping is performed by treatment with peroxide, hypochlorite, and caustic soda [7,8]. Ozone, a highly oxidative chemical with an oxidation potential of 2.07 V, may also be used to successfully remove reactive dyes from cotton fabric. Several studies have been carried out by ozone and it has been used in a variety of textile finishing processes, such as the bleaching of cotton, cleaning of disperse-dyed polyester and other fibers treated with polylactic acid, soy, rabbit, and wool. Its strong oxidative properties make it a valuable tool for efficient and versatile dye stripping in the textile industry [9–15]. Moreover the stripping requires specific combinations of reducing agents and stripping assistants, which are determined by the nature of the dye and the fabric type [9].

Biological stripping utilizing white rot fungus and specific enzymes are also emerging methods for the decolorization of woven dyed cotton fabric. However, the process involves an extended treatment duration to attain the desired levels of color removal [16–18]. A combined effect of acid, alkali, and peroxide treatment have been resulted in decolorizing cotton fabric up-to some extant [19]. A combined effect of acid, dithionite, and peroxide treatment has also been used to remove anthraquinone based Reactive Blue 19 dye covalently bonded with cotton [20]. All these stripping methodologies require much concentrated chemicals, long duration, intense energy which comes with good stripping efficiency but damage the fabric quality in terms of its strength and durability.

The scientific community recognizes the stripping process as a highly successful means of recycling and reusing flawed dyed fabric [21]. The raw materials used, the types of dyestuffs, the dyeing and stripping procedures, the types of stripping chemicals used, and operational parameters like temperature and time all have an impact on how efficient the stripping process is. For the recycling process to be successful, the appropriate requirements must meet throughout the stripping phase [2,22–24].

Prior study reveals the microwave assisted sequential stripping methods to decolorize reactive blue black 5 and reactive turquoise CLB from cotton substrate. A combination of Alkali hydrolysis followed by Oxidation and Reduction and, Acid hydrolysis followed by Oxidation and Reduction has been employed to get optimum results in case of stripping efficiency [25]. Sodium citrate serves as a microwave absorber during the stripping process of textiles. Its polar nature and specific dipole moment make it an effective initiator upon exposure to microwaves, generating rapid heat. This microwave absorber aids in increasing hydration and facilitates a microwave-assisted color stripping system, combining alkali hydrolysis and reduction for Reactive Turquoise CLB dyed cotton [26].

In this study, alternative treatments using microwave absorber for removing color from cotton fabric dyed with Reactive Yellow C4GL are explored. Reactive dyes form strong covalent bonds with the fibers during the dyeing process. This ensures excellent color fastness, meaning the dye remains attached to the fabric even after repeated washing and exposure to light. As a result, textiles dyed with Reactive Yellow C4GL maintain their color intensity and brightness over time, enhancing their durability. Therefore, color stripping of fabric dyed with Reactive Yellow C4GL is a difficult task. That's why Reactive Yellow C4GL was chosen.

Microwave absorber-assisted techniques offer several advantages in various applications, such as materials processing, heating, and sensing. However, they also come with certain limitations and challenges that need to be considered for a comprehensive evaluation of their practical implementation. Some of these limitations include: 1- Microwave energy has a limited penetration depth in certain materials, which can restrict its effectiveness for heating or processing thick samples.2-Not all materials are suitable for microwave heating or processing. Some materials may not absorb microwave energy efficiently or may exhibit undesirable reactions under microwave irradiation. This limits the range of materials that can be effectively treated using microwave absorber-assisted techniques.3- Achieving precise temperature control can be challenging with microwave heating. The rapid and non-uniform heating provided by microwaves may lead to temperature gradients within the sample, resulting in uneven heating or processing outcomes. Controlling these temperature gradients and ensuring uniform heating throughout the sample can be technically demanding. Despite these challenges, microwave absorber-assisted techniques hold significant potential for advancing various industrial processes and applications, particularly in fields such as materials science, chemistry, and food processing.

A combination of Microwave absorber along with alkali hydrolysis and reduction is employed and is compared with sequential stripping methods. Both microwave radiation and conventional heating methods were performed in these treatments. The effectiveness of each stripping method was evaluated with the aim of achieving optimal decolorization, which was measured by decreased K/S values and increased stripping percentage. To further assess the stripping process, it was conducted experiments involving redyeing on the stripped fabric. The results clearly demonstrated that the microwave absorber-assisted stripping process outperformed the sequential methods in terms of preserving the fabric's quality. Microwave method require less time, also consumed less energy. Therefore, the microwave-assisted stripping technique proved to be a unique and superior approach for efficiently removing reactive dyes from cotton fabric while minimizing the impact on fabric quality.

2. Experimental

2.1. Materials

Bleached 100 % cotton fabric used throughout the study, was obtained from Noor Fatima Textiles Faisalabad, Pakistan. Reactive Yellow C4GL was obtained from Archroma. The structure of Reactive Yellow C4GL is shown in Fig. 1 is previously reported in literature. All the other chemicals used were of commercial grade, were purchased from Faisalabad, Pakistan.

2.2. Dyeing of cotton with reactive dye

White cotton fabric was dyed with 1 % shade strength of Reactive Yellow C4GL on the basis of fabric (o.w.f) using material to liquor ratio 1:30, applying exhaust dyeing technique in HT dyeing machine. Dyeing solution was prepared as described in Ref. [25]. After dyeing, the dyed fabric was cold and hot washed to remove any unfixed dye.

2.3. Microwave absorber-assisted stripping

Different stripping approaches were employed for microwave absorber assisted stripping including Alkali hydrolysis and Alkaline dithionite reduction. Additionally, the treatments were performed with the aid of microwave absorber (pre- and meta-treatment), and a material-to-liquor ratio of 1:30 was maintained throughout the process. Following each treatment, the samples were thoroughly rinsed with water and air-dried.

2.3.1. Microwave absorber-assisted Alkali hydrolysis

Microwave Absorber-Assisted Alkali hydrolysis of dyed fabric was performed in microwave in two ways.

2.3.1.1. Pre-treatment in Alkali hydrolysis. To prepare the fabric samples for stripping, a pre-treatment was carried out in which the samples were subjected to microwave treatment with constant stirring in the presence of urea at varying concentrations of 10, 20, 30, 40, and 50 g/L for 120 s. Urea is chosen as microwave absorber for its efficient conversion of microwave radiations into heat, inexpensive and high solubility in water facilitating the uniform and rapid distribution of microwave throughout the surface of fabric during stripping process. Subsequently, alkali hydrolysis was performed using 10 g/L NaOH in the microwave for 120 s, after which the samples were thoroughly rinsed with water and air-dried.

2.3.1.2. Meta-treatment in Alkali hydrolysis. In addition, a meta-treatment was also conducted, whereby solutions of urea at varying concentrations of 10, 20, 30, 40, and 50 g/L along with 10 g/L sodium hydroxide were prepared. The fabric samples were then immersed in the solution and subjected to microwave treatment with constant stirring for 120 s.

2.3.2. Microwave Absorber-Assisted Reduction

In the reductive stripping of the dyed fabric, a solution containing 2.5 g/L of sodium dithionite and 2.5 g/L of sodium hydroxide was prepared. Microwave Absorber-Assisted Reduction was also employed in two ways in microwave medium.

2.3.2.1. Pre-treatment in reduction. Prior to the reductive stripping process, fabric samples were pre-treated with varying concentrations of urea solution (10, 20, 30, 40, and 50 g/L) in the microwave for 120 s. The pre-treated samples were then subjected to microwave treatment in an alkaline dithionite solution for 120 s, followed by thorough rinsing with water and air-drying.

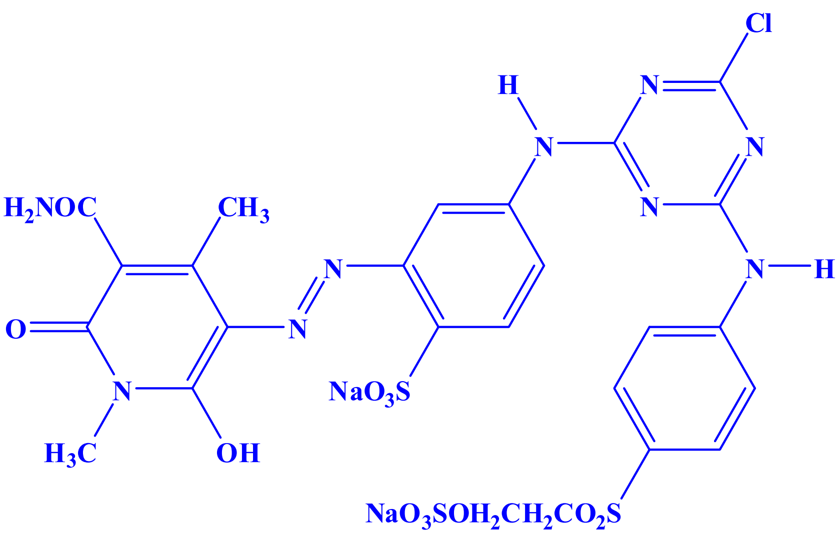


Fig. 1. Structural formula of reactive Yellow C4GL (CAS 129898-77-7). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3.2.2. Meta-treatment in reduction. In the meta-treatment process, solutions were prepared using varying urea concentrations of 10, 20, 30, 40, and 50 g/L along with alkaline dithionite. Fabric samples were then subjected to microwave treatment for 120 s, after which rinsed with water and air-dried.

2.4. Sequential stripping

There are multiple reasons of choosing sequential stripping method.

Each method targets different chemical bonds or properties of the dye molecules. Alkali hydrolysis typically breaks ester or amide bonds, acid hydrolysis targets azo bonds, while oxidative methods may disrupt conjugated systems or introduce reactive groups that aid in subsequent removal steps. Using a combination ensures comprehensive removal of the dye molecules.

Furthermore, Reactive dyes are designed to chemically bond with the fabric, which can make them difficult to remove without causing damage. By using multiple methods, it may be possible to reduce the duration or severity of each treatment, minimizing potential damage to the fabric.

Reactive dyes can form complexes within the fabric, making complete removal challenging. By employing different methods, it increases the likelihood of breaking these complexes and removing residual dye molecules.

Various sequences in Sequential stripping as Alkali Hydrolysis→Oxidation→Reduction, Alkali Hydrolysis→Reduction→Oxidation, Acid Hydrolysis→Oxidation→Reduction and Acid Hydrolysis→Reduction→Oxidation were performed to evaluate their combined effect on dyed fabrics. Out of these combinations optimized results were achieved using Alkali Hydrolysis→Oxidation→Reduction and Acid Hydrolysis→Oxidation→Reduction [25].

2.4.1. Alkali hydrolysis → oxidation → reduction

Microwave-assisted sequential alkali hydrolysis followed by oxidation and reduction was performed in microwave for 120 s each.

2.4.2. Acid hydrolysis → oxidation → reduction

A combination of acid hydrolysis followed by oxidation and reduction was performed in microwave sequentially for 120 s each to evaluate their efficiency.

2.5. Conventional stripping

Dyed fabric was used to decolorize conventionally to evaluate stripping efficiency in comparison with microwave absorber assisted and sequential stripping method.

2.5.1. Alkali hydrolysis

Alkali hydrolysis of dyed fabric was performed with 10 g/L NaOH solution heated conventionally at 90 °C for 60 min with constant stirring.

2.5.2. Reductive stripping

Conventionally, **r**eductive stripping of dyed fabric was performed with 2.5 g/L sodium dithionite and 2.5 g/L NaOH solution and heated at 90 °C for 60 min with constant stirring.

2.6. Analysis

The quality of fabric is assessed considering some key factors. These factors can impact the durability, comfort, and appearance of the fabric.

2.6.1. Colorimetric analysis

Color strength of the stripped and dyed fabric was measured by using the Spectra-Flash Spectrophotometer (SF-600). The stripping percentage was calculated from the K/S value, where the K/S is calculated by Kubelka-Munk equation (1) and it related the reflectance of the fabric with its scattering and absorbance parameters, by applying following formula:

$$\left(\frac{K}{S}\right)_{\lambda}=\frac{(1-R_{\lambda})^{2}}{2R_{\lambda}} \tag{1}$$

Where K and S are the coefficient of absorption and scatter respectively, R is reflectance expressed as a proportional value and λ is the wavelength. The K/S were calculated at λ_{max} of the dyed fabric. The stripping percentage of fabric was calculated by using equation (2):

$$\text{Stripping Percentage}=\frac{\frac{K}{S}\text{value before stripping}-\frac{K}{S}\text{value after stripping}}{\frac{K}{S}\text{value before stripping}}\times 100 \tag{2}$$

2.6.2. FTIR

FT-IR analysis of dyed and stripped fabric was analyzed using U-2001 PerkinElmer Spectrometer, to investigated the removal of dye chromophores completely.

2.6.3. Tear strength

Fabric quality was accessed in case of their tear strength after stripping treatments. The ASTM D1424 Elmendorf based tear test was applied to assess the tear strength of fabric. The Elmendorf test testing machine uses a falling pendulum to tear a fabric specimen. It measures the amount of energy required to perform the tearing operation by measuring the peak follow-through angle of the pendulum after the tearing action. The lower the follow-through angle the more energy has been transferred into tearing the specimen. The machine is setup to provide this tearing energy information in grams-force. The fabric specimen is 76.2 mm (3 in) tall by 101.6 mm (4 in) wide. It is pre-notched with a 12.7 mm (0.5 in) by 12.7 mm (0.5 in) notch at the center of the top of the fabric specimen. The falling pendulum propagates this pre-notch to a complete tear through the center of the fabric specimen.

One of the variables in Elmendorf tear testing is the orientation of the fabric. WARP direction of the fabric is in line with the weaving machine. WAFT direction is perpendicular to the orientation of the weaving machine. Tear strength is the force required to start or to continue to tear a fabric, in either WEFT or WARP direction under specified conditions. Its ability of the fabric to withstand wear and tear, and the amount of stress it can tolerate before it tears or breaks.

2.6.4. Weight loss

Weight loss, to test the quality of fabric, was measured by finding out the difference between the weight of the fabric before and after stripping, as it greatly contributes to look into the fabric's quality. Weight loss percentage is calculated by using equation (3):

$$\text{Weight loss }(\%) = \frac{\text{weight of dyed fabric} - \text{weight of stripped fabric}}{\text{weight of dyed fabric}} \times 100 \tag{3}$$

2.6.5. Re-dyeability of stripped fabric

To ensure complete dye removal after the stripping process, the fabric samples were redyed with 1 % shade of Reactive Yellow C4GL dye. By redyeing, any inconsistencies or defects in the stripping process can be identified.

3. Results and discussion

3.1. Effect of microwave absorber in Alkali hydrolysis

Colorimetric analysis of fabric after stripping treatment involves the measurement of the color of the fabric using a Spectra-Flash Spectrophotometer. This analysis was performed to determine the extent to which the stripping treatment has removed the dye from the fabric. Colorimetric analysis includes measuring various color attributes. By comparing the colorimetric data of the fabric before and after the stripping treatment, the degree of color removal or fading was assessed. The results of colorimetric analysis provided valuable information on the effectiveness of the stripping treatment, and also helped in selecting the appropriate stripping method for a particular fabric or dye.

The analyzed colorimetric analysis of dyed fabric showed K/S value 1.65 which is taken as standard throughout the study. The stripping percentage of treated fabric was calculated using equation (2) which tells that lower the K/S value higher will be the stripping efficiency. Stripping percentage of microwave assisted alkali hydrolysis along with microwave absorber is given in Fig. 2.

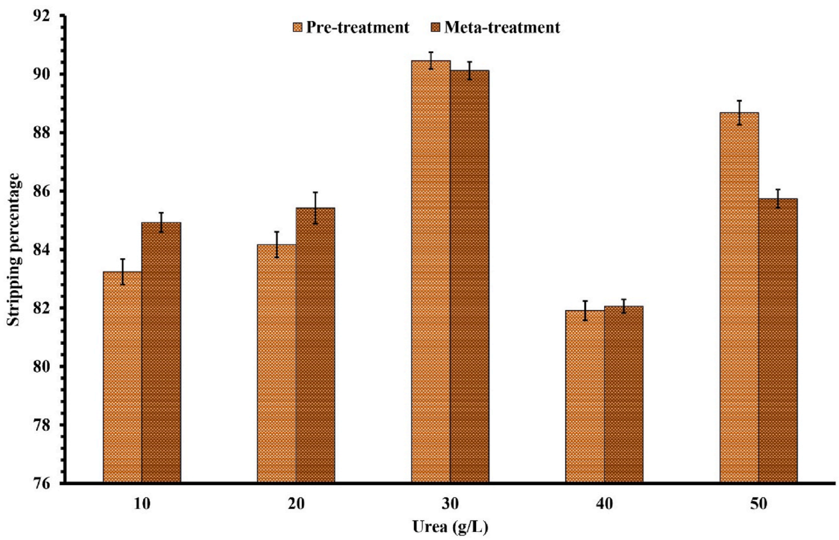


Fig. 2. Stripping percentage of Microwave absorber assisted Alkali hydrolysis.

The stripping percentage increased with the increase in amount of microwave absorber up to some extent. Maximum values of stripping percentage were calculated with 30 g/L urea and 10 g/L NaOH for both pre-treatment and meta-treatment as 90.46 % and 90.12 % respectively.

Microwave absorbers are the materials having ability to absorb microwave radiations and convert them into heat energy. They work as an interaction with electromagnetic radiations as shown in Fig. 3. Their dielectric constant is the key feature to the ability of any microwave absorber. Dielectric materials do not conduct electric energy but store it. When microwaves come in contact with a dielectric material it induces the electric field with in the material and dissipate energy in the form of heat. Materials with high dielectric constant have more ability to absorb microwave radiations. When urea is exposed to microwaves, it rapidly absorbs the energy and undergoes a process known as dielectric heating. In this process, the microwave radiation causes the polar molecules within the urea to rapidly rotate, which generates heat due to molecular friction. The heat generated by this process is then transferred to the surrounding dye molecules in the cotton fabric, causing them to break down and be released from the fabric [27].

Moreover, urea increases the solubility of dyes. Urea applies its hydrotropic effect when introduced in stripping bath, and disrupt the hydrogen bonding network of water resulting in increased solubility of dye molecules. Urea forms hydrogen bonds with both water and the dye molecules and acts as a bridging molecule. By doing so, urea helps to dissolve the dye molecules by absorbing microwave radiations facilitating the swelling of cotton fibers, and mitigates the hydrophobic interactions between the dye and the cotton fibers. This swelling results in significant changes in volume and physical properties while the solid or semisolid portions remain relatively unchanged [28].

Consequently, the dye becomes more dispersed and solubilized, facilitating its removal from the fabric easily. It accelerates the diffusion of dye molecules within the fabric during the stripping process. It acts as a carrier and facilitates the movement of dye molecules away from the cotton fibers, promoting their release into the stripping bath [27,29]. This can result in a more efficient removal of the dye. Furthermore, it lowers the required stripping temperature and extends the temperature range and reduce the risk of fabric damage as it acts as buffering agent and maintain more stable pH level of stripping bath which can help protect the integrity of the cotton fibers and minimize potential damage.

Alkali treatment of dyed fabric resulted in the swelling of cotton fabric removing maximum dye molecules. Energy absorbed by microwave absorber is used to assist the alkali hydrolysis in swelling of cotton fabric, making it easy for alkali to remove most of the dye molecules easily in no time [30]. The impact of alkali treatment on the color strength of reactive dyed fabric was found to be significant, indicating a limited stability of the dye chromophores and their covalent bond with cotton fibers. This can be attributed to the weak acid behavior of the hydroxyl groups on the glucose units of the cellulose backbone in cotton, which can undergo ionization in alkaline environments. The resulting disruption of the covalent bond between the dye and the cotton fibers can cause a moderate decrease in color strength. The extent of this effect is influenced by factors such as the concentration of the microwave absorber, alkali and the properties of the dye and fabric. Overall, these findings highlight the importance of considering alkaline treatments as a factor in the color fastness properties of reactive dyed fabrics [19,20,31,32].

On the other hand, alkali hydrolysis without microwave absorber resulted in stripping percentage of 63.86 % only. This major difference in stripping percentage 90.46 %, 90.12 %, and 63.86 % is only due to the role of microwave absorber, which efficiently assisted the alkali hydrolysis to remove maximum dye molecules from cotton fabric. Conventional alkali hydrolysis of dyed fabric resulted with 62.55 % stripping percentage. There is a major difference stripping percentage with microwave assisted methods and conventional methods clearly reveals the efficiency of microwave radiations over conventional heating. Microwave assisted methods took a few seconds to reach maximum results whereas conventional methods took 60 min giving results in much less stripping efficiency.

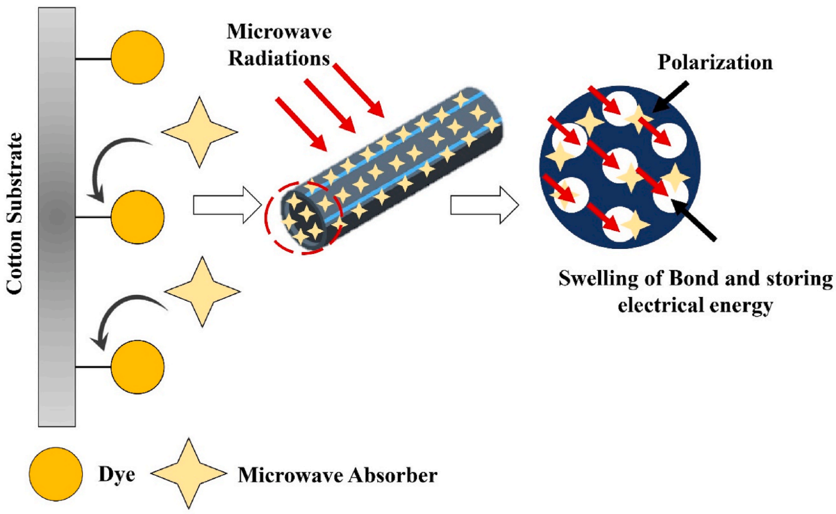


Fig. 3. Interaction of microwave absorber with electromagnetic radiations.

3.2. Effect of microwave absorber in reduction

Stripping percentage of microwave assisted reduction along with microwave absorber is given in Fig. 4.

The stripping percentage increased with the increase in the amount of microwave absorber. Maximum stripping percentage were calculated with 30 g/L urea and 2.5 g/L sodium dithionite for both pre-treatment and meta-treatment as 89.93 % and 90.66 % respectively. Sodium dithionite is a reducing agent, is capable of breaking the chemical bonds between the dye molecules and the fabric, allowing the dye to be removed. Microwave absorber assisted the action of reducing agent by providing enough heat energy sufficient to activate it and facilitate the removal of dye by dye-fabric bond cleavage. The advantage of use of microwave absorber is that it is rapid and efficient, allowing for the maximum removal of dye in a shorter time compared to conventional dye removal processes. Additionally, the use of microwave radiation allows for precise control over the heating process, reducing the risk of damage to the fabric [6,20].

On the other hand, reduction without microwave absorber resulted in stripping percentage of 77.05 % only. This major difference in stripping percentage 89.93 %, 90.66 %, and 77.05 % is only due to the action of microwave absorber, which efficiently assisted the reduction process to remove maximum dye molecules from cotton fabric. Conventional reductive stripping resulted with 81.05 % stripping percentage taking 60 min of treatment [6]. These results clearly show that microwave assisted technique is better over conventional method taking very small amount of time.

Microwave assisted sequential stripping of dyed fabric lower the color strength of the dyed fabric by maximizing it stripping percentage. Stripping percentage of microwave assisted sequential Alkali → Oxidation → Reduction, and Acid → Oxidation → reduction resulted as 96.90 % and 96.74 % respectively whereas, conventional Alkali + Oxidation + Reduction, and Acid + Oxidation + reduction resulted as 95.07 % and 95.94 % respectively. Microwave assisted and conventionally sequential stripping of cotton fabric resulted in removing maximum dye molecules from cotton fabric. There are almost same results in both situations but the difference is in case of treatment time. Microwave assisted sequential method took only 120 s whereas conventional method took 60 min to reach those maximum results. While the difference between microwave absorber assisted and sequential stripping is the amount of chemicals used during process. In microwave absorber assisted stripping process very low amount of chemicals are used in comparison with sequential stripping method. Microwave heating stands out for its notable efficiency, benefiting both reaction duration and product yield. By swiftly raising temperatures and ensuring uniformity throughout the reaction mixture, it participates in remarkable acceleration in chemical reactions. Consequently, products are obtained with heightened yields and within abbreviated timeframes, all while sidestepping unwanted side reactions. The concept of microwave heating operates through the interaction between matter and electromagnetic (EM) radiation. EM radiation consists of alternating electric and magnetic field components, propagating perpendicular to each other. When electric fields interact with charged particles, they induce rotation of the particles, a phenomenon typical in microwave radiation. This rotation causes the charged particles to align themselves based on the polarity of the electric field, resulting in dielectric polarization. As the applied electric fields oscillate, dipoles continuously realign, dissipating energy in the form of heat. This mechanism, known as the “dielectric heating effect,” forms the basis of microwave heating. Microwave radiation induces rotational movement in polar molecules, aligning them according to the polarity of the alternating electric field. As the electric field oscillates, the molecules continue to rotate and realign. In liquids and solids containing polar molecules, this interaction leads to rapid changes in molecular direction due to the concerted force exerted by the electric and magnetic fields. This rapid movement generates internal friction and dielectric loss, manifesting as heat and causing a rapid increase in temperature. This mechanism results in indirect heating. This has prompted its deliberate adoption as an alternative energy source for empowering reaction processes [33,34].

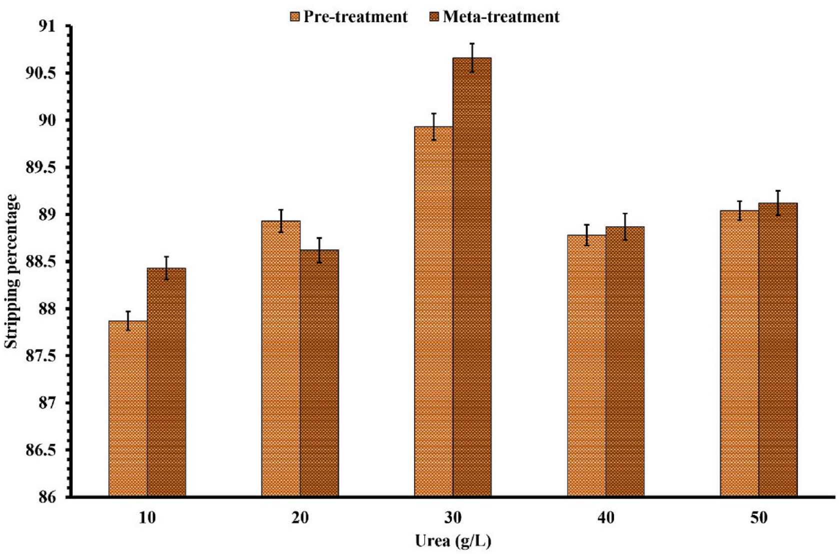


Fig. 4. Stripping percentage of Microwave absorber assisted Reduction.

Moreover, 90 % stripping efficiency was obtained by treating the fabric with alkali hydrolysis only whereas 96 % stripping efficiency was obtained when the fabric was treated back-to-back as acid hydrolysis, oxidative stripping and reductive stripping process. This proves the superiority of microwave absorber assisted color stripping treatment process. The visual presentation of optimized stripped samples is shown in Fig. 5.

3.2.1. FTIR analysis

The obtained results indicate significant color stripping efficiencies under varying conditions, indicating the successful destruction of fixed reactive dye molecules from the cotton substrate using microwave absorber assisted stripping methods. To gain a deeper understanding of the extent of chromophore removal and the fixed dye molecules of Reactive Yellow C4GL, colored cotton sample was subjected to different treatments and analyzed using Fourier-transform infrared (FT-IR) analysis. This analytical technique allows for the investigation of molecular interactions and chemical changes occurring in the samples. The recorded FT-IR spectra, displayed in Fig. 6, provide valuable insights into the structural alterations and functional group modifications that take place during the color stripping process. By examining these spectra, the mechanisms and dynamics of the color stripping reactions can be further elucidated, contributing to a comprehensive understanding of the microwave absorber assisted alkali hydrolysis and reduction efficacy for dye removal from cotton substrates.

The FT-IR spectra of the cotton substrates, which undergo various color stripping methods, exhibited significant differences compared to the reactive-dyed cotton substrate. In Fig. 6, a distinct peak at 3281 cm^{-1} was observed, indicating the presence of O–H stretching vibrations (mO-H) in the cotton substrate chains, as well as a combination of N–H stretching vibrations (mN-H) from the Reactive Yellow C4GL dye molecules that were originally attached to the cotton [35,36]. However, in the FT-IR spectra of the color-stripped cotton substrates, broader absorption bands resulting from the stretching vibrations of O–H (mO-H) and its combination with N–H (mN-H) were evident. Notably, these absorption bands exhibited a shift towards higher wavenumbers 3305 cm^{-1} for alkali hydrolysis as well as reduction. These findings provide compelling evidence of an increased presence of amino groups (-NH_2), and hydroxyl groups (-OH) within the cotton fibers. In the FT-IR spectra the broader and shifted absorption band reveals the modifications in the chemical composition of the cotton substrate after stripping. The increased stretching vibrations associated with O–H and N–H groups indicates changes in intermolecular interactions including hydrogen bonding within the cotton fibers. This alteration is likely a result of the removal of Reactive Yellow C4GL dye molecules from the cotton surface during the color stripping process. Overall, the FT-IR analysis provides valuable insights into the structural modifications occurring within the cotton substrates as a consequence of color stripping, highlighting the presence of amino groups as a significant outcome.

Furthermore, the broadening of the absorption bands also suggests a reduction in hydrogen bond interactions among the imino (–NH–) groups, hydroxyl (–OH) groups, as well as the amino (–NH_2), following color stripping. This decrease can be attributed to potential reduction of the hydroxyl (–OH) groups by microwave absorber assisted sodium dithionite adsorbed onto the cotton surface. Consequently, these factors contribute to the broadening and shifting of the absorption bands associated with hydroxyl (–OH) groups, amino (–NH2) groups, and/or imino (–NH–) groups on the color stripped cotton fabric. In Fig. 6 (a) and (b), absorption peaks at 2880

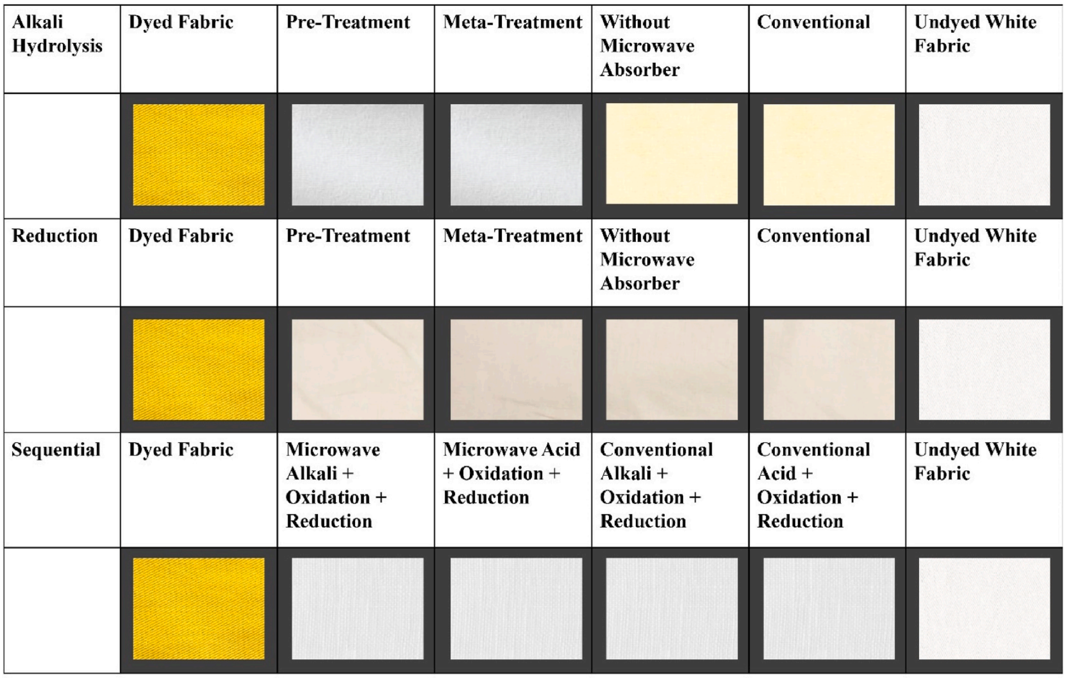


Fig. 5. Visual representation of Dyed, Undyed and Optimized Stripped samples.

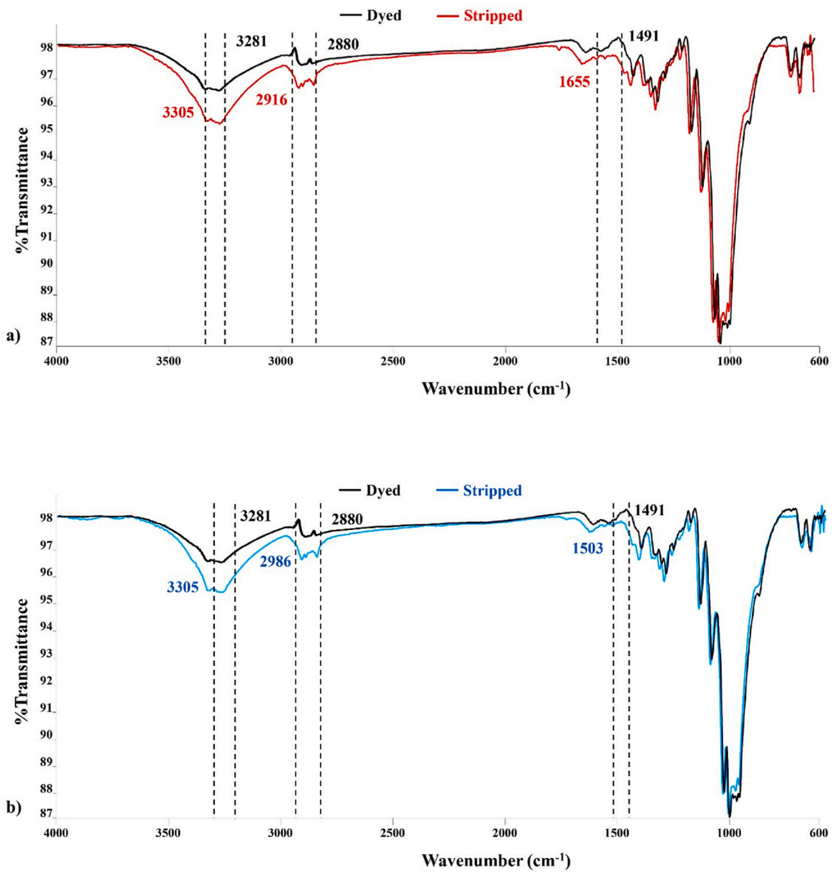
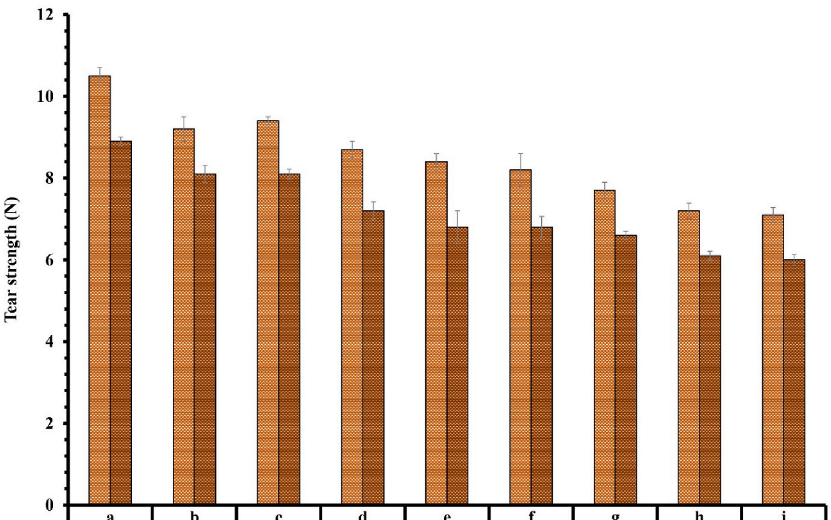


Fig. 6. FTIR spectral analysis of dyed and stripped samples after a) Microwave absorber assisted Alkali Hydrolysis b) Microwave absorber assisted Reduction.



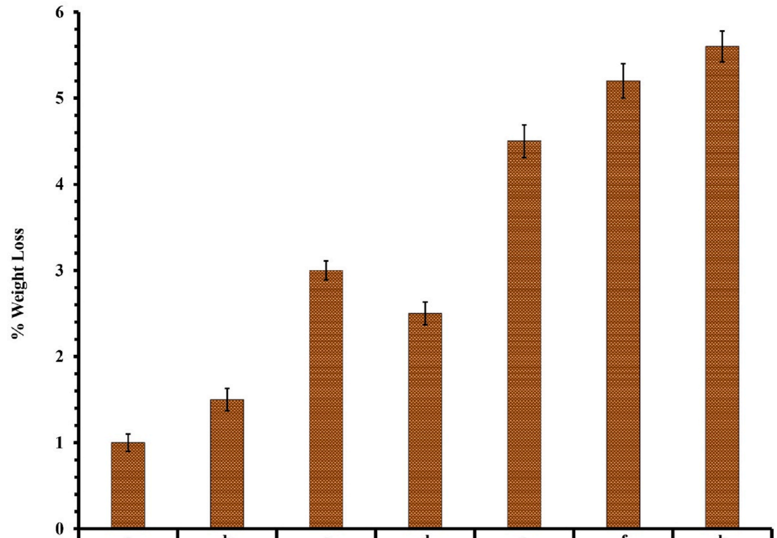
	a	b	c	d	e	f	g	h	i
Warp	10.5	9.2	9.4	8.7	8.4	8.2	7.7	7.2	7.1
Weft	8.9	8.1	8.1	7.2	6.8	6.8	6.6	6.1	6

Fig. 7. Tearing strength of Microwave assisted and conventionally stripped fabrics **a)** Standard **b)** Pre-treatment + Alkali Hydrolysis **c)** Meta-treatment + Alkali Hydrolysis **d)** Pre-treatment + Reduction **e)** Meta-treatment + Reduction **f)** MW Alkali + Oxidation + Reduction **g)** MW Acid + Oxidation + Reduction **h)** Conventional Alkali + Oxidation + Reduction **i)** Conventional Acid + Oxidation + Reduction.

cm^{-1}, corresponding to the symmetrical stretching vibrations of C–H in $–CH_2$- groups, were observed for stripped fabrics [35,36]. However, minimal changes were observed in these absorption bands before and after color stripping as 2916 cm^{-1} and 2986 cm^{-1}, indicating the highly inert nature of $–CH_2$- groups within the color stripping system. This result further suggests the presence of residual $–CH_2$- chains originating from the reactive vinyl sulfone groups of the Reactive Yellow C4GL dye molecules that remained on the stripped substrates. Overall, the widening of the absorption bands and the lack of significant changes in the C–H stretching vibrations indicate modifications in the hydrogen bonding and chemical composition of the cotton fibers during color stripping. A peak at 1491 cm^{-1} was observed in dyed fabric which was due to bending vibrations of N–H group [37,38]. The stripped fabrics showed this peak shifted at higher wavenumber as 1655 cm^{-1} and 1503 cm^{-1} for alkali hydrolysis and reduction respectively. This reveals that there happened some degradation process during stripping. These modifications are likely caused by Alkali hydrolysis and reduction, and the presence of residual reactive groups on the stripped cotton substrates.

3.2.2. *Tear strength*

Tear strength of a fabric refers to its ability to resist tearing or ripping when subjected to a force. Tear strength is an important factor in determining the durability and longevity of the fabric, especially in applications where the fabric is likely to be subjected to significant wear and tear. The tear strength of a fabric can be influenced by factors such as the type of fibers used in the fabric, the weaving pattern, and the finishing treatments applied to the fabric. Tearing strength of standard dyed fabric was measured as 10.5 N and 8.9 N in Warp and Weft directions respectively. It is clear seen from Fig. 7 that microwave absorber assisted stripping of reactively dyed fabric lost minimum strength in comparison with sequential stripping methods. Tear strength values of fabric in both warp and weft wise decreased from 10.5 N to 8.9 N to lower values as the result of use of chemicals during stripping process. While treating the fabric with microwave absorber the tear strength is decreased slightly due to use of less concentrated chemicals for very short time, as compared to sequential stripping process where fabric is treated back-to-back with concentrated chemicals. During conventional stripping process, the tears strength values decreased more than the all-other microwave assisted stripping processes as the fabric is faced much concentrated chemicals for a very long-time span. The tearing strength of the fabric is reduced to 9.2 and 8.1 for the sample b and 9.4 and 8.1 for sample c in both directions after pre-treated and meta treated alkali hydrolysis as alkali hydrolysis involves the breaking of the chemical bonds in the fibers which leads to the fiber degradation. It can also cause the damage to the fibers resulting in the roughness making it more suspectable to the tearing. Pre-treated and meta-treated reduction of the fabric reduced the tearing strength as 8.7 and 7.2 for sample d and, 8.4 and 6.8 for sample e in both directions, respectively. This loss in the tear strength is due to the reductive treatment as it leads to the fiber softening by altering the molecular structure of the fiber and reduce the stiffness of the fibers. During microwave assisted sequential stripping the tearing strength is reduced to 8.2 and 6.8 for sample f, whereas 7.7 and 6.6 for the sample g, this reduction in the tearing strength id due to the repeated treatments of the fabric one after the other. Each stripping step contributes to the weakening of the fibers which leads to the gradual reduction on the fabric strength over successive treatment. Moving to the conventional sequential stripping, there is noted a huge loss in the values as 7.2 and 6.1 for sample h and, 7.1 and 6 for sample i, in both warp and weft directions respectively. During the conventional sequential stripping, the fabric is treated with the chemicals for a very long-time duration for every treatment. Due to the successive treatments leading to increase in the fabric-chemical interaction time, a remarkable loss in the strength in noted in sample h and i (**Figure-7 a-i**).



	a	b	c	d	e	f	h
% Weight Loss	1	1.5	3	2.5	4.5	5.2	5.6

Fig. 8. Percentage weight loss after Microwave assisted and conventional stripping **a)** Pre-treatment + Alkali Hydrolysis **b)** Meta-treatment + Alkali Hydrolysis **c)** Pre-treatment + Reduction **d)** Meta-treatment + Reduction **e)** MW Alkali + Oxidation + Reduction **f)** MW Acid + Oxidation + Reduction **g)** Conventional Alkali + Oxidation + Reduction **h)** Conventional Acid + Oxidation + Reduction.

This difference in the loss of tear strength is due the difference in concentration of chemicals used in Microwave assisted and conventional stripping methods.

3.2.3. *Weight loss*

The quality of stripped fabric was evaluated by measuring percentage weight loss. Fabric weight loss refers to the decrease in fabric weight after subjecting in different stripping treatments like alkali hydrolysis, acid hydrolysis, H_2O_2 based oxidation and alkaline dithionite-based reduction. This loss in weight can be due to the removal of dyes and other chemicals from the fabric or it may be due to the loss of certain structural components. There are various factors which may affect the extent of weight loss including the fabric type, the specific dye or chemical being removed, the concentration of chemicals used, the duration of the treatment, and the treatment conditions. The evaluation of fabric weight loss after stripping treatments is necessary for assessing the effectiveness of the stripping process and understanding its potential impact on the fabric performance and durability. Fig. 8 illustrates the percentage weight loss observed after each treatment. Microwave absorber assisted stripping techniques resulted in small weight loss compared to sequential and conventional stripping methods. Pre-treatment in alkali hydrolysis lost 1 % resulting as more efficient in case of weight loss. Whereas, conventional acid hydrolysis followed by oxidation and reduction resulted with most weight loss of 5.6 %. This can be due to very low concentrations of chemicals in microwave absorber assisted methods, whereas sequential and conventional stripping requires concentrated solutions and long treatment time to achieve efficient results.

3.2.4. *Redyeing of stripped fabric*

Fig. 9 presents a visual representation of the re-dyed fabric's appearance following stripping treatment, employing both microwave absorber assistance and sequential methods. The primary objective of re-dyeing was to assess the removal of all chromophores from the previous dye. Upon completion of the stripping process, the fabric samples were subjected to re-dyeing to evaluate their re-dyeability, with a comparative analysis against a standard sample. The color strength of the fabric subsequent to re-dyeing exhibited exceptional outcomes, suggesting a remarkable elimination of chromophores from the previous dye during the stripping procedure. Table-1 provides the colorimetric data for both the standard fabric and the re-dyed fabrics, enabling comprehensive analysis and comparison (**Figure-9 a-i**).

Microwave absorber-assisted alkali hydrolysis and reduction techniques exhibit similar effectiveness as sequential stripping in breaking down dye-fabric bonds and facilitating the removal of chromophores. The K/S values of redyed fabric, following alkali hydrolysis with pre-treatment and meta-treatment, were measured at 2.09 and 1.97 respectively. Additionally, reduction treatments with pre-treatment and meta-treatment yielded K/S values of 2.11 and 2.29 respectively. Comparatively, microwave-assisted sequential alkali → oxidation → reduction, and acid → oxidation → reduction demonstrated K/S values of 2.12 and 2.02 respectively, while conventional methods showed K/S values of 2.1 and 1.87 for redyed samples. The findings clearly indicate that microwave absorber-assisted alkali hydrolysis, reductive stripping demonstrated greater K/S values when they were redyed, while sequential stripping techniques in microwave and conventional came with lower K/S value in comparison with earlier ones, Overall, redyeing after all these stripping methods outperform standard fabric in terms of K/S values. Microwave absorber-assisted techniques are proven to be superior methods over sequential stripping methods for effectively stripping reactive dye from cotton fabric while utilizing lower concentrations of chemicals.

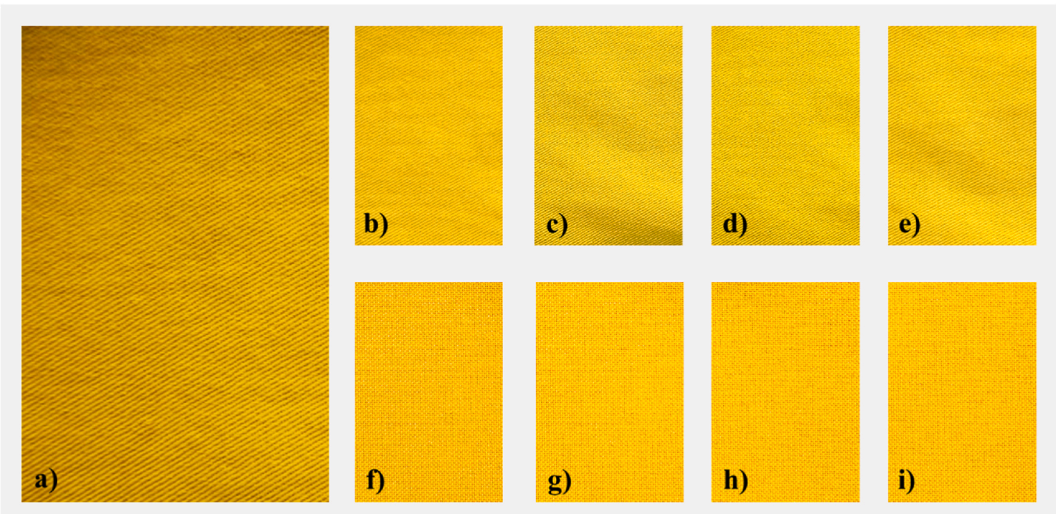


Fig. 9. Visual representation of redyed fabrics after stripping treatments **a)** Standard **b)** Pre-treatment + Alkali Hydrolysis **c)** Meta-treatment + Alkali Hydrolysis **d)** Pre-treatment + Reduction **e)** Meta-treatment + Reduction **f)** MW Alkali + Oxidation + Reduction **g)** MW Acid + Oxidation + Reduction **h)** Conventional Alkali + Oxidation + Reduction **i)** Conventional Acid + Oxidation + Reduction.

Table 1
Comparison of K/S values of Redyed fabric after stripping.

Sr.	Treatment	K/S of Standard Fabric	K/S of Redyed Fabric
1	Pre-treatment in Alkali Hydrolysis	1.65	2.09
2	Meta-treatment in Alkali hydrolysis		1.97
3	Pre-treatment in Reduction		2.11
4	Meta-treatment in Reduction		2.29
5	Microwave Assisted Alkali Hydrolysis + Oxidation + Reduction		2.12
6	Microwave Assisted Acid Hydrolysis + Oxidation + Reduction		2.02
7	Conventional Alkali Hydrolysis + Oxidation + Reduction		2.1
8	Conventional Acid Hydrolysis + Oxidation + Reduction		1.87

4. Conclusion

In conclusion, the study demonstrates that microwave absorber-assisted stripping techniques outperform microwave-assisted sequential and conventional stripping methods in terms of chemical concentration and time efficiency:

- By utilizing microwave absorbers (urea), the breakdown of dye-fabric bonds is achieved effectively, resulting in the removal of chromophores from the fabric. The obtained K/S values for redyed fabric after microwave absorber-assisted alkali hydrolysis and reductive stripping surpassed those achieved through microwave-assisted sequential stripping, indicating superior dye removal.
- Additionally, the microwave absorber-assisted techniques consumed lower concentrations of chemicals, reducing the environmental impact and potential health risks associated with concentrated chemical usage also the quality of the cotton fabric was retained.
- The microwave absorber-assisted methods exhibited faster stripping times, suggesting increased process efficiency. Therefore, microwave absorber-assisted stripping techniques emerge as the preferred approach, offering a dual advantage of reduced chemical consumption and shorter processing time compared to microwave-assisted sequential stripping methods.
- Future research could explore the scalability and practical implementation of microwave absorber-assisted stripping techniques in industrial settings. Investigating the cost-effectiveness and feasibility of integrating microwave absorbers into existing textile processing equipment would be valuable. Moreover, the environmental impact of microwave absorber-assisted techniques could be comprehensively assessed through life cycle analysis studies, considering factors such as energy consumption, chemical usage, and waste generation. This would provide valuable insights into the overall sustainability of these methods compared to conventional approaches.

Data and code availability

Not Applicable.

Ethical approval

Not Applicable.

CRediT authorship contribution statement

Anam Akhtar: Writing – original draft, Methodology, Data curation. **Mubashar Alam:** Writing – original draft, Validation, Investigation, Formal analysis. **Sadia Noureen:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Shaukat Ali:** Supervision, Resources, Project administration, Conceptualization. **Adina Tehreem Tahir:** Methodology, Investigation. **Aiman Shoukat:** Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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