Sustainable Technologies for Cellulosic and Protein-Based Textiles

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Abstract

Sustainability is not just a fashionable term. Economic growth, social welfare and environmental conservation are three pillars of sustainability, and each should be examined in relation to the others. With growing public awareness and societal consciousness about the environment, the textile industry is driven to manufacture eco-friendly products. The primary focus is linked to less and harmless waste formation, reduced consumption of energy, water, and chemicals, reusing/recycling and following ethical manufacturing processes. The use of advanced technologies based on enzymes, ozone, ultrasound, microwave, and laser-assisted processing helps achieve sustainability in the textile industry. Adopting such modern techniques would help reduce the environmental impact, resulting in energy savings, reduced water consumption, and the replacement of harsh chemicals in textile manufacturing. This article highlights various methodologies and explores research efforts toward sustainable pre-treatment of textiles and the potential of these technologies for other applications.

Keywords: *enzyme, microwave. ozone, sustainability, ultrasound*

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1. Introduction

The textile sector makes a considerable contribution to the economy of many developing nations. It is, however, considered one of the most polluting and energy-intensive industries in the world. The use of a high concentration of chemicals, alkaline or acidic pH conditions and high temperatures characterise traditional wet processing procedures used in the textile industry. As a result, these activities consume a lot of energy and water and pollute the environment [1]. Therefore, the legislative regulations and environmental concerns are pushing a transition toward the use of sustainable processing techniques. The enzyme, ozone, ultrasound, and microwave-assisted technologies have found a wide range of applications in the textile industry. These technologies reduce the environmental impact of textile wet processing, resulting in energy savings, reduced water consumption, and the replacement of harsh chemicals in manufacturing textile materials.

Enzymes in textile wet processing have proved environmental benefits and significantly contributed to textile and garment sustainability. An operation like bio-scouring in the cleaning of natural fibres, bio-stone-washing of denim to create a worn-out effect, removing residual hydrogen peroxide in the bleach clean-up stage, and biopolishing of cellulosic materials to prevent pilling, are some of the typical commercial applications of enzymes in textile processing [2]. Nowadays, Ozone bleaching is a green and sustainable approach and is accepted commercially at a more significant scale of production in the textile garment washing industry. Compared to the traditional hydrogen peroxide bleaching, the use of ozone gas helps achieve bleaching effectively at low temperatures, thus saving energy [3].

Microwave heating plays a significant role in textile wet processing thereby reducing the consumption of non-renewable energy use. There is no direct air pollution (indirect air pollution from electricity is still lower than that caused by traditional heating); localised heating lowers the amount of energy wasted during the heating process. Faster heating enhances productivity while reducing energy use [4]. The use of ultrasonic energy in textile processes is a fresh and exciting concept that has received much attention recently. Ultrasound energy enables process acceleration, achieving the same or better outcome than existing techniques while operating under less harsh conditions, such as lower temperatures and chemical concentrations [5].

The need for research into alternative techniques of retaining water during dry processes is critical. Energy audits, which are uncommon in the textile segment, are essential in determining adequate energy management and energy conservation possibilities. This article examines several methodologies and research efforts studied to sustainably pre-treat textiles and the potential of these technologies for other applications.

2. Sustainable and eco-friendly textile pre-treatment of natural fibres

2.1 Enzymatic pre-treatment

The enzyme is a biological agent with the ability to break down complex organic substances such as starch, oils, lipids, and dye chromophores. Because of its non-toxic and environmentally beneficial properties, enzymatic textile processing is one of the fastest-growing sectors in the era of textile wet processing. Enzymes are proteins that help biological reactions move fast [6]. Each enzyme acts on a specific substrate or reactant. Enzymes are distinguished by their increased activity, selectivity, and sensitivity to pH, temperature, and other environmental changes. The reaction occurs at lower activation energy, which is achieved by forming an intermediate enzyme-substrate (see Fig 1). The enzymes are not used up in the process; they do not become a part of the reaction's end product, but they influence the outcome.

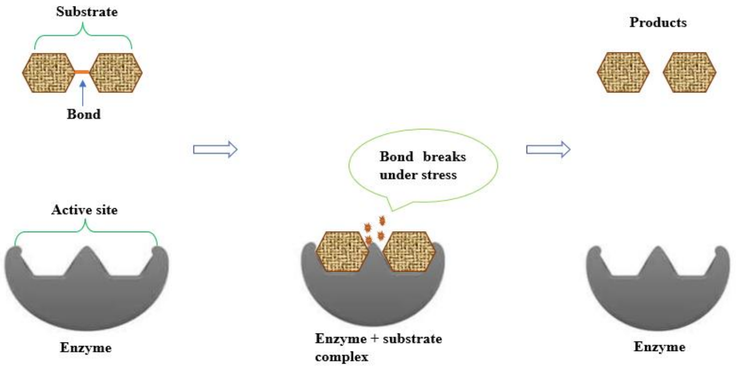

Figure 1: Principle of enzyme action

Table 1: Enzymes used in textile processing

Enzyme	Functions
Amylase	Decomposes starch in desizing
Cellulase	Breaks down the cellulosic chain to remove the protruding fibres
Catalase	Terminates residual peroxide after bleaching
protease	Removes protein-based impurities in scouring
Lipase	Removes oil and fatty substances during scouring
Pectinase	Removes pectin-based impurities in scouring
Laccase	Removes colour molecules

Scientists have been studying the use of enzymes in the textile industry for the past two decades. Bio-scouring, bio-washing, bleach cleaning and bio-polishing are only a few of the widely used bioprocesses in the industry (Table 1). Laccases and peroxidases have gained popularity in recent years for removing colour or polymerisation for colour creation. These enzymes could also be used to process bast fibres to improve bleaching and fibre separation. Cotton, wool, and silk, among other natural fibres, have played an essential part in textile sustainability. On the other hand, these fibres must be cleaned using extensive wet methods that consume a lot of water, energy, and chemicals. The fibres may be damaged as a result of these lengthy wet treatments [7].

2.2 Ozone pre-treatment

Ozone is a powerful oxidant that is found naturally in the atmosphere. The ozone layer protects us from UV radiation by acting as a shield as it absorbs the harmful UVB and UVC radiations3 (see Figure 2).

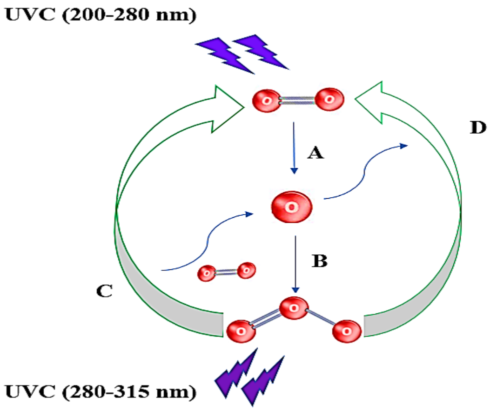

Figure 2: Cycle of formation and destruction of ozone

Ozone is a highly reactive gas that cannot be stored or transferred; it must be produced "in situ." The methods of artificially producing ozone are listed below.

- Photochemical process: Oxygen atoms generated by short-wavelength UV radiation on photodissociation react with oxygen molecules to form ozone.
- Electrolytic process: By flowing water across positively and negatively charged surfaces, ozone can be produced.
- Radiochemical process: The ozone creation can be aided by high-energy radioactive rays irradiating gaseous or liquid oxygen. The method's energy efficiency is higher than the ozone produced by electric discharge.
- Corona (silent electrical discharge) process: Ozone is produced by feeding air or oxygen gas into the generator, where the electric discharge converts oxygen or air into ozone. The most extensively utilised approach for water treatment is ozone creation by corona discharge.

There are two areas of ozone applications in the textile business, namely aqueous and gas ozone systems. As the operating principle of the finishing machine is ideal for a solution, aqueous ozone is more feasible than gaseous ozone for wet operations. Owing to the occupational health and comfort, the use of gaseous ozone necessitates the use of particular airtight machinery. The leakproof gasket material must be resistant to gaseous ozone [8].

Gaseous ozone concentration, temperature, pressure, solution composition (pH, ionic strength, and reactive chemicals), gas dispersion, turbulence, and contactor type are all factors that influence the physical mass-transfer rate of ozone into water. Ozone treatments are explored by various researchers and commercially used in some textile applications (Table 2).

2.3 Benefits of ozonation in the textile industry

- Consumes less water and chemicals and takes less time than traditional wet processes
- Minimises space as there is no need to store chemicals
- Prevents solid waste formation as ozone decomposes into oxygen
- Avoids formation of halogenated organic compounds (AOX)
- Creates distinct patterns and fading effects during the denim washing process
- Enhances dyeability of fibres
- Makes anti-felting treatment environment friendly
- Archives higher level of whiteness than the traditional bleaching
- Sanitizes non-durable materials such as bandages, tissues, surgical cotton

2.4 Drawbacks of ozonation in the textile industry

- Causes yellowing of the fabric
- Affects fibre strength in case of excessive ozone concentration
- Corrodes metal parts of machines owing to the high oxidation potential

- Requires a significant financial expenditure
- Necessitates onsite generation as it cannot be stored
- Hazardous if used ignorantly

Typical findings observed in the recent work related to the enzyme and ozone-based pre-treatment of textile material,

Table 2: Recent work related to the enzyme and ozone-based pre-treatment of textile material

Treatment	Substrate	Experimental conditions	Key findings
Ozone	Wool	Stainless steel ozone chamber (vol-226 cm3), conc. ozone gas- 6.2 % (v/v), flow rate 1 l/min. Temp-31 ^{0}C for 10 min at under atmospheric.	Ozone treatment does not change the morphology of wool. Increases oxygen content, and hence hydrophilicity. Helps improve dyeability [9].
enzymatic	Wool	Alkaline protease- 4.0 % (OWF), MLR- 1:20 Temperature- 40^{0}C Time-60 min pH- 8.5	Treatment brought the scales to flatten and made the fabric smooth and soft. Absorbency and dye uptake increased tensile strength decreased slightly [10].
enzymatic	Wool	Pre-treatment - Fatty acid surfactant - 30 mol/l, MLR - 1:50 Temperature- 20 - 90^{0}C Time-60 min. Enzymatic treatment- Alkaline protease- 4.0 g/l, MLR- 1:50 Temperature- 50^{0}C Time- 3hr pH- 7	Fatty acid surfactant pre-treatment a*ccelerates* enzymatic hydrolysis. Alkaline fatty acid surfactant at high temperatures causes damage to wool [11].
Enzymatic	Silk	Enzyme- alcalase, savinase - 1 g/l, sodium bicarbonate- 5 g/l, non-ionic surfactant- 5 g/l, Temp- 55^{0}C, Time- 30-60 min, pH- 8-9.	Around 20-22 % sericin removal with minimum damage in mechanical properties is achieved in a short treatment time compared to conventional degumming [12].
Enzymatic	Silk	Enzyme fungal protease, conc.- 3 ml/gm silk, temp- 37^{0}C, time- 3 hr	Treatment with fungal proteases gives around 20 % sericin removal without damage to silk fibroin [13].
Ozone	Silk	Ozone- 60 g/m3, flow rate- 0.5 L/min after treatment – soap - 2 g/l at 85^{0}C, for 10 min.	Reduction in yellowness, Reduction in tensile properties, The efficiency of treatment decreases as increases in pH beyond 4. Ozone destroys the dye absorbing sites present in the side chain of the silk molecules, resulting in less dye uptake [14, 15].
Enzymatic	Cotton	Pectinase- 1–10 g/l, non-ionic wetting agent-1 g/l for 30 min at 55°C, pH 8.5. Post wash with 0.2 g/l non-ionic wetting agent at 70°C.	Pectinase treatment exhibits more than 95 % pectin removal. Post hot treatment is necessary to remove the wax for uniform wettability [16].
Enzymatic	Cotton	Xylanase- 5.5 IU, Pectinase- 4.0 IU glycine–NaOH, buffer- 50mM, EDTA- 1.0 mM and 1% Tween-80, pH 8.5 for 60 min at 50°C, MLR- 1: 15	Bio scouring with Xylanase and Pectinase achieved 78 %. Whiteness and absorbency are less than sec with minimal rupture in mechanical properties [17].

Enzymatic	Cotton	Step1- production of hydrogen peroxide: D-glucose-10g/l, Glucose oxidase-25u/mL Sodium acetate 0.1 M Temperature 37°C pH-5.5. Step 2- bleach with hydrogen peroxide produced by glucose oxidase at 60°C for 30 min along with bleach activator and non-ionic wetting agent.	Better whiteness along with a soft touch of fabric. With the increase in time and temperature of bleaching, tear and tensile properties decreases [18].
ozone	Cotton	Ozone/oxygen mixture- 100 g/m3, flow rate- 0.5 mg/l, time – 1-3 min pH- 5, after treatment – peroxide bleaching and hot soaping.	An acceptable degree of whiteness is achieved. Two-stage ozone-peroxide bleaching shows improvement in whiteness with less cellulose modification [19].
ozone	Cotton	Ozone dose- 10 g/h, pH-5, treatment time- 45 min, temperature- 25-30^{0}C. anionic surfactant- 0.01- 0.5 g/l	The presence of surfactant in the ozone bleach bath significantly improved the quality of bleached fabric. Non-ionic surfactant also improved the absorbency (1.4 sec), almost equal to anionic surfactant but lacks in whiteness improvement compared with an anionic surfactant [20].

2.5 Ultrasound-assisted pre-treatment

Ultrasound is mechanical energy that does not absorb molecules and requires a medium to propagate. The effects of ultrasound (Figure 3) resulting from acoustic cavitation in liquid media, such as bubble formation, growth, and collapse, are widely accepted. Bubbles collapsing violently in less than a microsecond release a lot of heat, resulting in short-lived hot patches. Ultrasound irradiation can cause the degradation of organic molecules, the oxidation and reduction of inorganic compounds, and the sonolysis of water into reactive radicals -OH and H. Some of the impacts of ultrasound include accelerating chemical reactions, promoting mass transfer, shortening reaction cycles, improving reaction yield, changing the reaction pathway, increasing surface area between the reactants, and accelerating dissolution [21].

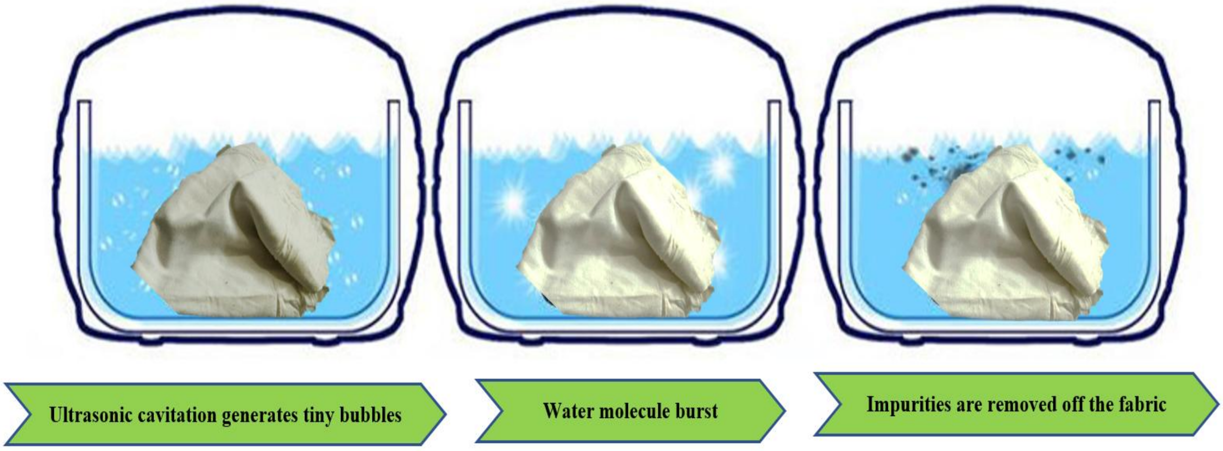

Figure 3: Principle of ultrasonic treatment in textile

In textile wet processing, ultrasound has been introduced as a promising method for reducing operation time, and energy consumption and improving product quality. Ultrasound's use in the textile industry dates back more than a century when it was first used to clean textile machinery parts like needles in knitting machines. It was then followed by ultrasound's dispersing effect to prepare pre-treatment baths such as quick starch sizing at low temperatures, development of long-term stable homogeneous emulsions, dye dispersions, and thickeners for print paste. The next step was to apply ultrasonic technology to remove contaminants from fibre surfaces and improve dye or chemical diffusion into fabrics while further studies were conducted (Table 3) [22].

Ultrasound's role in various textile applications can be divided into two categories: removing materials/impurities from the surface of textiles (sono-preparation process) and the diffusion and insertion of dye molecules /chemicals and nanoparticles into fibres (sono-dyeing/sono-printing and sono-finishing). Although it is difficult to differentiate between the chemical and physical parts of ultrasound that are responsible for the two different applications, cavitation is a significant factor that has been shown to improve the involved reaction rates.

2.6 Microwave-assisted pre-treatment

The term "microwave" (MW) was introduced in 1932, and it was initially employed in radiocommunication and radar technology during World War II. Microwaves are now widely recognised and used in various applications, including mobile phones, television, wireless computer networks, and even specialised applications like rocket launching engines.

In the textile finishing industry, electromagnetic waves have been utilised to dry thick textiles using radio frequency (RF) dryers that operate at various frequencies. The first use of MW in textile finishing dates back to the 1970s, when cellulose fabrics were treated with Durable Press (DP) finishing agents and cured in a microwave oven.

The activation of polar molecules in the treated media is the basis for microwave dielectric heating (polarisation phenomenon). The charge changes polarity approximately five billion times per second in a microwave electromagnetic field; it is pulsating at 2.5 GHz, a popular frequency for heating purposes. Microwave heating is faster, more uniform, efficient, and easier to penetrate to the inside of particles. However, there has been little research in the literature describing the feasibility of using a microwave for desizing, scouring, bleaching, dyeing, and finishing cotton-based fabrics (Table 3) [22].

Typical findings were observed in the recent work related to ultrasound and microwave-assisted pretreatment of textile materials.

Table 3: Ultrasound and microwave-assisted pre-treatment of textile materials

Treatment	Substrate	Experimental conditions	Key findings
Ultrasonic	wool	Ultrasonic system capacity 14 lit, temp range- 30–80^{o}C, ultrasonic power of 2 × 400 W with frequency 40 kHz. Optimized scouring condition- 0.5-1 g/l soda, 2-3 g/l soap, 35^{0}C, for 30-35 min	Ultrasounds cause emulsification of the suint. The high frequency of the acoustic wave and low vibration amplitude does not cause damage and entanglements to wool fibre [23].
Microwave	wool	Scoured fabric bleached with microwave treatment. hydrogen peroxide (30%)- 1-10 volume. pH-9. Microwave input power- 150–750 W. Temp- 45–75^{0}C. Time- 1-25 min, MLR- 1:5-25	Obtained High whiteness with a short treatment time and Minimum destructive effect on wool fibres. Treatment increases the COD and BOD of wastewater [24].
Microwave	silk	Microwave oven (output-1550 watt operating at Frequency- 2450 MHz) Recipes: Soda ash- 2.5-10 % (owf), time 1-5 min, microwave power- 70 %. hydrochloric acid- 0.01-0.5 m, time 2-10 min, microwave power- 100 %. savinase, conc.- 0.1- 4%, time 2-15 min, Temp- 60^{0}C, microwave power- 30 %.	Enzymatic treatment in microwave energy exhibits efficient sericin removal without fibre damage. Microwave-assisted degumming is possible at minimum enzyme dosage and treatment time [25].
Microwave and ultrasonic	silk	Microwave parameters- (1550 watt & 2450 MHZ)- power consumption- 50 %, time -5 min. Ultrasonic parameters - (220 W &40 KHz), Temp- 60 ^{0}C, time- 30 min.	Soda ash + hydrogen peroxide and enzyme (papain) show efficient degumming. Compared with conventional techniques, microwave and ultrasonic show efficient

		Recipes used in both treatment: Hot water Soda ash-5 g/l (pH 10.5) Non-ionic detergent- 1 g/l (pH 7.5) Soda ash-1 g/l + hydrogen peroxide (50%) -2 g/l (pH 9.6) Enzyme (papain)- 5 g/l (pH 6.8)	degumming without hampering the strength of silk fabric. Dye uptake improvement after degumming [26].
Microwave	cotton	Grey cotton is treated with desizing agents, scouring agents, bleaching agents, and auxiliary chemicals.	Complete pre-treatment is done within 5 min. Maximum removal of starch sizing agent obtained in the microwave oven at power 800 W for 2 min. Complete wax and impurities removal is achieved. Whiteness obtained by optimised microwave treatment is around 60 [27].
Ultrasonic	cotton	Scoured cotton were bleached with H2O2 (50 %): 10 mL/L, NaOH (50 %): 6 mL/L, Stabilizer: 1 mL/L, Wetting agent: 1 mL/L, liquor ratio: 20:1, pH: 10. Ultrasonic parameters – frequency-35 KHz, Temp- 30-90^0C, time- 30-60 min.	Ultrasonic treatment helps achieve better fastness properties like conventional pre-treated fabric with minimum time and temperature [28].

3. Summary

The problem of environmental stress exists and will not go away by magic. The impact of new technologies and techniques like as ultrasonic and microwave technology, ozone treatment, and enzymatic processing on the long-term viability of wet processing operations has been explored in this paper. However, even in the laboratory, the new processes are still encountering difficulties, necessitating further research and development to make them a viable alternative to traditional processing. These sustainable technologies would reduce the environmental impact, resulting in energy savings, reduced water consumption, and the replacement of harsh chemicals in manufacturing textile materials.

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