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Ultrasound-assisted sustainable and energy efficient pre-treatments, dyeing, and finishing of textiles – A comprehensive review

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ABSTRACT

Traditional pre-treatments, dyeing, and finishing of textiles have high environmental impacts because of the high usage of energy, water, and chemicals, and the production of effluent containing leftover harmful dyes and chemicals. In this comprehensive review article, the advances in applications of ultrasound in the sustainable pre-treatments, dyeing, and finishing of various types of textiles to reduce their environmental impacts are discussed and the advantages/disadvantages of such processes are outlined. The enhancement of pre-treatment, dyeing, and finishing performances along with a reduction in processing time, temperatures, and chemical usage by applying sonication has been summarized. The effect of sonication on dye adsorption isotherms, adsorption kinetics, and dye adsorption mechanisms of various fibers dyed with different dyes are also discussed. Moreover, challenges and prospects for ultrasound in the chemical processing of textiles are projected. The application of ultrasound considerably reduces processing time, temperature, and chemical usage and also enables low-liquor ratio dyeing of textiles. However, the lack of availability of convincing data on savings of energy, water, and chemical usage of using ultrasound in actual industrial production machinery is one of the key reasons that the textile industry is slow in adopting sonochemical processes.

1. Introduction

The conversion of fibers to finished fabrics requires a series of chemical treatments, such as pre-treatments (e.g., desizing, scouring, and bleaching), dyeing, and finishing. The processing route depends on the types of fibers and their applications. The desizing treatment is necessary only for the woven fabrics as sizing is needed for warp yarns for weaving. Cellulosic fabrics except the regenerated cellulose require robust pre-treatments before dyeing and finishing. For regenerated cellulose fibers, desizing is needed if woven fabrics are produced. Woven fabrics made from wool and synthetic fibers usually do not need desizing as sizing is not needed for warp yarns because of fibers' good extensibility. Raw fibers of animal origin, such as wool, contain a high level of grease (lanolin), suint, dirt, and pesticides. They are removed by scouring in a loose fiber state at low temperatures and mild conditions but woven wool fabrics also need light scouring and bleaching to remove oils and antistatic agents present in the fabric, and to decolorize natural pigments present in wool fibers. Synthetic fibers, such as polyester, nylon, and acrylic, need no scouring and bleaching as they need only washing with detergents to remove the antistatic agents and lubricating oils applied during their conversion to yarns by spinning. Dyeing is also an energy-intensive process as most of the dyeing is carried out at the boil for a long time depending on the depth of

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shade required. Aqueous dyeing produces effluent containing not only dyes but also dispersing agents, wetting agents, salts, and other textile auxiliaries (Hassan and Shao, 2015).

These traditional pre-treatment, dyeing, and finishing processes are energy-intensive and use a high volume of water ultimately producing a high volume of effluent containing dyes, alkalis/acids, detergents, salts, enzymes, finishing agents, and other chemical auxiliaries (Hassan and Hawkyard, 2002). To improve the sustainability of textile products, it is necessary to reduce the energy, water, and chemical usage in their processing to reduce production costs and environmental footprint. The energy savings can be realized by treating the textile materials at a low temperature and low liquor ratio or a shorter time, but they have various demerits including uneven pre-treatments, uneven dyeing, ring dyeing, and also decreased colorfastness to washing due to agglomeration of dye molecules and their poor diffusion into fibers. Ultrasound-based pre-treatments, dyeing, and finishing have been studied as an alternative to conventional methods due to their ability to accelerate the mass transfer of dyes and chemicals. Cavitation by sonication removes dirt and other impurities from the surface of the fiber, breaks down aggregation of dye molecules and permits nanoparticle-based finishing, and tremendously increases the mass transfer of dyes and chemicals from the treatment bath to the fiber surface and diffusion of dyes and chemicals into textile fibers. It also increases the rate of reaction between chemicals and textile fibers with savings in energy and processing time. Ultrasound can surely play a positive role in improving the sustainability of textile products.

Several review articles have been published over the years but they covered only selective sonochemical treatments of selective fibers, such as sonicated enzymatic treatment of cotton fabrics (Andreaus et al., 2019), synthesis of nanoparticles and their application on textiles (Harifi and Montazer, 2015), application of various radiation treatments including ultrasound in dyeing and finishing (Shahid-Ul-Islam and Mohammad, 2015), dyeing and decolorization of dyes (Vajnhandl and Majcen Le Marechal, 2005), and effluent treatment by adsorption (Mary Ealias and Saravanakumar, 2019). On the other hand, this comprehensive review article critically reviews the advances that have been made over the years in the applications of ultrasound to reduce energy, chemicals, and water usage in desizing, scouring, bleaching, mercerization, shrink-resist treatment, dyeing, and finishing processes of various textile fibers. The effect of sonication on dye uptake, dye adsorption isotherms, adsorption kinetics, and the mechanism of dye adsorption by textile fibers are also critically discussed. The challenges of implementation of sonochemical processing in the textile industry and prospects have been outlined.

2. What is ultrasound?

Sound with a frequency beyond the human hearing range, i.e., greater than 20 kHz is considered ultrasound, which forms ultrasonic waves and cavitation in a liquid causing extreme effects, which is a multi-scale and multi-physics phenomenon (Tsuda et al., 2008; Mirihanage et al., 2016). The nature of cavitation can be divided into two categories, stable and transient cavitation, which is illustrated in Fig. 1 (Rubio et al., 2016; Xu et al., 2016). In the case of stable cavitation, the bubble oscillates with the sound field for several cycles or more of the applied wave field. At this time, the bubble may grow due to a gas bubble driven into oscillation by an appropriate acoustic field, and when the bubble reaches its resonance radius, it collapses. As the liquids are sonicated at high intensities, sound waves propagate into liquid media in alternating high-pressure compression and low-pressure expansion cycles. In the low-pressure cycle, the high-intensity ultrasonic waves produce many microscopic vacuum bubbles, those bubbles explode causing in the high-pressure cycle causing localized high temperature and high-pressure shock waves and severe shear force that can disintegrate agglomerated particles and can cause milling, mixing, and disintegration of materials. Cavitation makes many sonochemical reactions possible, which produce local high temperatures (5500 °C or more) and local pressures (up to 500 MPa), enough to overcome the activation energy of a reaction (Easson et al., 2018). The sonochemical reaction of water can generate several chemical species (hydrogen peroxide, superoxide, hydroxyl radicals, etc.) within collapsing bubbles that are responsible for various redox reactions (Bhangu and Ashokkumar, 2016). In addition, cavitation can cause the fragmentation of reagents into reactive free radicals that can catalyze a reaction by providing another pathway for the target reaction to proceed (Thompson and Doraiswamy, 1999). Ultrasonic transducers are used for the sonochemical reaction that converts electrical energy into an ultrasonic vibration. In the case of transient

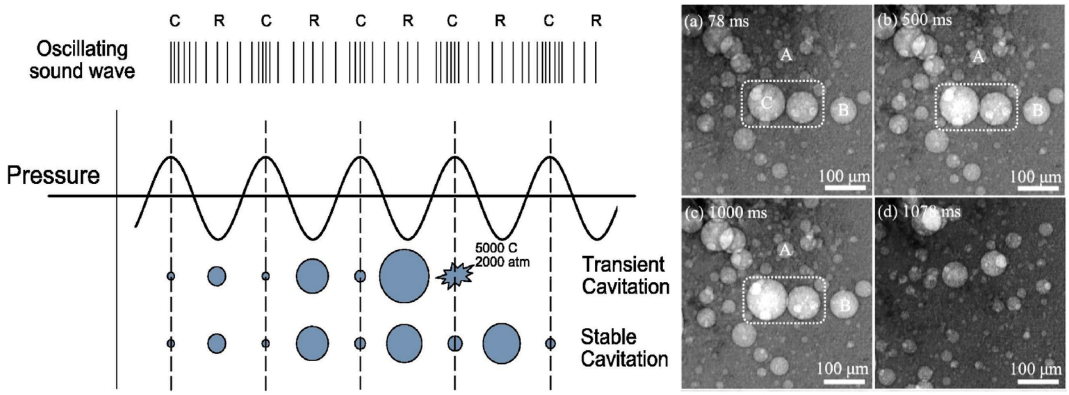

Fig. 1. Illustration of stable cavitation bubbles and the lifetime of transient cavitation bubbles in relation to an oscillating sound wave (left), and typical behavior of cavitation bubbles under sonication. Reprinted with permission from Refs. (Rubio et al., 2016; Xu et al., 2016).

cavitation, an oscillating bubble can collapse in one or at most only a few acoustic cycles, and the transient cavitation causes higher peak pressures and temperatures in the collapsing bubbles.

The formation of cavitation bubbles under sonication also was observed in the case of molten metals at high temperatures. Fig. 1 shows the typical appearance of cavitation bubbles formed during one cycle of 1000 ms when Al–Cu alloy was melted at 600 °C in a boron nitride crucible under an ultrasound field by capturing a series of radiographic images via in situ synchrotron radiation X-ray imaging (Xu et al., 2016). Fig. 1(a) shows the cavitation bubbles generated under the ultrasound field 78 ms after the start of sonication. Fig. 1(b) shows that sonication enabled a steady growth of cavitation bubble that stopped at 500 ms and became steady until 1000 ms as shown in Fig. 1(c). When a new cycle starts after 1000 ms, the existing bubbles disappear and new cavitation bubbles formed at 78 ms in the new cycle, which is shown in Fig. 1 (d).

3. Construction of ultrasonic transducer

Ultrasonic transducers are used for creating ultrasound and most of the ultrasonic transducers have a frequency from 20 kHz to a few MHz. The construction of an ultrasonic transducer is presented by a schematic diagram in Fig. 2. An ultrasonic transducer is consisting of an active element, a backing, and a wear plate. The active element is a piezoelectric element or a single crystal substance that converts electrical energy into ultrasonic energy. The piezoelectric element made of ceramic lead-zirconate-titanate or aluminum nitride is at the center of the transducer that can tolerate compressions and rarefactions to convert electrical energy to ultrasonic energy or vice versa. The backing is made of a dense substance that absorbs energy emitted from the back of the piezoelectric element and it is necessary to control the acoustic impedance of the backing substance of the element. The wear plate is used as a support for the piezoelectric element with the backing substance which protects the piezoelectric element from wear and corrosion. The wear plate works as an acoustic converter between the element and the target (e.g., water). When an electrical signal is sent to a piezoelectric element or crystal, it starts vibrating at a designed frequency and converts electrical energy into ultrasonic energy (Uchino and Nakamura, 2012).

4. State of the art of ultrasound in textile chemical processing

The use of ultrasound in textile chemical processing offers many potential advantages, such as energy savings, reduced chemical usage, reduced processing times, environmental improvements, process enhancement, improvement in product quality, and overall lower processing costs compared to traditional processes. The application of ultrasound in the chemical processing of various fibers and their role in improving process efficiency and reducing environmental impacts are described below.

4.1. Sonicated pre-treatment of fabrics made of various fibers

Cavitation formed by sonication is powerful enough to remove dirt and other loosely-held contaminants from various fibers and also can degrade the scales of wool fibers (Li et al., 2011; Hurren et al., 2008). Therefore, sonication has been extensively studied for the pre-treatments of textiles to improve their performance and reduce energy and chemical usage.

4.1.1. Sonicated desizing and mechanism

For the manufacturing of woven fabrics, the warp yarns are sized with polysaccharides and other polymeric compounds to strengthen them and enhance their extensibility so that they do not break at the time of frequent shedding that occurs during weaving. After weaving, these sizing agents need to be removed so that they do not affect the fabric's further processing and cause uneven treatments including uneven dyeing. The removal of the sizing agent is implemented by a process called desizing and enzymatic desizing is the most popular desizing method. Amylases are the most popular enzymes for the desizing of cellulosic fabrics that have un-

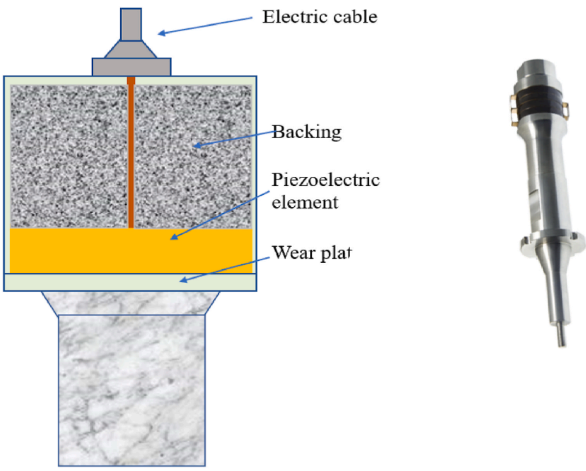

Fig. 2. Schematic diagram of an ultrasonic transducer.

dergone sizing with starches as they degrade starch to water-soluble amylose and amylopectin which can be easily removed by washing. Ultrasound irradiation has been studied for the desizing of cotton fabric to accelerate desizing efficiency using enzymatic and chemical bleaching agents. The formation and collapse of bubbles formed by ultrasonic sound waves in the aqueous desizing bath are generally considered responsible for most of the ultrasound's physicochemical effects in solid/liquid or liquid/liquid systems. The powerful agitation of the liquid border layer caused by cavitation substantially improves the transport of bulky enzyme molecules toward the fiber surface and increases the degradation of the sizing agent (Yachmenev and E.JBlanchard, 2004; Abou-Okeil et al., 2010). It is commonly perceived that powerful shock waves produced by the collapse of cavitation bubbles will severely damage and inactivate the sensitive and complex structure of enzyme macromolecules. However, it was reported that enzymes and microorganisms had high resistance to ultrasound. Yachmenev et al. studied the pre-treatment of greige cotton fabric with acidic (Viscozyme) and alkaline (Bioprep 3000) pectinase in a reactor fitted with ultrasonic transducers of two different frequencies (16 and 20 kHz) and found that sonication did not affect the enzyme activity (Yachmenev and E.JBlanchard, 2004). The introduction of ultrasonic energy during enzymatic bio-processing of cotton resulted in improvement in pre-treatment efficiency and 15 min treatment halved the wicking time. Similarly, sonicated desizing of cotton fabrics with amylase in an ultrasonic bath of 49 kHz frequency and 200 W power increased the catalytic activity of the enzyme and halved the time required for desizing and reduced the treatment temperature by 10 °C with substantial energy and cost savings (Wang et al., 2012; Hao et al., 2013). Thakore and Abate studied sonicated enzymatic desizing of cotton fabric in an ultrasonic bath fitted with ultrasonic transducers of 53 KHz frequency and 50 W output power, which reduced the requirement of enzyme concentration and treatment time by 75% compared to non-sonicated desizing without compromising the desizing performance with huge savings in energy and chemicals (Thakore and Abate, 2017).

The mechanism of sonicated desizing is quite complex. The key mechanism may include the accelerated and efficient transfer of enzymes to the surface of fibers, quick adsorption of enzymes into fibers, accelerated hydrolytic degradation of sizing agents by enzymes, and faster removal of loosened sizing agents from the fiber surface due to vibrations created by sonication (Wang et al., 2012; Hao et al., 2013). Overall, the sonicated enzymatic desizing method was found highly effective in reducing treatment time and temperature.

4.1.2. Scouring

Cellulosic fibers, especially bast fibers, contain lignin, hemicellulose, and processing aids, such as lubricating oils, that are used during the spinning of fibers to make yarns. They need to be removed before dyeing otherwise they may cause uneven dyeing. In the case of cellulosic fibers, scouring is carried out with a cocktail of alkali, detergent, and wetting agent at the boiling temperature but for protein fibers (such as wool), it is carried out at milder conditions, i.e., at lower temperatures and weakly alkaline conditions to protect the fibers from alkali-induced degradation. The synthetic fibers mainly need washing with a detergent to remove the dirt, lubricating oil, and antistatic agents present in them. Ultrasound has also been studied for the scouring of various types of fiber including jute (Patil et al., 2023; Hassan and Saifullah, 2018), wool (Czaplicki et al., 2021; Bahtiyari and Duran, 2013), cotton (Easson et al., 2018; Agrawal et al., 2010), and flax (Fakin et al., 2006). Mild alkali treatment of flax and hemp fibers under sonication showed no change in fiber fineness (Borsa et al., 2016) but was found beneficial for the removal of hemicellulose, soluble lignin, and pectin from them (Sirghie et al., 2015). The sonicated aqueous scouring of flax, hemp, and coir showed only the removal of hemicellulose but not of lignin and pectin (Renouard et al., 2014). Similarly, the sonicated scouring of loose wool fibers with enzyme considerably modified the fiber surface with enhanced dyeability but had a negligible effect on fiber bending and abrasion resistance (Pan et al., 2018a). With the introduction of ultrasound to 5-bowl loose wool scouring using conventional wool scouring chemicals, a 25% reduction in chemical and energy consumption, and time was achieved (Kadam et al., 2013). The pilot-scale scouring of wool fibers with a typical dosage of detergent and alkali on a 6-bowl scouring machine with ultrasonic transducers retrofitted in the second bowl showed an increase in the whiteness and a decrease in yellowness of fiber and the scoured fibers had less residual grease compared to the non-sonicated treatment (Li et al., 2014). On the other hand, sonicated scouring of cotton slivers with pectinase enzyme followed by ozone bleaching enhanced the hydrophilicity of fibers that showed enhanced absorption of polyphenolic pomegranate peel and green tea-derived natural dyes in the subsequent dyeing operation (Erdem and İbrahim Bahtiyari, 2018). In natural silk yarns extracted from cocoons of *Bombyx mori*, two fibroin filaments are bonded together by a gummy protein substance called sericin, and it is removed by degumming (scouring) with detergent at mild alkaline conditions to separate the two filaments. Sonicated degumming of silk using enzymes and soap was studied to enhance the degumming efficiency (Wang et al., 2019; Mahmoodi et al., 2010; Yuksek et al., 2012). Sonicated enzymatic degumming with papain at 60 °C for 60 min produced the best degumming performance as the whiteness index reached 92 with reasonable weight loss (Wang et al., 2019). Sonicated degumming with alcalase provided the lowest tensile strength loss (Mahmoodi et al., 2010) but degumming with natural turpentine soap increased the tensile strength and whiteness index to 73.0 and 7.16 cN/tex (Yuksek et al., 2012). The scouring of silk and wool fibers under sonication helps the scouring liquor to penetrate through the intersection points of fibers and yarns in a fabric providing a uniform and efficient removal of sericin and helping in uniform dyeing and finishing of their fabrics in the subsequent steps (Pan et al., 2018a; Kadam et al., 2013; Yuksek et al., 2012).

4.1.3. Bleaching

Sonication of water also produces a very small amount of hydrogen peroxide that can help in bleaching and decolorizing natural pigments present in various textile fibers but high-power ultrasound can produce hydroxyl radicals from the produced peroxide that can damage fibers and degrade enzymes and other chemicals including dyes. Ultrasound has been studied for the bio-bleaching of cotton fabric with glucose oxidase (Davulcu et al., 2014), and linen fabric with laccase/hydrogen peroxide (H_2O_2) (Li et al., 2011). The sonicated bleaching with glucose oxidase improved the whiteness index of the fabric from 59.9 to 75.6 due to the enzymatic generation of H_2O_2, which helped in bleaching. In the sonicated bleaching of linen fabric with laccase/H_2O_2, the bleaching efficiency (lightness or L^* value of fabric) increased with an increase in ultrasound power until 150 W, and beyond no further increase in bleaching efficiency was observed. However, the tensile strength decreased with an increase in ultrasound power (Abou-Okeil et al., 2010). The sonicated bleaching of linen fabric was also studied with potassium permanganate ($KMnO_4$)/oxalic acid, and $KMnO_4$/citric acid. However, they are impractical for industrial treatment as both $KMnO_4$ and oxalic acid are very toxic to aquatic life with long-lasting effects (Hebeish et al., 2011). Only the $KMnO_4$/citric acid bleaching after 10 min of treatment slightly increased the whiteness of the fabric, which decreased for longer treatment time and considerably decreased the strength of the fabric. $KMnO_4$/oxalic acid bleaching decreased the whiteness index but showed lower strength loss compared to $KMnO_4$/citric acid bleaching. Bahtiyari et al. found that sonicated peroxide bleaching of wool fabric produced better bleaching performance with higher hydrophilicity compared to conventional peroxide bleaching (Bahtiyari et al., 2012). It was reported that sonicated ozone bleaching of cotton fabric at 30 °C for 30 min produced a similar level of whiteness of the fabric bleached at 60 °C for 90 min with a considerable decrease in processing time and COD of the produced effluent (Eren et al., 2014). Farooq et al. also found a similar effect for the sonicated bleaching of cotton fabric with peroxide (Farooq et al., 2013). The cotton fabric bleached with glucose peroxidase under sonication produced similar whiteness compared to the fabric bleached by traditional peroxide bleaching but at a much lower temperature (Yuksek et al., 2012). However, the sonicated bleaching of flax showed no increase in the whiteness of the fiber, but the color and luster improved (Andrassy et al., 2005). When compared with conventional methods, combined sonicated laccase-hydrogen peroxide bleaching improved the whiteness at lower energy and increased peroxide usage resulting in cost reduction. The sonochemical bleaching of cotton, fabric with laccase provided bleaching performance like conventional peroxide bleaching but at a shorter treatment time (Basto et al., 2007). Ultrasound-assisted bleaching of cotton fabric was studied on a pilot-scale unit with hydrogen peroxide and laccase using a combination of low-frequency high-power (22 kHz and 2.1 kW) and high-frequency low-power (850 kHz and 400 W) ultrasonic transducers, which enhanced the bleaching action of the oxidants and enhanced hydrophilicity and whiteness index with considerable savings in energy and process cost (Gonçalves et al., 2014a). Gonçalves et al. studied pilot-scale bleaching of cotton fabric with laccase/hydrogen peroxide and managed to reduce the treatment temperature to 70 °C but found that no reduction in enzyme usage was possible (Gonçalves et al., 2014b).

4.1.4. *Combined desizing, scouring, and bleaching*

Perincek and Duran studied the combined ultrasound-assisted desizing and scouring of linen fabric with laccase and pectinase enzymes using different concentrations of enzymes, treatment temperatures, and times (Perincek and Duran, 2016). The combined desizing and scouring under sonication considerably increased the desizing and scouring efficiency with huge savings in cost, energy, and time. The sequential ozone gas treatment of loom-state cotton fabric followed by sonicated washing without using any other chemicals provided improved hydrophilicity, a high degree of desizing and whiteness index like the cotton fabric desized with enzyme, scoured with alkali//detergent and bleached with hydrogen peroxide by the conventional methods (Benli and Bahtiyari, 2015). The spandex-containing cotton fabric combined scoured and bleached with peracetic acid (PAA) and tetraacetylethylenediamine (TAED) at 40 °C under sonication showed a similar whiteness index but increased hydrophilicity and dyeability compared to the fabric conventionally scoured and bleached at 60 °C without sonication (Li et al., 2020). Combined sonochemical scouring and bleaching of jute fabric showed considerably higher whiteness index and weight loss compared to the conventionally scoured and bleached jute fabric at the same conditions (Patil et al., 2023).

4.1.5. *Mercerization of cellulosic fabrics*

In the mercerization process, cotton fabrics are treated with a high concentration of alkali (20–30% w/v NaOH) at room temperature, which causes swelling of fiber resulting in making the fiber surface smooth and lustrous. Mercerization also increases the dye uptake producing a deeper shade compared to the non-mercerized cotton fabrics. The application of ultrasound in cotton fabric mercerization considerably reduces the alkali (NaOH) consumption (Khajavi et al., 2015) reducing the processing cost and increasing the conversion of cellulose I to cellulose II up to 71% and 61% for slack and under tension conditions respectively (Khajavi et al., 2013).

4.1.6. *Effect of sonication on shrink-resistance of wool fabrics*

The shrinkage of wool fabrics occurs due to the scaly structure of wool fibers. During laundering at moist and warm conditions, due to friction and cloth movement, wool fibers migrate and scales of wool fibers interlock with the scales of the neighboring wool fibers through a rachet-like mechanism, not allowing the fibers to return to their original positions, causing an irreversible shrinkage (Hassan and Carr, 2019). It not only reduces the size of clothes and impairs their appearance but also incurs a great monetary loss for the consumers. The aqueous treatment of wool under sonication disrupts the fiber's internal waxy lipids and causes the rearrangement of protein chains in the macrofibrils to a more regular and less flexible structure and enhances water absorption and tenacity along with reduced fiber extensibility (Li et al., 2012). It was reported that sonicated shrink-resist treatment without using any chemicals had little effect on scales but reduced the migration of wool fibers and felting shrinkage (Hurren et al., 2008). The enzymatic treatment of wool fiber under sonication showed improved shrink resistance compared to the enzymatic treatment without sonication (Rositza et al., 2011). It was also reported that the sonication reduced the treatment time in binding chitosan onto the wool fiber, which not only improved the dyeability of wool fabric but also reduced its felting shrinkage (Ranjbar-Mohammadi et al., 2013). In the case of wool fiber treatment with $CaCO_3$ nanoparticles, the abrasive action of the nanoparticles under sonication caused the descaling of the wool fiber surface and increased the coefficient of friction of fibers, potentially improving the shrink-resistance of wool fiber (Ghasemi et al., 2016). The sonicated anti-felt treatment of wool fibers with savinase allowed shrink-resist treatment at lower temperatures and shorter times than other enzymatic shrink-resist treatments (Liu et al., 2011). It will be easy to retrofit.

4.1.7. Effect of sonication on pre-treatment performance

Table 1 summarizes the effects of sonication on the reduction of treatment time, temperature, and chemical consumption in the various pre-treatments of textiles made with various types of fibers. It is evident from the published literature that for all types of fibers, the introduction of ultrasound in the pre-treatment processes made positive impacts on the reduction of energy consumption (Xu et al., 2016; Thompson and Doraiswamy, 1999; Khajavi et al., 2015). Sonication caused an enhanced transfer of enzymes and oxidants from the pre-treatment bath to the surface of fibers and uniformly and rapidly distributed them over the fabric surface causing an increase in the reaction rate of chemical reactions between enzymes/oxidants with the fibers and helping the removal of sizing agents, dust, and dirt from fiber surfaces (Thompson and Doraiswamy, 1999). Some improvement in fiber whiteness was also observed due to the bleaching effect of hydrogen peroxide produced by the sonolysis of water that caused the decolorization of natural pigments present in the fibers (Thakore and Abate, 2017; Li et al., 2014; Weissler, 1959). The effect of ultrasound in the chemical processing of textiles can be sonochemical (e.g., production of H_2O_2 leading to the generation of hydroxyl radicals), and or cavitation and heating effects (supplying energy to the system for increased agitation, mass transfer, and increased rate of reaction). For desizing and scouring mainly cavitation effects are present but for bleaching both effects are present. Low-power (<0.1 W/cm^2) sonication is beneficial for textile treatments and high-power (>0.1 W/cm^2) sonication produces hydroxyl radicals, which can degrade fibers.

Table 1
Effect of ultrasound on functions and properties of fibers in sonochemical pretreatment of different fiber types.

Fiber type	Types of sonicator	Effect of sonication on treatment performance and sustainability	Ref.
Cotton	Ultrasonic bath, 40 kHz, 980 W	Higher ultrasonic frequencies and power leads to optimal pectin removal	Easson et al. (2018)
	Ultrasonic reactor, 16 kHz, 1.4 kW	Reduces consumption of expensive enzymes and shortens processing time (from 100 min to 40 min) for the same wettability of fabric (wetting time 200 s)	Yachmenev and E.JBlanchard (2004)
	Ultrasonic bath, 53 kHz, 180 W	Reduces treatment time from 30 min to 10 min for 72% desizing efficiency	Wang et al. (2012)
	Ultrasonic bath, 30 kHz, n/a	Decreased the scouring time to less than 5 min compared to 60–120 min required for traditional scouring	Agrawal et al. (2010)
	Ultrasonic bath, 40 kHz, 100 W	Less alkali is needed (~17% less) compared to the traditional method to achieve a similar mercerization effect and increases fiber tenacity (~23%)	Li et al. (2020)
Bast fibers	Ultrasonic bath, 40 kHz, 250 W	Sono-enzymatic scouring of jute fiber decreased the whiteness index from 59.8 to 54.1 and increased the yellowness index and tensile strength from 40.3 to 40.9 and 20.8 kgf to 21.4 kgf respectively compared to the conventional enzymatic scouring	Patil et al. (2023)
	Ultrasonic bath, 35 kHz, 300 W	Improved the wettability of jute fabric (27 s–0 s), and decreases yellowness index (50.2–29.3 and tensile strength (30.5–27.8 kgf)	Hassan and Saifullah (2018)
	Ultrasonic bath	The porosity of hemp in the mesopore range increased, but for flax, porosity decreased by sonochemical scouring	Borsa et al. (2016)
	Ultrasonic bath, 32 kHz, 400 W	Increases delignification efficiency of flax fibers without using enzyme	Sirghie et al. (2015)
	Ultrasonic bath, 45 kHz, 400 W	24 h sonochemical aqueous treatment without any chemicals increased the weight loss and lignin removal of flax fibers to 4.5% and 0.2% respectively	Pan et al. (2018a)
Wool	Ultrasonic bath, 40 kHz, 2 × 400 W	Loosens wool grease and accelerates the penetration of scouring detergent to fiber bundles for the easy grease removal Reduces scouring time from several hours to 30 min	Czaplicki et al. (2021)
	Ultrasonic bath, 36 kHz, n/a	Enhances bleaching efficiency and whiteness degree (by approx. 20%)	Bahtiyari and Duran (2013)
	Ultrasonic bath, 28 kHz, 300 W	Causes uniform removal of wool fiber cuticles and alters the surface morphologies with a marginal loss in single fiber strength (4.30 MPa–4.2 MPa)	Pan et al. (2018a)
	Ultrasonic probe retrofitted, 80 kHz, n/a	Increased removal of grease, hydrophilicity, and water absorption and decreased felting shrinkage of fabrics	Li et al. (2014)
	Ultrasonic probe retrofitted, 80 kHz, n/a	20–25% reduction of water, detergent, and energy usage was achieved in wool scouring	(Bahtiyari and Duran, 2013; Yuksek et al., 2012)
	Ultrasonic probe retrofitted, 80 kHz, n/a	Sonicated bleaching produced brighter wool with a considerable reduction in treatment time or temperature	Bahtiyari et al. (2012)
Silk	Ultrasonic bath, 40 kHz, 130 W	Sonicated enzymatic degumming with papain at 60 °C for 60 min produced the best degumming performance as the whiteness index and weight loss reached 92 and 14% respectively	Erdem and İbrahim Bahtiyari (2018)
		Helps in the detachment of the sericin layer from the surface of silk fibers and provides uniform removal of sericin from the surface of silk fibers	Erdem and İbrahim Bahtiyari (2018)
	Ultrasonic bath, n/a, 70 W	Enzymatic degumming with alcalase caused only 3.7% strength loss while with savinase the strength loss was 13.3%	Mahmoodi et al. (2010)
	Ultrasonic bath, 20 kHz, 205 W	Sonicated degumming with natural turpentine soap increased the tensile strength and whiteness index to 73.0 and 7.16 cN/tex	Yuksek et al. (2012)

Ultrasonic transducers in a pre-treatment machine to realize the potential environmental and cost-saving benefits of sonochemical processes.

4.2. Dyeing

The dyeing temperature varies depending on the classes of dyes used. Various dyes including direct, acid, basic, reactive, azoic, vat, disperse, and sulfur dyes are used for the coloration of textiles. The dyeing with vat, azoic, and reactive dyes is carried out at moderate temperatures but dyeing with disperse dyes requires not only a high temperature (130–140 °C) but also a high pressure. The dyeing with acid, basic, direct, and sulfur dyes is also carried out at the boil. The application of ultrasound has been extensively studied in the dyeing of various textile fibers with various classes of dyestuffs, such as reactive, acid, vat, disperse, and natural dyes. The initial studies were limited to the acceleration of exhaustion of dyes for enabling rapid dyeing of textiles (Smith et al., 1988; Shimizu et al., 1989; Thakore, 1990). Later it was also studied for accelerating the reduction of vat dyes and for the deagglomeration of dyes at low liquor ratios.

4.2.1. Low-liquor ratio dyeing

Traditional dyeing of textiles is carried out at the boil using various textile auxiliaries at a high liquor ratio (more than 1:8) increasing the usage of energy and chemicals required for dyeing. On the other hand, the ultralow liquor ratio dyeing (1:3 to 1:5) is beneficial as it reduces the usage of water, energy, and various textile auxiliaries along with the production of a lower volume of effluent compared to the traditional dyeing methods. However, the reduction of the liquor ratio causes agglomeration of dyes in the dyebath which is further exacerbated when a large quantity of electrolytes is added to improve dye absorption by the fiber, resulting in uneven dyeing (Hassan and Bhagvandas, 2017a). To overcome the issues and disintegrate dye agglomerates, sonication was found useful for the dyeing of wool with acid dyes (Hassan and Bhagvandas, 2017b) and cotton with natural dyes (Ma et al., 2020). The use of sonication reduces or eliminates the dye aggregation as shown in Fig. 3 and also shortens the dyeing time. The low-liquor ratio dyeing of cotton fabric with reactive dyes under sonication increased the dye uptake percentage and color strength by 120.0% and 25.6% respectively, when compared to the results of the conventional dyeing process (Bian et al., 2022).

4.2.2. Dyeing with acid dyes

Polyamide fibers, such as wool, silk, and other animal hair protein fibers, and synthetic polyamide fibers (such as nylon) are dyed with acid dyes at a boil as anionic acid dyes can be bonded to cationic polyamide fibers at acidic conditions. Sonochemical dyeing of polyamide fibers was mainly studied for energy saving by reducing dyeing temperature and time. Sonochemical dyeing was also studied for the dyeing of wool (Abdelghaffar et al., 2018; Pan et al., 2018b; Actis Grande et al., 2017; Sanislav et al., 2015; Nazmul Islam et al., 2017), silk (Shukla and Mathur, 1995), nylon (Jatoi et al., 2017; Merdan et al., 2004), and cashmere (Dong and Hu, 2014) fibers. The application of sonication increases dye uptake at a range of dyeing temperatures with no damage to the fiber (Shukla and Mathur, 1995). The application of sonication has enabled low temperature dyeing of wool with acid dyes with huge savings in energy and chemicals (Ferrero et al., 2012). Sonicated dyeing is more beneficial for low liquor ratio dyeing as the agglomeration of dyes is more common for low liquor ratio dyeing than normal dyeing (Hassan and Bhagvandas, 2017b). In the case of acid dyes, sonication breaks the dye aggregation, disrupts the boundary layer between the liquor and the fiber surfaces, and enhances the transportation and diffusion of dye molecules into the interior of the fiber (Hassan and Bhagvandas, 2017b; Ferrero et al., 2012).

4.2.3. Dyeing with reactive dyes

Reactive dyes are popular for the dyeing of cellulosic fibers because of their excellent colorfastness to washing as only this class of dye covalently binds to the fiber. Although, dyeing with reactive dyes is carried out comparatively at lower temperatures compared to

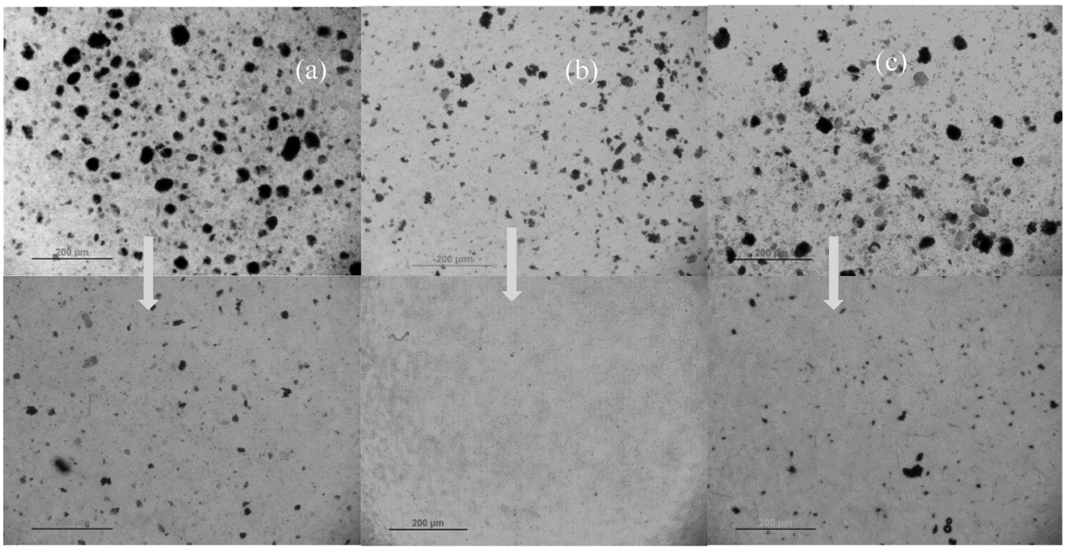

Fig. 3. Optical micrographs of Sandolan Blue MF-BLN dye solution in the presence of various dye agglomeration-preventing agents at the liquor ratio of 1:5 before (top) and after (bottom) sonication. (a) Control; (b) citric acid; and (c) Teric 13A9. Reprinted with permission from Ref. (Hassan and Bhagvandas, 2017b).

the disperse, acid, basic, and sulfur dyes but dyeing takes longer time and needs to use a large quantity of salt and alkali increasing the pollution load of the produced effluent. The published studies show that sonicated dyeing of cotton (Tissera et al., 2016; Khatri et al., 2011), bamboo (Larik et al., 2015) cellulosic fibers, and nanofibers (Khatri et al., 2016) reduced energy, water, and salt consumption compared to the traditional dyeing process. Ultrasound-assisted dyeing and washing show that the washing time can be halved by using ultrasound compared to the traditional washing of textiles (Thakore, 2011). Sonochemical dyeing is certainly beneficial for the dyeing of cellulosic with reactive dyes. The ultrasound-assisted dyeing of lyocell (regenerated cellulose) fiber with reactive dyes also showed enhanced dye adsorption and 7% better color yield compared to the fabric dyed without sonication along with lower pollution (Babar et al., 2019).

Reactive dyes are applied to cellulosic fibers under aqueous alkaline conditions as the covalent bond-forming reactions between the hydroxyl groups of cellulose and the reactive groups of the dyes take place at those conditions. At alkaline conditions, the hydroxyl groups of cellulose are deprotonated to form strongly nucleophilic cellulosae anions. The electrolytes (e.g., sodium chloride) are added to reduce the negative charge formed to enhance the dye substantivity toward cellulosic fibers to ease dye absorption. At a low liquor ratio, dye molecules are aggregated, which is exacerbated in the presence of a high concentration of electrolytes (sodium chloride or sulfate). The effects of sonication on the dyeing of cellulosic fabrics with a vinyl sulfone-type reactive dye are schematically represented in Fig. 4. Sonication breaks down the dye molecule aggregations and increases the transfer and diffusion of dye molecules into the interior of the cellulosic fiber, increasing the rate of dyeing. Sonication also increases the rate of fixation reaction due to the availability of more dye molecules in the fibers compared to non-sonicated dyeing.

4.2.4. Dyeing with basic dyes

The dyeing of anionic fibers, such as polyacrylonitrile and anionic polyester with basic dyes is usually carried out at the boil, which has high energy demand. Ultrasound was studied to reduce energy usage and dyeing time for the dyeing of acrylic fibers with basic dyes (Kamel et al., 2010). The application of ultrasound in dyeing saves energy consumption and reduces dyeing time along with the reduction in environmental impacts. The sonochemical dyeing does not alter the morphology of the acrylic fiber but still, increases its tensile strength (Kamel et al., 2010). The dyeing of meta-aramid fabric with a basic dye under combined ultrasonic-microwave irradiation showed improved dye uptake and the dyed fabric exhibited enhanced color strength (Amesimeku et al., 2021). The effects of sonication on the dyeing of textiles with basic dyes are similar to the sonicated dyeing of textiles with acid dyes, i.e., sonication breaks down dye agglomeration and increases the transfer and diffusion of dyes into the fiber.

4.2.5. Dyeing with disperse dyes

The application of ultrasound was initially studied for the dyeing of hydrophobic cellulose acetate fiber with water-insoluble disperse dyes, which showed increased dye absorption due to cavitation (Alexander and Meek, 1953). Later the investigation was extended to the low-temperature dyeing of polyester fiber with disperse dyes to reduce energy costs as the traditional dyeing is energy-intensive and is carried out at a high temperature (130 °C) under high pressure (Lee and Kim, 2001; Lee et al., 2003; Ahmad and Lomas, 1996; El-Apasery et al., 2017). Sonication can reduce the particle size of disperse dyes easing their absorption into the poly-

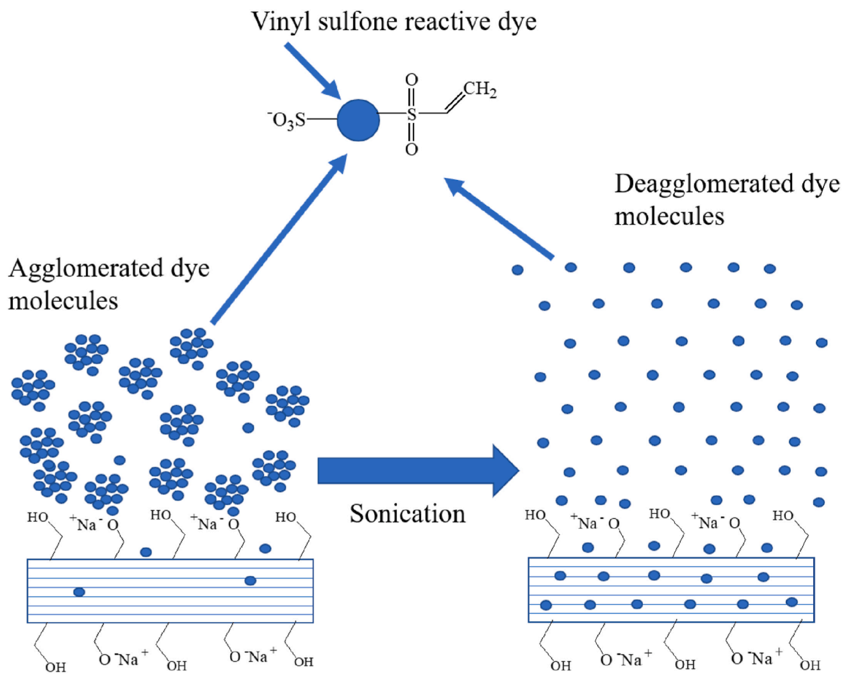

Fig. 4. Schematic representation of the effect of sonication on deagglomeration, transfer, and diffusion of vinyl sulfone-type reactive dye molecules into cellulosic fibers.

ester fiber at a lower temperature increasing the dye exhaustion rate (Altay et al., 2018) and reducing the amount of residual dye in the effluent. Sonication showed no effect on the glass transition temperature of polyester (Smith et al., 1998). The application of ultrasound disrupts the boundary layer of dye liquor in contact with the fiber, decreases dye aggregation and thereby increases dye solubility in the dye bath, and eases diffusion of dye molecules into the fiber, resulting in increased dye uptake by the fiber (El-Apasery et al., 2017). The sonochemical process was also studied for the dyeing of spun-bonded non-woven polyester fabric with a positive effect on dye absorption rate and reduction in dyeing time (Smith et al., 1998). Ultrasound was also studied for the dyeing of cellulose acetate fabrics (Wahab et al., 2019; Udrescu et al., 2014). However, the benefit will be low as small savings in energy can be achieved compared to polyester dyeing as they are dyed at a boil under atmospheric conditions. For sonochemical dyeing of polyacrylonitrile with basic dyes, a dyeing time of 60 min at 80 °C was found the optimum, whereas traditional dyeing is carried out at the boil for 120 min (Amesimeku et al., 2021).

The mechanism of traditional high-temperature and high-pressure (HTHP) dyeing as well as low-temperature sonicated (LTS) dyeing is presented by a schematic diagram in Fig. 5. In the HTHP dyeing, water-insoluble disperse dyes are dispersed in the dyebath with a dispersing agent and at HTHP, the dyes become soluble in water and are absorbed into the fiber. On the other hand, for LTS at 80 °C, the aggregated dispersed dye particles are disintegrated into smaller particles by cavitation and form a very fine dispersion. These dye particles are adsorbed onto the surface but very little of that is diffused into the interior of the fiber and therefore the dyed fabric shows lower colorfastness to washing compared to the traditional HTHP dyed polyester fibers (Altay et al., 2018).

The application of ultrasound increases dye adsorption and also accelerates the rate of dyeing on nylon and cellulose acetate fibers (Wahab et al., 2019). In the case of cellulose acetate dyeing, sonication is only beneficial for low-temperature dyeing (up to 60 °C) as an acceleration in the rate of dyeing and diffusion of dyes into the fiber can be achieved at that temperature but at temperatures higher than 60 °C, sonication does not show any real beneficial effect (Udrescu et al., 2014).

Polyester fibers have low molecular weight polyester oligomers on their surface that are formed during the polymerization stage and these oligomers have high thermal sensitivity, causing them to migrate from the interior of the fiber towards the fiber surface due to the high temperature and high-pressure used for dyeing. They also absorb the applied disperse dyes and the surface deposition of these oligomers can cause faulty dyeing. They are usually removed after dyeing by the 'reduction clear' by treating with a strong reducing agent in alkaline conditions that remove the oligomers by degrading them. Sonication was found beneficial for the reduction clearing of surface deposited polyester oligomers from polylactic acid (PLA) fiber, and the treatment can be carried out at 10 °C lower compared to the usual reduction clearing temperature saving energy cost (Burkinshaw and Jeong, 2008a, 2012). In the case of sonicated dyeing of PLA fiber, the sodium dithionite used in traditional reduction clearing of polyester dyed with disperse dyes can be replaced with a detergent that has no effect on the degradation of PLA and produces non-toxic effluent (Burkinshaw and Jeong, 2008b).

4.2.6. *Dyeing with vat dyes*

Cellulosic fibers are dyed with vat dyes because of their exceptional colorfastness to light and washing. Like reactive, basic, direct, and acid dyes, vat dyes are not bonded to cellulosic fibers by ionic or covalent bonds. Vat dyes are insoluble in water but for aqueous dyeing, they are reduced to temporarily water-soluble leuco vat form by reduction with a strong reducing agent, absorbed into fiber,

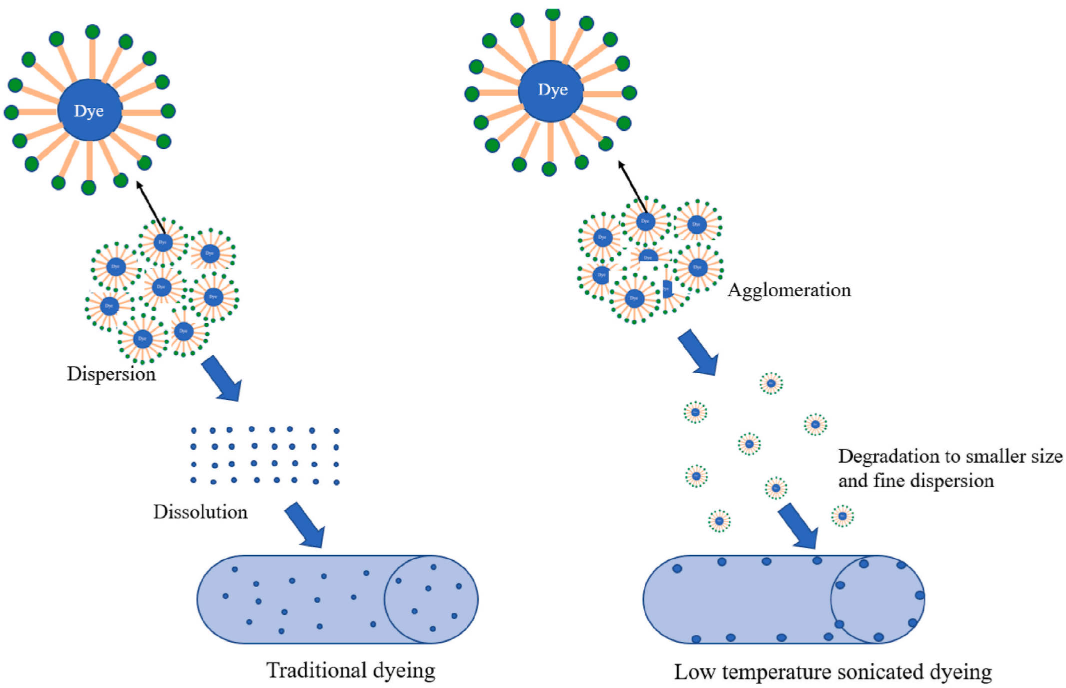

Fig. 5. Mechanisms of traditional HTHP (left) and LTS (right) dyeing of polyester fiber with disperse dyes.

and then again oxidized to the insoluble form so that they cannot come out of the fiber. The commonly used reducing agents are sodium sulfoxylate formaldehyde or sodium dithionite, and both produce toxic effluent. Therefore, the primary interest of ultrasound in vat dyeing was looking for the possibility of dissolution of dyes in water by sonication (Marte, 1995). Initial studies showed that the particle size of vat dyes can be reduced to a smaller size by cavitation. For example, it was reported that sonication reduced the particle size of C.I. Vat Violet 1 and C.I. Vat Green 3 dyes suspended in water from 2.447 μm to 0.606 μm and 0.941 μm–0.268 μm respectively (Good et al., 1995). However, the reduction of particle size to nanosize is not as still they cannot be absorbed into the fiber and retained there. For example, Hakeim et al. managed to reduce the dye particle size of C.I. Vat Violet 16, C.I. Vat Orange 17, and C.I. Vat Green 11 up to 20 nm using ultrasound, which formed a stable dispersion in the presence of sodium dodecyl sulfate (Hakeim et al., 2013). The cotton fabric dyed with that dispersion produced a much higher color yield compared to conventional dyeing but exhibited a lower colorfastness to washing than the fabric dyed by the traditional method. Possibly the dye particles could not penetrate the interior of the fiber because of their larger molecular size compared to the conventional water-soluble dyes and remained on the surface or near the surface. Sonication was also studied for the vatting of vat dyes using conventional reducing agents and also for the dyeing of cotton with reduction solubilized vat dyes, which reduced the amount of the reducing agent required for the vatting process and increased the dye uptake by the substrate, resulting in reducing the time and energy required to obtain the desired shade (Adeel et al., 2020; Božič and Kokol, 2008). The cavitation energy produced by sonication accelerates the movement and deagglomeration of dye particles in the dyebath causing rapid diffusion of dye molecules into the interior of the fiber.

4.2.7. Dyeing textiles with natural dyes

Ultrasound was also studied for the dyeing of textiles with natural polyphenolic dyes and other pigments. Natural polyphenolic dyes are large molecules compared to the traditional synthetic dyes and sonication is highly effective to increase their mass transfer from the dyebath to the fiber surface and diffusion into fibers. A large quantity of natural polyphenols is left in the dyebath after dyeing because of their poor absorption into textile fibers due to their large molecular size. Ultrasound was studied for increasing the dye uptake for the dyeing of wool fibers with lac dye (Kamel et al., 2005), cotton fibers with red cabbage extracts (Ben Ticha et al., 2016), wool fibers with betanin extracted from cactus pears (*Opuntia ficus-indica* L.) using chlorophyll as a mordant (Guesmi et al., 2013a), cationized cotton fabrics with the extracts from *Acacia cyanophylla* yellow (Guesmi et al., 2013b), silk fabrics with anthocyanin extracted from sweet potato skin (Yin et al., 2017), cotton fabric with turmeric (Dong et al., 2014), cotton fabrics with polyphenols extracted from mulberry leaves (Ohama, 2014), jute fibers with sumac gallotannin (Hassan and Saifullah, 2021), and polyamide fabrics with polyphenols extracted from olive (Haddar et al., 2015). Sonochemical cationization of cotton fabric with polyaminochlorohydrin quaternary ammonium polymer with epoxide (Kamel et al., 2009), and 2,3-epoxypropyltrimethylammonium chloride (Kamel et al., 2011), were studied as cationization is known to increase the dye absorption capacity of cotton fabric and allows dyeing at neutral conditions (Ramasamy and Kandasaamy, 2005). The degree of substitution of hydroxyl groups of cellulose increased to 0.21 by the cationization with an epoxidized aliphatic polyamine (Zhang et al., 2015). It was reported that wool and silk fibers pretreated with neem oil and dyed with chlorophyll, saffron red and yellow natural dyes under sonication showed color fastness to rubbing, washing, and perspiration, and antibacterial activity similar to the fibers dyed under microwave irradiation (El-Khatib et al., 2020). In the dyeing of wool fabric with rhubarb extract, the application of ultrasound in the dyeing procedure helped to decrease the dyeing temperature, thereby reducing energy consumption, and maintaining the extracted and dyeing quality (Ali et al., 2019).

4.2.8. Effect of sonication on color strength and colorfastness to washing and rubbing

Table 2 shows various beneficial improvements achieved in the dyeing of textiles with various dyes. We have not attempted to compare the results as treatments were carried out by various researchers using different sonication methods, and treatment conditions. Ferrero and Periolatto found that for dyeing of wool fabric at 60 °C, the application of sonication, enhanced colorfastness to wet rubbing and washing from grade 3.5 to 5 and from grade 4.5 to 5 respectively but little/no improvement was observed for dyeing at 80 °C or above (Ferrero et al., 2012) as sonication is beneficial only below 60 °C. Another research group also observed similar results and reported that the color strength improved from 14.99 to 18.29 (Nazmul Islam et al., 2017). The dyeing of cellulose (II) nanofibrous mat with reactive dyes shows that sonicated dyeing provided better color yield and colorfastness to washing compared to traditional dyeing (Larik et al., 2015). In the case of cotton fabric dyed with reactive dyes, the dyeing carried out at 30 °C under sonication provided a 230% increase in the color strength, and the batching time was reduced from 12 h to 8 h (Tissera et al., 2016). For the bamboo cellulose fabric, sonicated dyeing offered a 5–6% increase in color strength and savings of 15 min dyeing time and 10 g/L salt at 10 °C lower dyeing temperature compared to the conventional dyeing (Larik et al., 2015). However, sonication did not affect the colorfastness properties (Khatri et al., 2011). In the case of dyeing acrylic fabrics with basic dyes, sonication increases dye uptake by 50% and improves the color yield by 23% along with an increase in colorfastness to washing and rubbing (Babar et al., 2019) and tensile strength (Amesimeku et al., 2021). For dyeing of polyester with disperse dyes, sonication reduces dye particle size (Lee and Kim, 2001), enhances dye uptake by the fiber.

(Lee et al., 2003), and enables dyeing at 80 °C with an increase in color yield compared to dyeing at the same temperature without sonication but still, the color yield is half of the normal high-temperature-dyed polyester (Altay et al., 2018). The application of ultrasound also allows the reduction clearing of dyed PLA fibers without using any chemicals (Burkinshaw and Jeong, 2008b, 2012). By using sonication, the dye particle size of vat dyes can be reduced by 20 nm, which can be used for dyeing cotton without chemical vatting with toxic strong reducing agents making the dyeing more environmentally friendly compared to traditional dyeing (Hakeim et al., 2013). In the case of dyeing cotton fiber with natural lac dye, the dye uptake increases by 47% (Kamel et al., 2005). For sonicated dyeing of cotton with betaine dyes using chlorophyll as a biomordant, the dye absorption increases by 60% (Guesmi et al., 2013a).

Table 2
Effect of ultrasound on dyeing performance of textiles with different dyes.

Dyes	Fiber types	Types of sonicator	Effect of sonication on dyeing performance and sustainability	Ref.
Acid	Wool	Ultrasonic bath, 35 kHz, 130 W	Saves 50–60% energy and more than 80% textile auxiliaries, and enabled dyeing at a liquor ratio of 1:5 at 60 °C instead of 98 °C	Hassan and Bhagvandas (2017b)
	Wool	Ultrasonic bath, 37 kHz, 150 W	For dyeing at 60 °C, sonication enhances colorfastness to wet rubbing and washing from grade 3.5 to 5 and grade 4.5 to 5 respectively	Ferrero et al. (2012)
	Wool	Ultrasonic bath, 40 kHz, 130 W	Improved color strength (14.99–18.29) with uniform dyeing	Nazmul Islam et al. (2017)
	Silk	Ultrasonic bath, 26 kHz, 120 W	For dyeing at 50 °C for 15 min, Methylene Blue 2 B and Malachite Green dye uptake increased by 71% and 104% respectively	Shukla and Mathur (1995)
Reactive	Cotton	Ultrasonic bath, 40 kHz, 300 W	For 30 °C pad-batch dyeing, color yield increases by 235% but for 60 °C dyeing only a 16% increase in color yield and decreases the required batching time from 12 h to 8 h	Khatri et al. (2011)
	Bamboo	Ultrasonic bath, 40 kHz, 300 W	For dyeing with C.I. Reactive Black 5 and C.I. Reactive Red 147 dyes, savings in salt and alkali are 20% and 16.7%, and 20% and 20% respectively with 20% reduction in fixation time and temperature	Larik et al. (2015)
	Cellulose	Ultrasonic bath, 37 kHz, 320 W	Sonicated dyeing provided 20.4% and 14.5% increased color yield for CI Reactive Black 5 and CI Reactive Red 195 dyes respectively	Khatri et al. (2016)
	Lyocell	Ultrasonic bath, 53 kHz, 180 W	For C.I. Reactive Red 195 and C.I. Reactive Blue 250 dyes, sonication increased color yield and dye fixation efficiency by 4–7% and up to 5% respectively	Babar et al. (2019)
Basic	Acrylic	Ultrasonic bath, 38.5 kHz, 450 W	Improves dye uptake (~50%) by acrylic fiber with improved color yield (28.5%) Showed no effect on colorfastness to washing with a marginal increase in colorfastness to rubbing and perspiration	Kamel et al. (2010)
	Meta-aramid	Ultrasonic transducer, 25 kHz, n/a	Enabled low-temperature dyeing (70 °C) compared to 130 °C in conventional dyeing with a decrease in the use of water, dyeing time, and pollutant load in the effluent	Amesimeku et al. (2021)
Disperse	Polyester	Ultrasonic bath, 45 kHz, n/a	Dyeing at 80 °C increases the color yield from 3.95 to 7.61 compared to 14.2 can be achieved by conventional dyeing at 130 °C	El-Apasery et al. (2017)
	Acrylic nanofiber	Ultrasonic bath, 60 kHz, 55 W	Sonicated dyeing increased the tensile strength from 8.27 MPa to 17.2 MPa. Color yield also increased by 48.4% and 55.1%, and 51.2% and 66.33% for 1% and 4% shades of C.I. Disperse Blue 56 and C.I. Disperse Red 167 dyes respectively.	Wahab et al. (2019)
	Cellulose acetate	Ultrasonic bath, 37 kHz, 150 W	Sonication was only beneficial for low-temperature dyeing (up to 60 °C) but higher than 60 °C sonication did not show any beneficial effect in increasing color yield and colorfastness to rubbing	Udrescu et al. (2014)
Vat	n/a	n/a	Reduces the particle size of Vat Violet 1 and Vat Green 3 from 2.447 μm to 0.606 μm and 0.941 μm–0.268 μm respectively	Good et al. (1995)
	Cotton	Ultrasonic homogenizer	In the case of C.I. Vat Violet 16, C.I. Vat Orange 17, and C.I. Vat Green 11, dye particle size reduces to 20 nm, but cotton fabrics dyed with them show lower colorfastness to washing	Hakeim et al. (2013)
	Cotton	Ultrasonic bath, 40 kHz, 50 W	Showed the benefit of using sonication only at low temperature	Adeel et al. (2020)
Natural dyes	Cotton	Ultrasonic bath, 38.5 kHz, 450 W	In the case of cotton dyed with lac dye, the adsorption of dye increases by 47% compared to conventional dyeing	Kamel et al. (2005)
	Cotton	Ultrasonic bath, 40 kHz, 450 W	Enhanced betaine dye adsorption from 30% to 60%	Guesmi et al. (2013a)
	Silk	Ultrasonic probe, 20 kHz, n/a	Enhances extraction of dye from various plants and biomasses but not studied for dyeing	Yin et al. (2017)
	Cotton	n/a	Enhanced dye uptake and color yield	Dong et al. (2014)
	Cotton	Ultrasonic bath, n/a, 80 W	22.2% in color extraction from mulberry leaves and a 14% increase in dye uptake were achieved	Ohama (2014)

Sonication causes controlled adsorption of dye molecules onto the fiber surface and their diffusion into the interior of the fiber resulting in improved colorfastness to washing and rubbing. The dyeing of cellulose (II) nanofibrous mat with reactive dyes shows that sonicated dyeing provided better color yield and colorfastness to washing compared to traditional dyeing (Larik et al., 2015). However, for the samples dyed at 80 °C, no improvement was observed as fabrics dyed without sonication already had the highest grade of colorfastness to washing and rubbing. Coman et al. found that sonication improved the colorfastness washing of monochlorotriazinyl cyclodextrin-grafted flax fibers with anthocyanin extracted from onion peel (Coman et al., 2014). Similar results were reported for the sonicated dyeing of jute fabrics with basic dyes (Patil et al., 2023), cotton fabric with Marigold flower extract (Baig et al., 2021), and wool fibers with acid dyes (Li et al., 2014). The application of sonication improved dye exhaustion, and color yield, and reduced dyeing time.

4.2.9. Effect of sonication on tensile strength of the fabric

The review of various published articles shows that sonication has a marginal effect on the tensile strength of cotton but for bast fibers, a considerable loss in tensile strength occurs. For example, the spandex-containing cotton fabric combined scoured and bleached with peracetic acid (PAA) and tetraacetylethylenediamine (TAED) at 40 °C under sonication showed a marginal loss in tensile strength compared to the fabric conventionally scoured and bleached at 60 °C without sonication (Khajavi et al., 2013). Bast fibers, such as jute, combined scoured and bleached under sonication showed considerably lower tensile strength compared to the jute fabric conventionally scoured and bleached under the same conditions (Patil et al., 2023). Sonication negatively affects the tensile strength of lignocellulosic fibers possibly due to the removal of some of the surface-bound lignin. For wool fibers, Kadam et al. observed no damage of wool fibers during sono-scouring (Mahmoodi et al., 2010), but Pan et al. reported severe cuticle damages, such as cracking, tip lifting, scale peeling, severe scale disruption, and scale removing occurred for wool fibers sono-scoured, and the damages were more severe at lower ultrasound frequencies (28 kHz) compared to higher frequencies [45 or 80 kHz) (Renouard et al., 2014). Hassan and Bhagvandas observed that sonicated dyeing of wool fabric with acid dyes did not cause any damage to the fiber and no loss in the tensile strength of the fabric occurred (Hassan and Bhagvandas, 2017b). Similarly, the sonicated scouring of wool fibers with enzyme considerably modified the fiber surface with enhanced dyeability with reactive and acid dyes but had a negligible effect on the tensile strength, and abrasion resistance (Li et al., 2014). Wool fibers are dyed with acid dyes at acidic conditions, and they are quite stable in that conditions than in alkaline conditions. It shows that for wool fibers, the treatment pH plays a role, and no damage occurs when the treatment is carried out in acidic conditions. On the other hand, for some types of fibers, sonication improves their tensile strength. For example, for acrylic fibers, sonication improved the tensile strength of the fibers.

4.2.10. Dye adsorption kinetics under sonication

Adsorption kinetics is used to estimate the time required to reach an equilibrium of dye transfer from the dyebath to the substrate. Dye sorption from aqueous solutions by solid fibers can be considered a two-step process. The first dye sorption kinetics is governed by the rate of surface reaction but when the adsorbed amount reaches about 80% of the equilibrium, the sorption kinetics is governed by the rate of intraparticle diffusion (Rudzinski and Plazinski, 2008). The two most important factors are the rate constant and the equilibrium dye absorption capacity. It was reported that the absorption of disperse dye by polyester fiber under sonication followed the.

Nernst isotherm model and the dye adsorption kinetics followed the pseudo-second-order kinetic model as shown in Fig. 6 (Abadi et al., 2021). The thermodynamic evaluation showed that Gibbs's free energy was negative, indicating that the dye absorption process was spontaneous. In the case of dyeing wool with the lac dye, it was found that for the conventional dyeing, the dye adsorption capacity of fiber was 83.3 mg/g which increased to 122.2 mg/g for the sonicated dyeing (Kamel et al., 2007). Udrescu et al. utilized the Arrhenius equation for the calculation of activation energies and the deduced Arrhenius plot shows (Fig. 7) that the activation energy for the sonicated process was 48 kJ/mol compared to 169 kJ/mol for the mechanical agitation (Burkinshaw and Jeong, 2008a).

5. Textile finishing

Other than the pretreatment and dyeing of textiles, sonochemical treatments have also been studied for the finishing of textiles. Parvinzadeh studied sonicated coating of cotton fabric with a non-ionic fatty acid amide and found that the sonicated coated fabric showed better properties compared to the non-sonicated coated fabric (Parvinzadeh, 2009). Sadanandan et al. studied the coating of textiles with nanoplatelets of graphene by ultrasonic spray coating to fabricate electronic devices directly on the fabric (Sadanandan et al., 2021). Perkas et al. coated Nylon 6,6 fabric with Ag nanoparticles by ultrasound-assisted coating, which provided durable antibacterial activity against a range of bacteria (Perkas et al., 2007). Pan et al. fabricated a highly wash-durable superhydrophobic cotton fabric using ultrasound-assisted in-situ growth of silica nanoparticles on the fabric using various silane compounds (Pan et al., 2018c). The treated fabric showed a high contact angle of 154 ± 0.5°, suggesting the conversion of the fabric to superhydrophobic. Moosavi et al. found that the particle size of AgBr nanoparticles increased with an increase in the number of dipping by sequential dipping in alternating baths of potassium bromide and silver nitrate under sonication (Moosavi et al., 2012).

The sonochemical coating of polyester fabric with TiO_2 nanoparticles made the fabric self-cleanable and also enhanced the durability of the treatment to washing compared to the fabric treated with the same nanoparticles without sonication (Harifi and Montazer, 2017). The sonochemical treatment enabled the single-step coating of cotton fabrics with CuO and ZnO nanoparticles to produce antibacterial fabric (Perelshtein et al., 2016; Petkova et al., 2016; Salat et al., 2018) and with ferric hexacyanoferrate (Prussian blue) to produce smart textiles that can sense the presence of bacteria (Ferrer-Vilanova et al., 2021). Sonochemical coating of cotton fabric with copper nanoparticles was studied to introduce antibacterial and superhydrophobic properties in the treated fabric (Han and Min, 2020). Ultrasound was also used for the coating of cotton fabric with TiO_2 nanoparticles in a 55% $ZnCl_2$ ionic liquid

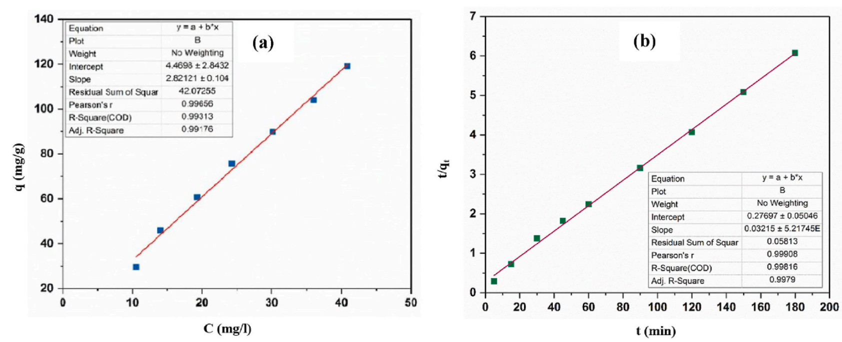

Fig. 6. Nernst adsorption isotherm (a) and pseudo-second-order adsorption kinetics of polyester fiber dyed with C.I. Disperse Blue 79 dye under sonication. Reprinted with permission from Ref. Abadi et al. (2021). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

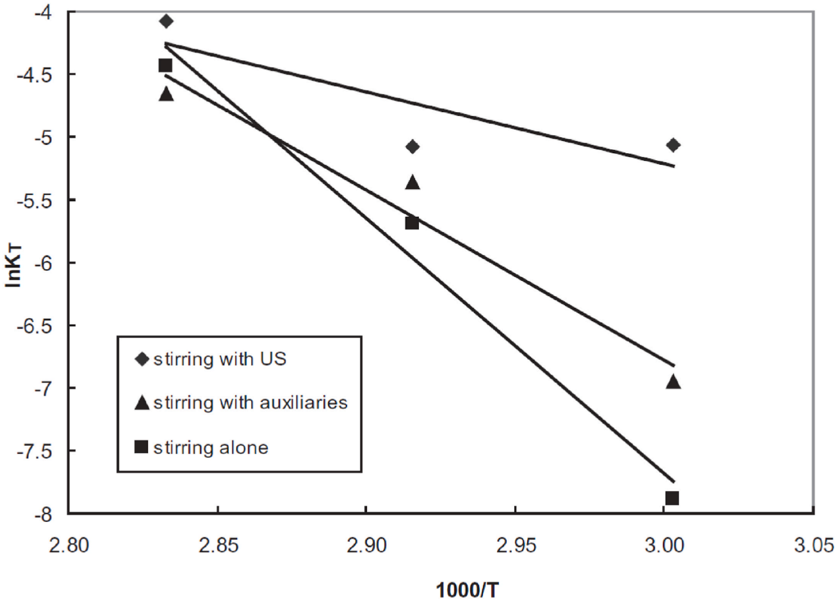

Fig. 7. Arrhenius plot for the dyeing of cellulose acetate with C.I. Disperse Red 60. Reprinted with permission from Ref. Udrescu et al. (2014).

bath to make the fabric multifunctional, in which case the ionic liquid acted as a cellulose swelling agent and helped in the improvement of the treatment to washing (Hu et al., 2019). Ultrasound was also studied for the coating of cotton fabric with ZnO nanoparticles to make the fabric antibacterial, which also degraded methylene blue dye by photocatalysis (Perelshtein et al., 2016; Petkova et al., 2016; Ghayempour and Montazer, 2017). Rastgoo et al. coated cotton/polyester blended fabric with magnetite under sonication to make the fabric antibacterial, and antifungal (Rastgoo et al., 2016). Tissera et al. studied the sonochemical for the coating of cotton fabric with amphiphilic graphene oxide to make the fabric superhydrophobic and electroconductive (Tissera et al., 2015). Zhou et al. studied the co-deposition of trimethyl chitosan and polyphenols extracted from *Glochidion ericarpum* Champ leave extract onto the cotton fabric under sonication at 80 °C to enhance the fabric's UV shielding and antibacterial properties (Zhou et al., 2022). It was found that sonication enhanced their adsorption rate constant by 23.8% and the half-adsorption time was shortened by 37.9%. The sonicated treatment of cashmere fabric with grape seed proanthocyanidins made the fabric anti-pilling, antistatic and antibacterial but the application highly decreased the treatment time as the half-adsorption time was reduced by 34.0% (Li et al., 2021).

6. The challenges and prospects

There are a few challenges in using ultrasound-assisted chemical processing in the textile industry. Firstly, for textile manufacturers, ecology is an obligation as modern consumers want sustainably processed products but still, the manufacturers consider sustainability as a cost-incurring process. Secondly, the installation of an ultrasound transducer in existing textile chemical processing machinery is cumbersome and also may void the warranty of the machinery, discouraging textile manufacturers to use ultrasound-assisted process technology. There are conflicting results regarding the effect of sonication on the degradation of fibers causing strength loss, and also degradation of dyes and chemicals as researchers used different ultrasound powers and frequencies, ultrasonic baths, ultrasonic horns, and also treatments were carried out at various conditions. Therefore, it is necessary to optimize ultrasonic powers and frequencies safe for various fibers, dyes, and chemicals, i.e., up to which ultrasonic powers and frequencies no degradation of fibers, dyes, and chemicals will not occur. Published research shows that the application of ultrasound in the chemical processing of textiles enables a reduction of treatment time and temperature but very little data on savings in energy, water, and chemicals and the pollutant load in the produced effluent are available. Moreover, very few published works reported the performance and energy savings of sonicated textile processing that was carried out on a pilot or industrial scale. Most of these studies were carried out on a lab scale using ultrasonic baths rather than using actual ultrasonic transducers fitted in a fully working machine on the factory floor. Therefore, it is difficult to predict how much actual energy, water, and chemical savings can be achieved in a real-life situation. No published research shows life-cycle analysis of sonochemical processed various textile products to show their benefits over conventionally processed textiles to confirm whether sonochemical processing of textiles can reduce environmental carbon footprints compared to conventional processes. Moreover, in most cases, no cost-benefit analysis was carried out. Therefore, further research is needed using industrial-scale machines fitted with ultrasonic transducers to realize the actual cost-benefit of using ultrasound with the proper calculations of energy, chemicals, water savings, and carbon footprints, which will encourage the textile industry to use sonochemical processes. It is encouraging that a few leading textile machinery manufacturers (e.g., Brückner Trockentechnik GmbH & Co. KG, and Sonotronic Nagel GmbH of Germany) have started commercializing sonicated textile finishing and washing machinery for the processing of various types of textiles, which will encourage textile industry to use sonicated processes.

7. Conclusion

This review demonstrates that the introduction of sonication in the pre-treatments, and dyeing and finishing of textiles certainly shows a positive effect in reducing the requirement of dyes and chemicals, the treatment time, and energy and water usage and plays a role in improving the sustainability of the chemical processing of textiles by decreasing the need for auxiliary chemicals (e.g. leveling agents, electrolytes, etc.), energy and water usage, and increasing dye absorption resulting in reducing pollutant loading in the effluent. Sonicated dyeing also allows dyeing of textile fabrics at ultra-low liquor ratio saving energy, water, and chemicals along with reducing the amount of effluent produced. Lab and pilot-scale trials confirmed that ultrasound does not degrade enzymes, as opposed to the common perception but rather enhances their reaction rate by increasing the uniform distribution of enzymes over the surface of the fibers. However, that may not be true if high-powered sonication is used which may degrade enzymes. The hydrolysis of starch in sonicated desizing is faster compared to the non-sonicated desizing and also due to vibrations created during sonication treatments, the applied sizing agents on the surface of fabrics become loose and easily removed by washing. The application of ultrasound enables ultra-low liquor ratio dyeing by eliminating dye aggregation and thereby improving dyeing uniformity without negatively affecting the tensile strength of the dyed fabrics.

It is a fact that the textile industry rarely uses sonicated chemical processing for textile processing. No analysis of real savings of energy, water, and chemical usage by using ultrasound for industrial-scale processing has been conducted to convince textile manufacturers to use sonicated chemical processing methods. When textile manufacturers will find that sonication-based sustainable eco-friendly processes are advantageous for their business growth and profitability, they will certainly adopt them in their manufacturing.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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