Challenges in Sustainable Wet Processing of Textiles

Sujata Saxena, A.S.M. Raja and A. Arputharaj

Abstract Textile wet processing is an important step in textile production as it adds maximum value to the textiles by improving its aesthetics, comfort and functional properties. However, as the name indicates, a large amount of water is used as the medium which during the processing operations gets contaminated with unfixed dyes, chemicals and auxiliaries and is discharged in the end as effluent. The cocktail of chemicals present in this effluent makes it difficult to treat or biodegrade. It creates pollution problems and leads to further demand for good-quality water for processing. Natural textile fibres such as cotton need water and agrochemicals for growing, and petroleum resources are utilized for the manufacture of synthetic fibres. Energy is also needed at various steps of textile manufacturing process. Textile industry is thus water-, chemical- and energy-intensive industry and puts a lot of strain on global resources. Textiles now no longer just fulfil the basic human need of clothing; they have rather become a fashion statement. Rising income levels across the globe have led to manifold increase in world's textile production and consumption in recent years. Average per capita world fibre consumption in the year 2014 was 11.4 kg and estimated that it may increase further in forthcoming years. Present times are therefore very challenging for textile processing industry as the quantum of textiles to be processed has greatly increased and the environmental regulations are getting stricter. As the economies of the countries improve, they move out of the textile processing activities, which then shift to lesser developed nations. This has resulted in lack of serious efforts on improving the sustainability of textile wet processing and poorer adoption of the available methods. The present status of textile wet processing technologies, various developments to tackle the sustainability issues and future prospects would be discussed in this chapter.

Keywords Water quality · Energy · Chemical intensive · Agrochemicals · Cotton · Synthetic fibres · Sustainable wet processes

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1 Introduction

Textiles today not only fulfil the basic human need for clothing but are also a fashion statement. The rising income levels have started fast fashion trend which has tremendously increased per capita consumption of textiles in past few decades. It is estimated that the global textile and garment industry including textile, clothing, footwear and luxury fashion is currently worth nearly $3000 trillion [1]. Contribution of the textile industry to the GDP and economy of many countries is substantial. However, it is a highly input-intensive industry. Textile fibres, the raw material used for making textiles whether natural or man-made, have their own environmental impact. These are then converted into yarns and fabric which are subjected to wet processing to impart aesthetic and functional values. Textile materials are treated with a number of dyes, finishing chemicals and auxiliaries in the process, and as the name suggests, water is used as carrier which gets discharged at the end of the process. This discharged water is highly polluting in nature as it contains a cocktail of unfixed residual chemicals and requires extensive treatment before it can be disposed. Increasing demand for textiles is increasing the quantum of wastewater from textile wet processing and is straining the scarce freshwater resources of the world. Textile industry in China, which accounts for nearly 54 % of the world's total textile production, discharges over 2.5 billion tons of wastewater every year [1]. The use of harmful, hazardous and persistent chemicals in wet processing is harmful for the ecosystem and human health. Today, most of the textile wet processing operations have shifted from the developed nations to the developing nations. As industries in these countries lack the resources to tackle pollution problems, it is leading to environmental damage. The 'Dirty Laundry' report published by Greenpeace International [2] highlighted the issue of discharge of toxic chemicals from textile wastewaters in Chinese textile processing units. A later study by the same organization conducted across remote mountain regions of 10 countries across three continents found the hazardous per- and polyfluorinated chemicals (PFCs) to be present in all snow and many water samples [3]. Such release of hazardous, persistent substances in aquatic environment threatens the sustainability of textile production. Sustainability has been defined as 'the ability to meet the needs of the present without compromising the ability of future generation to meet their needs and desires' (World Commission on Environment and Development). Besides water and chemicals, textile wet processing also consumes a lot of energy which is needed for heating the process water, for intermittent drying of textile material and for running the machines which results in the emission of greenhouse gases and increases the carbon footprints of the textiles. This chapter attempts to analyse the major sustainability challenges at various steps of textile wet processing such as consumption of water, energy, carbon footprints and usage and disposal of harmful chemicals and looks into the currently available solutions for sustainable processing. Technological advances such as the use of enzymes and biomaterials, recent developments in dyes, finishing chemicals and auxiliaries and the developments in processing machinery for source reduction and better sustainability have been explored. The present status of the futuristic waterless technologies such as supercritical carbon oxide and plasma technologies has been examined. Role of various eco-labels and standards in promoting sustainable chemical processing, the social and economic issues in adoption of sustainable chemical processing and responsibilities of various stakeholders in making the textile processing operations sustainable have been discussed in this chapter.

2 Textile Wet Processing Practices and Sustainability Issues

Textile material to be dyed and finished is first made water absorbent to make the fibres accessible to dyes and finishing chemicals. Size applied for weaving operations and natural impurities present on the fibres such as waxes, pectins and colouring matter in case of cotton and other natural cellulosics, wax and gum present on wool and silk, respectively, and also the oil, lubricants and waxes applied to the textile during spinning and knitting operations are all removed during the preparatory processing. The prepared absorbent textile is then dyed with a dye suitable for the fibre, and appropriate finishing chemicals as per the end use requirement are then applied to the textiles. Thus, preparatory processing, dyeing and finishing are the major textile wet processing operations.

Challenges in sustainability of textile wet processing operations mainly relate to the consumption of water energy, chemicals and discharge of unexhausted chemicals. Current practices followed in various wet processing operations and their sustainability aspects have been examined in the following sections.

2.1 Preparatory Processing

Desizing or removal of size is usually the first preparatory process. Size added to facilitate fabric weaving affects the fabric wettability and hence needs to be removed to facilitate proper wetting. Process employed for desizing depends upon the nature of size applied. Sizing materials are mainly of two types—natural sizing agents which include native and degraded starch and starch derivatives and cellulose derivatives such as CMC and protein sizes and synthetic sizes which include polyvinyl alcohol (PVA), polyacrylates and styrene–maleic acid copolymers.

Cotton is the most important natural fibre used in the textile industries worldwide and accounts for nearly 40 % share of the total global fibre consumption. Starch-based sizing agents are generally used for sizing cotton yarns as these are economical and provide satisfactory weaving performance. These sizing materials can be removed by hydrolysis with dilute acids or enzymes such as amylases. Hot caustic soda or detergent treatment can also remove these sizing materials but is comparatively less efficient. Though the water requirement of the process is relatively small, starch hydrolysis products greatly increase the biological oxygen demand (BOD) of the desizing effluent, and therefore, desizing process is the main contributor to BOD in cotton processing. In general, about 50 % of the water pollution is due to high BOD wastewater from desizing that renders it unusable [4]. Oxidative desizing processes such as cold pad-batch process based on hydrogen peroxide with or without the addition of persulphate and the oxidative pad-steam alkaline cracking process with hydrogen peroxide or persulphate are comparatively harsh on fibre, but they also simultaneously scour the fabric by removing the impurities. Synthetic sizing materials such as PVA though higher in cost can be removed by simple treatment with hot water and can be recovered from the bath by techniques like ultrafiltration which not only reduces the cost by facilitating reuse but also reduces the pollution.

Natural and added impurities present on textile materials such as waxes, oil, lubricants, gums and dirt, etc. removed by scouring to make it clean and hydrophilic. Cotton fibres contain many non-cellulosic substances such as wax, pectin, and proteins, which are removed during the scouring process. Conventionally, scouring of cotton is carried out at temperatures reaching up to 120 °C in a strong alkaline medium. Auxiliaries such as wetting agents, emulsifiers and sequestering agents are also added to the scouring bath to improve the process efficiency. The process can be carried out in kiers in a discontinuous manner or on a continuous range. Silk scouring or degumming is carried out with soap/surfactants under mild conditions to remove the gummy material known as sericin from the fibres which are made of fibroin protein. The process results in about 24–28 % weight loss and gives the silk a lustrous appearance and soft handle. Protease enzymes can also be used which remove sericin by hydrolysis. Wool which is also a protein fibre is scoured with surfactants and emulsifiers to remove greasy matter. Synthetic fibres both man-made and regenerated are free from the inherent impurities and comparatively need only a mild scouring with surfactants to remove dust, oil, lubricants, spin finishes, etc. added during yarn and fabric manufacturing process. As the impurities are emulsified and converted to soluble form, the scouring process effluent has high BOD, COD, TDS and alkalinity [5]. As the amount of sericin and wool grease in silk and wool, respectively, is substantial, these should be recovered from the processing water as it would otherwise result in very high BOD. Recovered materials can be further utilized for varied applications. Wool grease recovered from the scouring effluent has been used to obtain lanolin and wool wax alcohols.

Scoured textile material is hydrophilic, but it still contains natural or added colouring matter. These impurities are degraded in bleaching operations by oxidative or reductive agents to make the appearance of the textile pure white. Mostly, oxidative agents are employed for bleaching. Chlorine-based bleaching agents such as hypochlorites were widely used in the past, but their use has now been restricted due to the generation of adsorbable organohalides (AOXs) [6]. Hydrogen peroxide is considered an eco-friendly alternative to chlorine bleaching as its degradation products, water and oxygen are harmless. However, this process requires a large amount of water, high temperature, inorganic/organic stabilizers and neutralizing agents. Auxiliary chemicals which are used in the bleaching bath such as phosphate-based peroxide stabilizers increase the TOC and COD values of effluents. Upon neutralization of highly alkaline waste baths, large amounts of salts are produced. Apart from water and chemicals, huge energy is also required for the peroxide bleaching because this process is carried out at temperatures ranging from 90 to 120 °C. Large amounts of water and treatment with chemicals like thiosulphate are needed to remove residual hydrogen peroxide from fabrics which would otherwise cause problems in dyeing especially in reactive dyeing where it would accelerate dye hydrolysis. A more specific enzyme-based process targeting only the coloured substances would be advantageous. Preparatory processing, especially of natural fibres, consumes a lot of water and generates effluent with high BOD and COD values. Cotton preparatory processes including bleaching consume nearly 38 % of the total water consumption for cotton processing [7].

Alkyl phenol ethoxylates (APEOs) such as nonylphenol ethoxylates and octylphenol ethoxylates have been widely used in the textile industry as wetting agents and detergents. They are also used in the preparatory processes like scouring and bleaching. APEOs have hormone-disruptive properties and are found to be toxic to aquatic organisms. They are non-biodegradable and highly persistent and thereby cause problems in the wastewater treatment [8].

2.2 *Dyeing and Printing*

Colour is imparted to the textiles by dyeing and printing processes employing dyes and pigments. Differentiation between dyes and chemicals was historically based on their solubility. Colouring matters which were soluble or could be made soluble in water were known as dyes, and the insoluble ones were designated as pigments. An aqueous solution or dispersion of dyes is used for dyeing, and it imparts solid shade all over the textile material, whereas in printing, surface application of dye in the form of a pattern using a dye/pigment printing paste thickened using a sizing material is used. Dyes used for commercial textile applications are mostly synthetic in origin being derived from aromatic chemicals found in coal tar and have poor biodegradability.

Not all dye used for dyeing textiles gets fixed onto it. Dye fixation depends upon the application class and dye chemistry. Amount of unfixed dye remaining in the dyebath during dyeing of various textile fibres is presented in Table 1.

The unfixed dye results in highly coloured effluent which has a highly detrimental effect on aquatic ecosystems. Colour affects the photosynthetic capability of aquatic plants by reducing the light availability. Besides, dyes and their degradation products may be toxic, carcinogenic or mutagenic [10]. Azo dyes derived from certain carcinogenic or suspected to be carcinogenic aromatic amines have been banned by Germany and then other EU countries since 1990s. Majority of synthetic

Table 1 Percentage of unfixed dyes in dyeing of different fibrous materials [9]

Fibre	Dye type	Unfixed dye %
Wool and nylon	Acid dyes/reactive dyes for wool	7–20
	Premetallized dyes	2–7
	After chromes	1–2
Cotton and viscose	Azoic dyes	5–10
	Reactive dyes	20–50
	Direct dyes	5–20
	Pigment	1
	Vat dyes	5–20
	Sulphur dyes	30–40
Polyester	Disperse	8–20
Acrylic	Modified basic	2–3

dyes used are non-biodegradable. Therefore, these do not get degraded during the conventional effluent treatment process and are rather precipitated and separated as solid sludge which is dried and sent for landfills where it has the potential to contaminate land and groundwater. Large amount of Glauber's or common salt used for better exhaustion of dyes contributes to high TDS (total dissolved solids) content of the dyeing effluent. High TDS water is unfit for human, industrial or agricultural use. It cannot be reduced by conventional treatment, and costly processes like reverse osmosis (RO) or evaporation are needed to reduce it.

Commercial dyes are not pure compounds with the content of active ingredient ranging from 20 to 80 %. Some of them may also contain heavy metals in their structure. Copper and chromium are present in some metalized direct, reactive and metal complex dyes [11]. Metal salts are also used in wool dyeing with mordant dyes. Potassium dichromate often used for the oxidation of vat and sulphur dyes on cellulosic materials would result in the discharge of Cr^{6+} in the effluent which is a known carcinogen. All this can increase the heavy metal content of the textiles which is restricted by many eco-labels and standards. Also, the effluent containing such unfixed dyes and chemicals would require special treatment to bring down the heavy metal content within the permissible limits.

Many dyeing auxiliaries used during dyeing process are non-biodegradable and not recyclable and increase the BOD and COD loads of the effluent. Carriers used to facilitate dyeing of polyester (PET) under milder conditions are toxic and may affect the health of workers besides creating problems in effluent treatment. Decomposition products of sodium hydrosulphite (hydros) and sodium sulphide used as reducing agent in vat and sulphur dyeing increase the sulphide content of the effluent creating disposal problem as it has the potential to form sulphuric acid by bacterial oxidation.

Effluent volume is lesser in printing, as dye and pigments are applied in the form of thick printing paste, but there are concerns about the volatile solvents used in printing pastes which release VOC (volatile organic compounds) in the environment. Unfixed dyes and pigment, however, get discharged as effluent during the subsequent washing-off process, and cleaning of printing screens and other equipments also consumes water and organic solvents and releases the chemicals present in printing pastes to the environment. Many dispersing agents and auxiliaries added to the printing pastes may not be eco-friendly as they may contain formaldehyde from the use of formaldehyde-based fixer/binder and other harmful chemicals. The use of PVC and phthalates in plastisol printing pastes is another issue of concern as both of these are harmful.

2.3 Textile Finishing Operations

Hand and functional characteristics of textiles are modified by using various finishing chemicals. Formaldehyde has been widely used in the manufacturing of a large number of textile auxiliaries such as dye fixing agents, softeners, and cross-linking resins. Formaldehyde-based resins have been used to impart easy care and durable press properties to cellulosic textiles by the formation of cross-links, and these have also been used in many finishing formulations as cross-linking agents to improve durability. Such textiles during use may release formaldehyde which may cause eye irritation, skin rashes and allergic reaction, and it has also been classified under group 1 'carcinogenic to humans' since 2004 by the International Agency for Research on Cancer (IARC).

Durable water, oil and stain repellency in textiles has been achieved by polymeric finishes having perfluoroalkyl chains having eight or more fluorinated carbons [12]. These long-chain fluorinated polymers often contain residual raw materials and trace levels of long-chain perfluoroalkyl acids (PFAAs) as impurities. The residual raw materials and the product themselves may degrade in the environment to form long-chain PFAAs. On account of their widespread use and low biodegradability, long-chain PFAAs including perfluorooctanoic acid (PFOA) and perfluorooctane sulphonate (PFOS) having toxicological properties of concern have been detected globally in the environment, wildlife and humans [13].

Textiles are often treated with antimicrobial agents for health and hygiene purposes and to prevent odour formation due to bacterial action on perspiration. Among synthetic antimicrobial chemicals, usage of triclosan (2, 4, 4-trichloro-2-hydroxydiphenyl ether) which was very popular due to its efficacy is now being restricted as it gets degraded to 2, 8-dichlorodibenzo-p-dioxin by the action of sunlight which being a polychlorinated dioxin is toxic.

Many finishes used for imparting flame-retardant properties to textiles are toxic. Brominated flame retardants such as polybrominated diphenyl ethers (PBDEs) have been found to be very toxic to humans [14] but are still in use for textile finishing [15]. They are chemically similar to polychlorinated biphenyls (PCBs), which have been banned in many countries. Some flame retardants have toxicity due to the heavy metal content in their structure. Antimony oxide-based flame retardants are also used, though the amount of antimony on textiles has been restricted by eco-labels.

Textiles finished using harmful chemicals, catalysts and auxiliaries are not only harmful to the users of these textiles but also an occupational health hazard to the workers in processing units. The unfixed chemicals get discharged into effluent and pollute the ecosystem affecting a large number of people. Most of the finishing processes involve curing at high temperature for fixing the finish onto the textile substrate which requires energy which can contribute to the carbon footprints of textiles if it is derived from the burning of fossil fuels.

3 Environmental Impact of Textile Wet Processing

It transpires from the discussions in the previous section that there are many sustainability issues in the current wet processing operations in the textile industry. It is highly chemical-intensive, a number of eco-unfriendly and non-biodegradable products are being used in these operations, and a large amount of these chemicals remains unused at the end of operations which gets discharged along with the process water as effluent. The toxic non-biodegradable chemicals used in chemical processing are difficult to remove from wastewaters and may require tertiary and further treatments, and a failure to do so results in environmental contamination. As most of the textile wet processing operations are now located in developing or less developed countries where most of the processing is carried out by small-scale units, which lack the resources to adopt modern expensive technology for proper treatment of this effluent, it is being discharged into the environment without sufficient treatment to make it harmless. This has resulted in large-scale environmental damage in the area around these units. These contaminants can enter the food chain, and their increasing content over the food chain due to bioaccumulation may result in harmful levels of these contaminants for humans and animals. It was observed in a study conducted by Rajkumar and Nagan [16] in and around Tirupur, a major textile processing hub in the southern part of India, that untreated and partially treated effluent discharged in the river Noyyal by textile dyeing units for the past 20 years has accumulated in soil and water at many locations and it has affected the groundwater, surface water, soil, fish and the natural ecosystem in Tirupur and downstream area. Apart from the detrimental effect of the effluent discharge from processing units, burning of fossil fuels to provide energy for the various processing operations also results in the emission of greenhouse gases which adds to the global warming and climate change concerns. Detailed discussion of the environmental impact of textile wet processing has been made in the following subsections.

3.1 Impact on Water Resources

As the effluent coming out from textile processing units is discharged into the water bodies, these are the first to be affected by the textile wet processing operations. A large quantity of good-quality water is needed for these operations as water is used as a medium and solvent for dissolution of process chemicals as well as washing-off agent, besides generation of steam for heating the process bath. The actual amount of water used for processing depends upon the type of material being processed, nature of dyes and finishing agents and type of processing machinery employed; on an average, 50–100 L water (world average) is required for processing one kg of textile material [17]. Natural fibres usually consume more water for processing in scouring and bleaching comparison with synthetic fibres as natural impurities present on these fibres need water for their removal. General requirement of water for dyeing in different machineries is presented in Table 2.

Most of the water used along with unfixed dyes, chemicals and auxiliaries is discharged as effluent at the end of wet processing operations. Effluents from textile industries are complex mixtures of chemicals varying in quantity and quality. Both inorganic and organic pollutants are present in these effluents. These have high chemical oxygen demand (COD), BOD, TDS, pH, total suspended solid (TSSs) values and low dissolved oxygen (DO) value as well as strong colour [18]. The major concern with colour is its aesthetic character at the point of discharge as also the visibility of the receiving waters [19, 20]. Inorganic pollutants are mostly metallic salts, and basic and acidic compounds. These inorganic components undergo different chemical and biochemical interactions in the water bodies and deteriorate water quality. The organic pollutants are both biodegradable and non-biodegradable in nature. The biodegradable organic components degrade water quality as oxygen is consumed during their decomposition which depletes the DO affecting the aquatic animal forms. The non-biodegradable organic components persist in the system for a long time and pass into the food chain. As these substances move up the food chain, bioaccumulation takes place, affecting animals and humans.

Clean good-quality water is essential for humans as well other life forms. It is also needed for industrial activities and irrigation purposes. Inorganic and organic waste mixed with textile wastewaters leads to changes in both biological and chemical parameters of the receiving water bodies [21]. The scarcity of clean water and pollution of freshwater has led to a situation in which one-fifth of the urban dwellers in developing countries and three quarters of their rural dwelling

Table 2 Comparison of water usage (litre/kg of material) by different dyeing machines [9]

Nature of the equipment	Direct	Reactive	Vat	Disperse
Jigger	7.1	16.0	10.1	
Beck	18.4	37.9		22.5
Beam				19.5
Continuous			4.1	

population do not have access to reasonably safe water supplies [22]. The ecological and toxicological problem resulting from the discharge of effluent from textile industry into the streams and other inland water bodies is a major issue all over the world, especially in developing countries where textiles contribute substantially to the national GDP. A study conducted by Kumar et al. [23] in Haridwar, India, found that discharge of textile effluents into the stream had considerable negative effects on the water quality and the water was not suitable for human consumption and domestic use. Toxic substances present in textile effluent also affect plants and vegetation, and the polluted water adversely affects agricultural production. It was observed in a study at Lagos, Nigeria, that watering with treated textile mill effluent mixed stream water reduced the photosynthetic pigments by 59.9 % and resulted in 41 % growth inhibition [24].

A study conducted in the Narayanganj district of Bangladesh concluded that the values of various water quality parameters including heavy metals like cadmium (Cd), copper (Cu), lead (Pb) and chromium (Cr) in water samples collected in the vicinity of effluent discharge area of a textile mill were much higher than the prescribed standards, and therefore, the water around the experimental area was unsuitable for recreation, drinking, domestic, irrigation and industrial purposes [25]. In Ethiopia also, discharge from textile factory was found to make the Blue Nile River water highly polluted. The values of most metrics followed pollution gradient and showed deteriorated water quality conditions [26].

3.2 Energy Consumption and Carbon Footprints

Globally, textile and clothing sector significantly contributes to carbon footprints and greenhouse gas emissions due to its lengthy and complicated supply chain [27]. To determine the carbon footprint of any product, it is essential to find out the level of 'embedded energy' within the product; this is all of the energy utilized at each stage of the production process [28]. The carbon footprint of a textile product depends on the nature of the raw material, i.e. fibre used and the method adopted for its processing. Though the energy requirement of chemical processing is only about 38 % of the total energy requirement of the textile production [29], energy use is very inefficient. Apart from a small amount of energy required for running textile machines, most of the energy required for chemical processing is thermal. Table 3 compares the energy requirement of different stages of chemical processing.

Table 3 Energy requirement for processing of 1 kg of textile material [30]

S. No.	Process	Energy (MJ/kg)
1	Scouring without drying	5–18
2	Bleaching and drying	8–33
3	Bleaching, dyeing and drying	10–35
4	Dyeing, finishing and drying	8–18
5	Finishing	6–12

As many textile processing operations are conducted at high temperature, energy is required for heating the bath and intermittent fabric drying operations. Reducing the water consumption for processing may reduce the energy consumption because heating of water and its removal will require less energy. Hence, dyeing in cabinet hank dyeing machine requires more energy than cheese dyeing process as amount of liquor to be heated up is more [31]. The use of low liquor ratio machines would therefore result in energy savings. Conservation of energy can be made through process and machine modification, proper chemical recipes and new technologies. Heat loss to ambient air from machines operating at high temperature can be reduced by proper insulation of the machines. Steam pipes supplying the thermal energy are often leaky, poorly maintained and not properly insulated leading to energy losses. Proper insulation provides resistance to convectional heat transfer with less steam and fuel consumption in heating contents up to the required temperature. In addition, insulation reduces the outer surface temperatures, which lessens the risk of burns. A well-insulated system also reduces heat loss to ambient workspaces, which can make the working environment in the factory more comfortable.

Thermal energy in textile mills is usually supplied by steam generated by burning of fossil fuels which results in the emission of greenhouse gases and contributes to the primary carbon footprints of textiles. These depend upon the type of fossil fuel used as emissions of carbon dioxide from natural gas are only around half of those produced from coal. The use of renewable energy therefore has great potential in reducing the carbon footprints of textile processing industries.

Indirect carbon footprints of textiles are derived from the embedded energy of chemicals and raw materials used. Textile fibres differ widely in their carbon footprints with synthetic fibres having larger carbon footprints due to embedded energy costs in their manufacturing. But there is not much difference in the carbon footprints of these fibres at processing stage. Regarding the emission contribution of various processing steps, in a fully continuous textile finishing process for cotton textiles, about 50 % emissions come from drying, 40 % from washing and steaming and 10 % from the use of chemicals. In finishing of knitwear by exhaust process, 60 % emissions are caused by heating the water [32]. Apparel and textiles account for approximately 10 % of the total carbon impact in the world. The estimated consumption of electricity for the annual global production of 60 billion kilograms of fabrics was estimated to be 1 trillion kilowatt hours [33].

3.3 Use of Toxic and Non-biodegradable Products

About 8000 different chemicals are used in textile processing, and many of these as discussed in the earlier sections are toxicologically and environmentally harmful. It is estimated that about six million tonnes of textile chemicals are used every year [34]. The use of alkalis for scouring, hypochlorite for bleaching, APEO as wetting agents, formaldehyde-based auxiliaries and cross-linking agents, petroleum-derived non-biodegradable and heavy metal containing dyes, Glauber's and common salt for dyeing of cellulosics, carriers for dyeing of PET under milder conditions and use of bromine/antimony-based chemicals for functional finishing are some of the examples. The presence of these unfixed substances in the process wastewaters at the end of the process is an environmental hazard as its treatment and disposal is a problem due to the potential to pollute the land and water bodies wherever it is discharged. Besides, the use of toxic chemicals also poses an occupational health hazard to workers in the processing unit. It is therefore suggested that hazardous and non-eco-friendly chemicals used in wet processing should be substituted by less toxic and more eco-friendly products so that toxicity of the discharged effluent gets reduced and it has better biodegradability. Some such alternative chemicals for various processes to reduce effluent toxicity are listed in Table 4.

Table 4 Eco-friendly alternative chemicals for textile wet processing [35]

S. No.	Purpose	Chemical	Alternative
1	Sizing	Starch	Water-soluble polyvinyl alcohol
2	Desizing	Hydrochloric acid	Amylases
3	Scouring of cotton	Sodium hydroxide	Pectinases
4	Bleaching	Hypochlorites	Hydrogen peroxide
5	Oxidation of vat and sulphur dyes	Potassium dichromate	Hydrogen peroxide, sodium perborate
6	Thickener	Kerosene	Water-based polyacrylate copolymers
7	Hydrotropic agent	Urea	Dicyanamide (partially)
8	Water repellents	C8 fluorocarbons	C6 fluorocarbons
9	Crease recovery chemicals	Formaldehyde-based resin	Polycarboxylic acids
10	Wetting agents and detergents	Alkyl phenol ethoxylates	Fatty alcohol phenol ethoxylates
11	Neutralization agent	Acetic acid	Formic acid
12	Peroxide killer	Sodium thiosulphate	catalases
13	Mercerization	Sodium hydroxide	Liquid ammonia
14	Reducing agents	Sodium sulphide	Glucose, acetyl acetone, thiourea dioxide
15	Dyeing	Powder form of sulphur dyes	Prereduced dyes
16	Flame retardant	Bromated diphenyl ethers	Combination of inorganic salts and phosphonates
17	Shrink proofing	Chlorination	Plasma treatment

4 Technological Developments in Source Reduction for Mitigating Environmental Impact

As treatment of textile effluent to make it safe for disposal in a manner which is not harmful to the environment is difficult and costly, various attempts have been made to reduce the input requirement in textile processing which can reduce the pollutant load as also the quantity of effluent generated and thereby improve the sustainability of textile industry. Some of these approaches have been described in the following sections.

4.1 Use of Biomaterials and Renewable Energy

The use of materials of biological origin is an approach which has excellent potential to reduce the pollution load as these materials are biodegradable and are generally safe. Bioprocessing or the use of enzymes for textile preparatory and finishing processes, the use of natural dyes for coloration and the use of natural product-based materials for functional finishing of textiles are the fields where biomaterials have been used with varying degree of success and the same has been discussed in the following lines.

Bioprocessing Using Enzymes

Processing using enzymes generally requires less energy, less water and less effluent problems as enzymes being biocatalysts are readily biodegradable. Alpha amylase enzymes which degrade starches into glucose have successfully replaced the acidic desizing of starch-based sizes used for cellulosics. As enzymes are very specific in action, no fibre damage takes place during the desizing process, whereas acids have a degrading action on cellulose which also increases the effluent load besides the acidic nature of the effluent. The use of amylase for desizing can also reduce the consumption of water, chemicals and energy [36]. Both amylases and acids, however, degrade the starch to glucose which results in high BOD of effluent. Glucose oxidase enzyme has been used to convert the glucose generated during desizing into hydrogen peroxide [37]. Alkaline pectinase enzyme-based process can be an alternative to alkaline scouring at high temperature and pressure in kiers. The enzymatic scouring can be carried out at moderate temperature resulting in energy savings, and also the gentle action of the enzyme on cotton fabric results in less damage, less pilling and uniform dye uptake [38].

Huge savings in energy and water by bioscouring have also been illustrated by Menezes and Choudhari [39]. Enzymatic desizing cum scouring results in lower, about 2–3 % fibre loss as compared to 7–8 % in conventional process resulting in about 5 % lower TSS value. Hebeish et al. [40] have tried to combine enzyme-based scouring with activator-assisted bleaching in single bath to remove the non-cellulosic impurities from the cotton textiles at moderate temperature.

The use of laccases from different sources for removal of colouring substances from cotton textiles has recently been looked into to make the process more eco-friendly. Though hydrogen peroxide is considered an eco-friendly bleaching agent as its degradation products are harmless, it is applied at alkaline pH and temperatures close to boiling are required for effective bleaching action which can cause fibre damage. A more specific process targeting only the coloured substances would be advantageous. If an enzyme-based system for bleaching can be developed, it can be integrated in the pectinase-based bioscouring process which has recently been implemented at an industrial scale. Laccase/mediator systems have been successfully used for the bleaching and modification of wood pulp fibres. Based on the observation that fungal laccases oxidize phenolic moieties of lignin in pulp and their capability of attacking phenolic hydroxyl groups, attempts have been made to use them to decolorize or eliminate flavonoids responsible for colour in cotton, thus resulting in bleaching action [41].

Laccases for bleaching denims to produce stone wash effect without the problem of back staining have become commercially available [42]. The laccase enzyme has also been used in combination with cellulase or after cellulase treatment to impart back-staining free washed look to denims [43, 44], as the use of cellulase alone causes back-staining due to redeposition of indigo dye [45].

Huge amounts of water and treatment with chemicals like thiosulphate are needed to remove hydrogen peroxide from fabrics which would otherwise cause problems in dyeing, especially in reactive dyeing where it can accelerate the dye hydrolysis. Catalase enzymes have been effectively used to clean up or remove the residual hydrogen peroxide in place of chemicals. Less water is required as rinsing steps are reduced, and the catalase-treated fabrics show uniform dyeing and good dye uptake [46]. Catalase-treated bleach cleanup bath itself can be subsequently used for dyeing [47].

Natural Dyes

Colouring matters derived from plant, animal and mineral resources were the only dyes available to man since prehistoric times till the first half of the nineteenth century. After the discovery of first synthetic dye in 1856 followed by many more, the traditional dyes being derived from natural sources were termed natural dyes. Subsequent rapid strides made in the field of synthetic dyes, their ease of application, ready availability in a wide range of colours, good colour fastness properties and suitability for use in large industrial set-up led to almost complete replacement of natural dyes with synthetic dyes for mainstream textile production.

However, the environmental awareness about the pollution caused by the use of synthetic dyes resulted in a global revival of interest in natural dyes since the last decades of twentieth century. The ban on certain azo dyes by Germany and other EU countries in 1995 in view of their being derived from suspected carcinogenic amines further boosted this interest which led to a rediscovery of natural dyes. Natural dyes are considered to be eco-friendly as these are renewable and biodegradable; are skin-friendly; and may provide health benefits to the wearer as many natural dye-yielding plant parts have been used as medicines in various traditional medicinal systems.

As the bulk of traditional knowledge in this area was lost due to many years of neglect, attempts were made to reconstruct the dye extraction and application processes by interacting with a few surviving traditional dyers and scanning whatever old records of this practice were available and by conducting research to know about the potential natural dye sources for textiles. It led to the publication of a number of books and articles about various natural dye sources and their application processes for textile fibres [48–58].

Natural dyes are usually not a single entity but a mixture of closely related chemical compounds whose content will vary depending upon the maturity, variety, and agroclimatic variations such as soil type and region. This makes the task of shade reproducibility difficult. Therefore, it is not possible to produce the same shade with a particular natural dye in every dyeing operation [59]. Even the differences in mineral content and pH of the water at two different places will produce a different shade with the same dye. That is a constraint in promoting large-scale use of natural dyes. The use of metallic mordants such as copper, tin and chrome for fixing and/or improving the colour fastness properties of natural dyes is not eco-friendly, and therefore, it is to be ensured that the content of restricted heavy metals in the dyed material is in compliance with the eco-regulations.

Dye-bearing natural materials contain only about 0.5–5 % dye; hence, these materials cannot be directly used in dyeing machinery as the large amount of plant matrix made up of a variety of non-dye constituents would result in patchy and uneven dyeing. This requires an additional dye extraction step to separate dyeing matter from non-dye plant matrix. Purified dye extracts commercially available now in countries such as USA, Europe, China and India are costly and are mainly used by hobby groups for the uniqueness of the shades. It is estimated that only about 1 % of the total textiles produced in the world are dyed by using natural dyes [60]. Traditional dyers, enthusiasts and hobby groups are the main users of natural dyes who work at cottage level.

Many natural dyes, if applied properly, can match the colour fastness properties of good synthetic dyes, but their colour range is rather limited with colours being soft and earthy. The most important advantage of natural dyes is their biodegradability. Bechtold et al. [49] have reported a reduction in pollution load with plant-based dyes in comparison with the use of synthetic dyes even with the latest dyeing techniques. Nayak [61] have found that the cost of dyeing textiles in blue, black and yellow shades with natural dyes is competitive with synthetic dyes when environmental cost of dyeing is also taken into account. Thus, the usage of natural dyes has the potential to reduce the risk of polluting the local water resources and offers a clean production model. The current dyestuff requirement from the industry being about 0.7 million tonnes [62] the use of natural dyes in mainstream textile processing is a big challenge as agricultural land is primarily required to feed an ever-increasing world population and support livestock. Also, biodiversity should not be compromised for the extraction of dyes, and therefore, in spite of being the natural choice for dyeing of organic textiles, the standard for such textile, GOTS, has banned the use of dyes and materials from endangered plants and has permitted the use of synthetic dyes having low environmental impact. Further, reasonable colour fastness levels are also required, and so only some natural dyes fulfilling these criteria can be used.

The use of agro and agroprocessing residues, microbial sources and cultivation of suitable dye plants in wastelands has the potential to enhance the availability of natural dyes for cottage and small-scale processors who can use these dyes for cleaner production to make their operations more sustainable as they do not have access to costly effluent treatment processes.

Use of Bioagents for Finishing

Use of Enzymes: Cellulase enzymes now find wide use in biopolishing of cotton textiles. Loose fibres adhering to the fabric which were previously removed by singeing can be removed by the treatment with cellulase. Thus, pilling can be reduced with a softer and smoother feel without the danger of fabric damage or yellowing due to exposure to the flame, and the fossil fuel used in singeing is saved. PET-based textile materials have been treated with esterase, lipase and cutinase enzymes to improve the moisture absorption characteristics as well as surface softness and to reduce pilling. Conventionally, the PET fabric has to be treated with sodium hydroxide to improve the above properties which led to higher strength loss and damage to the fabric. Enzymes have the potential to substitute the harsh chemical treatment and make the process eco-friendly [63].

Papain, a plant-origin proteolytic enzyme, has been used for shrink proofing of wool. However, the wool has to be first pretreated with a reducing agent such as sodium sulphite to achieve an effective shrink-resistant property.

Functional Finishing: Textile surfaces may act as nutrient for microbial growth which may cause unpleasant smells, staining, loss of mechanical strength and health-related problems for the wearer. An antimicrobial finish reduces the growth of microorganisms by either killing or inhibiting their growth through contact with the fabric surface [64]. Antimicrobial agents have been used on textiles since thousands of years ago; the use of spices and herbs as preservatives in mummy wraps by ancient Egyptians is an example [65]. Natural dyes and mordants such as myrobalan and turmeric used in earlier days for textile dyeing also possessed antibacterial properties in addition to providing colour. Antibacterial activity of many natural dyes can be attributed to the presence of tannins which have been reported to have antimicrobial properties against several strains of bacteria through in vitro studies [66–68]. Textiles dyed with such materials are also likely to show antimicrobial properties, and the same has been reported by many researchers [69–71].

The antimicrobial efficacy of these natural substances therefore would depend upon the type of tannins and their concentration in the substrate. Antimicrobial action of tannins can be due to their binding action with the proteins and enzymes present in the cell wall of microorganisms, thus inhibiting their metabolism and growth. Their capacity to bind with vital metal ions required by the microorganisms may also be a factor for growth inhibition [72]. Tannins generally have higher efficacy against Gram-positive bacteria as compared to Gram-negative bacteria. Their efficacy as antimicrobial agents for textiles may get limited due to the problems in getting a durable build-up of the required inhibitory concentration on textile material. Neem extract, due to the presence of azadirachtin, a tetranor-triterpenoid, has also been found to impart good antibacterial properties to textiles; however, its durability was poor.

Durability of plant extract-based antibacterial finishes in general is poor due to their lack of affinity to textile substrates. Application of these extracts after microencapsulation to trap the active antimicrobial agent using modified starch, gum acacia, sodium alginate, etc., as wall materials resulted in improved wash durability [73, 74].

Chitosan, obtained by alkaline deacetylation of chitin, a waste product of crab and shrimp processing industry, has also been reported to be effective against many common bacteria though the efficacy may vary according to molecular weight and degree of deacetylation. Chitosan and its derivatives have been used by for imparting antibacterial properties to textiles [75–77].

UV-Protective Finishing: Many natural dyes absorb in the ultraviolet region, and therefore, fabrics dyed with such dyes should offer good protection from ultraviolet light. Improvement in UV protection characteristics of natural cellulosic fibres after treatment with natural dyes has been reported by various researchers [78–80]. It was observed by Grifoni et al. [81] that treatment with tannins during mordanting itself improved the UV protection of fabrics. Saxena et al. [82] also reported that tannin-rich pomegranate rind extracts showed strong absorption in the UV region, and cotton fabrics treated with these extracts were imparted excellent UV protection which was durable to washing.

Aroma and Other Finishing: Microencapsulated essential oils have been used for aroma finishing of textiles. Such textiles not only create a feeling of freshness to the users but also have medicinal properties depending upon the essential oil used.

Microencapsulated citronella oil has been used for providing mosquito-repellent properties to textiles [83]. Chrysanthemum oil nanoemulsion has been used for wash-durable mosquito-repellent treatment of nylon nets [84].

Basak et al. [85] have used banana pseudostem sap to impart flame-retardant property to bleached and mercerized cotton textiles which were earlier pretreated with tannic acid and alum.

4.2 Process Improvement and Optimization

Combining two or more processes in a single step makes the process more sustainable due to lower consumption of water, chemicals and energy. For example, desizing and scouring processes can be combined. Also, scouring and peroxide bleaching can be combined as both require alkaline conditions. It may be possible to combine desizing, scouring and bleaching steps by using peracetic acid for bleaching. Various approaches to improve wet processing operations to reduce their environmental footprints have been tried, and some of these developments are reported here. Optimization of various process parameters also results in better sustainability by judicious use of resources.

Reactive dyes are mainly used for dyeing of cellulosics and their blends due to their good performance and cost-effectiveness. But the large quantity of salt (sodium chloride or sodium sulphate) used in dyeing is a cause of concern as it results in very high TDS of effluent which cannot be reduced by conventional effluent treatment methods, and costly processes like RO and ultrafiltration are needed. Cationization of cotton has been suggested for salt-free or low-salt dyeing with reactive dyes. Cationic agents such as 1-amino-2-hydroxy-3-trimethylammonium propane chloride [86] and 3-chloro-2-hydroxypropyl trimethyl ammonium chloride—CHTAC [87] have been suggested for this purpose. Applications of cationic polymers such as dimethylamino ethyl methacrcrylate [88], polyepichlorohydrin dimethylamine [89], polyamide–epichlorohydrin resin [90], poly(4-vinylpyridine) quaternary ammonium compound [91], dendrimers [92] and amino-terminated polymers [93] have also been suggested to make cotton cationic. Chitosan and its derivatives such as O-acrylamido-methyl-N-[(2-hydroxy-3-trimethylammonium) propyl] chitosan chloride (NMA-HTCC) have also been used for imparting cationic charge to cotton for low-salt dyeing of cotton [94, 95].

Replacement of the inorganic salts with biodegradable organic salts has also been attempted. Prabhu and Sundarajan [96] found that sodium citrate can be used as an alternative to inorganic electrolytes for dyeing of cotton fabrics with reactive and direct dyes with satisfactory results and significant reduction in TDS. An organic salt trisodium nitrilo triacetate was used as an alternative to sodium chloride for reactive dyeing of cotton by pad-steam method [97]. Dyeing was satisfactory with low pollution load. Organic electrolytes such as sodium edetate [98], sodium oxalate [99] and polycarboxylic acid sodium salts [100] have also been proposed as an alternative for inorganic electrolytes for dyeing.

Processing method used also has an effect on the effluent load. Exhaust processes usually require a higher material-to-liquor ratio; therefore, more water, energy and chemicals are required, and amount of effluent generated is also higher, whereas processes can operate at lower material-to-liquor ratio and therefore are more efficient. Cold pad-batch process for reactive dyeing has significant sustainability advantages. In this semicontinuous method, fabric to be dyed is first padded with liquor containing a mixture of reactive dyes and alkali (sodium silicate or sodium carbonate). It is then covered with polythene sheets to prevent evaporation of water and stored onto rolls. After a batching period of 6–12 h, the material is washed with water and hydrolysed dyes are removed by soaping. As salts, lubricants, levelling agents, fixatives and defoamers are not used in the process, effluent load is very less. Energy consumption is very less as dyeing and fixing takes place at ambient temperature.

Digital printing is an innovative development which has considerably improved the sustainability. Automatic rotary screen printing technique is mostly used for the textile printing. Digital printing is an inkjet-based application of colourants onto textile materials. The concept of this recent development in the printing field of the textile industry was initially introduced by Dr Sweet in early 1980s. Today, inkjet printers have become very popular for printing on textile substrates. It is a clean technology because of a high degree of utilization of printing inks and minimum water and energy consumption during post-treatment. It has the following advantages:

- Unlimited colour sampling and very good fastness,
- Easy switch over of designs without stopping the machine, whereas in conventional printing, each design requires making of screens, adjustment of pattern and sample printing before new design can be taken up and therefore a long downtime,
- Good reproducibility of designs,
- No limitation of size of the repeats of designs.

However, there are some limitations of the digital printing process also such as slower printing speed, requirement of high-quality special inks and specialized pretreatment of textiles to get good print quality which have slowed down its adoption rate.

4.3 Developments in Textile Chemicals, Dyes and Auxiliaries

There has been a general enhancement of awareness about environmental impact of textile processing among all stakeholders. Textile chemicals, dyes and auxiliary manufacturers have also made consistent efforts to develop chemistries which are more eco-friendly and sustainable. Dyes which have better exhaustion and can be dyed at lower temperature can reduce dye and energy consumption. Initial reactive dyes for dyeing of cellulosics had only a single functional group; hence, a good amount of dye was getting hydrolysed by reacting with water resulting in dye wastage and highly coloured effluent. To overcome this problem, bi- and multifunctional reactive dyes were introduced resulting in better dye utilization and less dye in effluent. It is claimed that Avitera® SE 3 range of polyreactive dyes introduced by Huntsman for cellulosic fibres and their blends can reduce water and energy usage by 50 % and also the salt consumption by 20 % during the dyeing process.

Prereduced vat and sulphur dyes have been made available by dye manufacturers. This significantly reduces the pollution caused by the use of reducing agent during dyeing and also simplifies the dyeing process. Archroma has recently launched dyes based on natural waste materials such as almond husks.

Coming to auxiliaries too, fatty alcohol-based ethoxylates have been commercially introduced as biodegradable non-ionic detergents in textile processing to replace poorly degradable nonyl and octyl phenol ethoxylates used earlier.

Sugar-based reducing agents have been introduced to replace sodium hydrosulphite for dyeing with vat and sulphur dyes.

Water, oil and stain repellency to textiles was earlier being provided by fluorocarbon finishes based on C8 chemistries. Due to the environmental issues associated with these finishes, shorter-chain C6 chemistry products have been introduced. Recently, Huntsman has introduced Phobotex® 3 an advanced range of fluorine-free hydropolymers for providing rain protection and stain management properties suitable for a wide range of textile end uses: outdoor rainwear, active wear, career wear and technical fabrics such as tarpaulins, boat covers, outdoor furnishings and shower curtains.

4.4 Development in Textile Machineries

Many developments have taken place in machinery design which result in substantial reduction in consumption of water, energy and chemicals during textile wet processing and make it more sustainable. Today, in batch processing of textiles, there is an emphasis on low liquor ratio processing as a reduction in the amount of process water use per unit textile weight would not only save water, but also reduce the chemical usage, energy requirements and the quantity of generated effluent. Many types of machinery which use low and ultralow liquor ratios for processing of textile materials are now available from various machinery manufacturers. Processing machinery equipped with microprocessor-based controllers reduces energy consumption and CO_2 emission. Similarly, installation of an automated chemical dispensing system optimizes chemical use. Savings due to lower consumption of energy and chemicals ensure a short payback time.

Continuous bleaching and dyeing ranges (CBRs and CDRs) have been introduced by machinery manufacturers and adopted by the processing industry as continuous processing is more efficient than batch processing. The latest CBRs are equipped with prewashers, dosing system with automatic controls, combi steamer, efficient washing units and dryers. Continuous, efficient, counter-current flow washers reduce effluent volume. Open width washers based on continuous interchange of water around fabric with lower contamination wash waters with built-in spray, multinips, vacuum extraction and ultrasonic technology drastically reduce water and steam consumption and provide a highly concentrated effluent for recycling. These also have smaller space requirements and lower operational costs [101].

Vacuum application of dyes; high-efficiency padders; and other dye application systems for continuous dyeing have reduced the environmental impact of the dyeing process. Vacuum dyeing systems for smaller lots have also been developed where dyebath size can be reduced to less than 15 L from 140 to 150 L required for conventional exhaust dyeing systems such as winch. Air flow dyeing technology is an improvement over soft flow dyeing system where liquor ratios of 1:3 can be used and overflow liquor mixed with air in mist form moves the fabric. It is therefore a very gentle process highly suitable for processing of delicate fabrics such as knits. Closed HTHP jiggers have been developed which can be used for dyeing of PET in open width using ultralow liquor ratios of 1:2.

e-control dyeing process introduced by Monforts in collaboration with DyStar at ITMA in 1995 slightly modifies the reactive dyeing process as both, drying and fixation, take place at the same time. The e-control climate inside the fixation chamber ensures a perfect dyeing result during the drying process. By using this process, cotton, viscose, tencel, and linen can be dyed. It is claimed that this process uses less energy, water and chemicals than conventional processes [102].

High-speed stenters with self-lubricating chains requiring very low maintenance have been developed for textile finishing operations. Process control and automation for high energy efficiency have been introduced. Cleaning of exhaust air is undertaken to reduce pollution, thereby making stenters eco-friendly.

Insulation of steam pipes and machinery conserves energy and makes the environment less hot for the workers. The use of heat exchangers can conserve energy usage in wet processing operations and can also bring down the temperature of the effluent.

5 Developments in Recycling and Reuse of Process Inputs

Recycling and reuse of process inputs can reduce the costs by economizing on the quantity of inputs to be procured and also reduces the environmental impact. Advanced membrane processes such as microfiltration, ultrafiltration, nanofiltration, RO, advanced oxidation processes, electrochemical processes, adsorption and ion exchange processes are quite effective for the removal of colour and COD from textile wastewater and appear promising in terms of their performance and cost for treatment and reuse of textile effluents.

5.1 Recovery and Reuse of Process Chemicals

As textile processing baths usually contain a number of chemicals and auxiliaries in dilute solutions or dispersions, their individual recovery is difficult and may not be cost-effective. Also they may undergo changes during the process. Therefore, only a few instances of recovery and reuse of process chemicals are found in textile wet processing. It is common knowledge that alkali containing mercerizing wash liquor can be used for scouring and bleaching. Also, recovery of synthetic sizes like PVA from process waters through membrane filtration techniques is being used by the industry to improve the process economy and reduce the pollution load. As dyes remaining unused in supercritical fluid dyeing process are recovered in pure form, these may be reused for dyeing fresh samples.

5.2 Water Recovery and Reuse

As textile chemical processing operations are carried out in aqueous medium, water is the input which is used in larger quantities. Clean soft water is a precious commodity. Therefore, attempts have been made to reuse the treated effluent for various wet processing operations as that reduces the demand for freshwater. Recovery and reuse of water is beneficial both for conserving and supplementing available water resources and for reducing the environmental pollution. Water recycling and reuse is a necessity for implementing zero liquid discharge system now being promoted due to environmental concerns. Efficiency and cost economics for recycling and reuse of water would, however, depend upon the process parameters, chemicals and machinery used.

Lu et al. [103] in a study conducted in a 600 m^3/day pilot plant observed that the average removal efficiencies of COD, colour and turbidity from wastewater were about 93, 94.5 and 92.9 %, respectively, by using biological treatment and membrane technology. Treated water had COD value below 50 mg/L, no suspended solids and acceptable values for colour and turbidity, and its quality was satisfactory for dyeing and finishing process except for dyeing light shades. Operating cost for wastewater reclamation was approximately 0.25 US$/$m^3$, and thus, wastewater reclamation and reuse was found to be quite promising. Lanza [104] has reported that in a carpet dyeing and finishing plant using approximately 150,000 gallons of water per day, installation of chemical treatment and polymer filter disks for treatment of process effluent could result in $300 per day savings by reusing treated water for processing and the savings were sufficient to recover the initial installation costs within a year.

6 Use of Waterless Technologies for Pollution-Free Textile Processing

Wet processing as the name suggests is carried out in aqueous medium. Some new revolutionary developments intend to carry out these operations without using water as a medium so that the pollution issues can be avoided. The use of supercritical fluids as processing medium and use of plasma are two such emerging technologies discussed in the following sections though the use of laser technology to achieve a faded look and worn-out effect on denim materials is also a waterless technology. Special novel effects not possible earlier have now been produced by combining computer designing and laser engraving. Varied degree of colour removal with little or no damage to the other properties of denim material can be achieved by using different laser parameters. As it is a waterless process and has high potential for innovation, it has an edge over other conventional processing techniques [105–107].

6.1 Supercritical Fluid Technology

A gas is a supercritical fluid above its critical values of temperature and pressure where distinct gas and liquid phases do not exist. Such fluids have physical properties somewhere between those of a liquid and a gas. They are able to spread out along a surface more easily than a true liquid because they have much lower surface tension than liquids. As their viscosity is also low, they have very good diffusivity and thus better interaction with the substrate. Critical temperature and pressure values for carbon dioxide (CO_2) are 31.4 °C and 1070 lb per square inch (psi) or 73.8 bars, respectively, which are much lower than those for many substances. It is non-toxic, non-inflammable, cheap and easily available and does not leave residues. Being a non-polar molecule, it behaves like a non-polar organic solvent in its supercritical state. Supercritical carbon dioxide (SC CO_2) has been employed for extraction of high-value compounds from natural substances, especially for food applications as unlike organic solvents; there is no residual solvent in the extracted material.

SC CO_2, due to its non-polar nature, can easily dissolve water-insoluble dyes such as disperse dyes without using any dispersing agent. Materials dyeable with dyes, such as PET, polypropylene (PP) and poly lactic acid, which are problematic to dye in aqueous medium, can be dyed easily using SC CO_2. Though the concept of SC CO_2 dyeing was proposed in 1980s, its use for practical dyeing applications started only in the last decade of the twentieth century.

These dyeing systems operate at high temperature and pressure and basically consist of an HTHP vessel, CO_2 tank, dye container, and a compressing and a circulation pump. The material to be dyed is placed in the HTHP vessel. Then, the system is brought to the required pressure and temperature to bring CO_2 into supercritical state which then dissolves the dye. The resultant dye liquor is circulated in and out of the HTHP vessel by the circulating pump. After completion of dyeing, dye solution is depressurized which brings the CO_2 into gaseous state leaving behind the dyes. Both CO_2 and dyes are collected and reused. Pure SC CO_2 is then circulated in the HTHP vessel to remove the unfixed dyes from the dyed material. Thus, no water is used and there is no effluent generation.

Most work on dyeing using SC CO_2 has been carried out on PET and has come up to the commercial level. The operating conditions for the PET dyeing range from 60 to 150 °C and 100 to 350 bar pressure [108]. Heat setting prior to dyeing is recommended to avoid strength reduction and shrinkage. It is also useful for dyeing of PP fibres as their high crystallinity and non-polar nature create problems in aqueous dyeing. These can be dyed with good all-round fastness properties by using SC CO_2 system. Polylactic acid (PLA) fibre in spite of its sustainable nature has found limited application in textile industry due to loss in mechanical properties during traditional aqueous-based processing. These fibres could be successfully dyed using disperse dyes in SC CO_2 medium with good retention of mechanical properties [109].

The SC CO_2 dyeing process is highly advantageous over the conventional aqueous-based systems from the sustainability viewpoint. Both dyes and CO_2 used as solvent in its supercritical state are recovered; there is no effluent generation and therefore no adverse effect on the environment. The cost incurred for treating the effluent is saved as also the energy required for drying of dyed material as the solvent used is a gas under normal atmospheric conditions. There is a complete saving of about 100–150 L water which is normally required to dye one kg of PET.

Dutch company, DyeCoo Textile systems, was the first to launch commercial SC CO_2 dyeing system. It has partnered with Huntsman Textile Effects to jointly develop supercritical CO_2 textile processing technology. Adidas was the first brand to introduce a product line using this technology with the manufacturing of 50,000 drydye T-shirts in 2012 [110]. This technology has also been found useful in wax removal/scouring of cotton textiles [111].

In spite of the many sustainability advantages, high equipment cost has restricted the widespread adoption of supercritical CO_2 technology by the textile industry. Poor dyeability of natural fibre and man-made cellulosic textiles in SC CO_2 due to poor solubility of polar dyes in SC CO_2 and poor affinity of non-polar disperse dyes towards these fibres have also restricted its use. Different approaches such as fibre modification, dye modification and adding of a cosolvent or a modifier to improve the solubility of slightly polar solutes have been attempted to solve this problem but have not achieved much success, and therefore, more innovations are required for better adoption of this technology.

6.2 Plasma Technology

Plasma is generated when a substance in its gaseous state absorbs high energy and gets ionized into positively charged atoms and free electrons. Also termed the fourth state of the matter, it consists of positive and negative ions, electrons, neutrals, radicals and photons. It is thus highly reactive and can easily react with many substances. Existing chemical bonds on the surface are broken, and new bonds are formed in the process, thereby introducing new functionalities. Besides, some physical changes on the surface may also take place. These physicochemical changes take place at surface only, and the bulk remains largely unaffected. It has therefore many applications in textiles where surface properties are responsible for various end use properties of textile products such as wettability, dyeability, printability, felting shrinkage in case of wool, pilling, electrostatic properties and water resistance. It may be possible to obtain surface characteristics to meet specific requirements by appropriate selection of plasma composition, i.e. selection of gases one or more from O_2, N_2, H_2, air, Ar, He, NH_3, hydrocarbons and fluorocarbons, and process conditions such as treatment time, power, pressure and gas flow rate.

Plasma can be of two types: hot or thermal plasma where temperature of the plasma zone exceeds 1500 °C, and cold or non-thermal plasma where temperature of the plasma zone is close to ambient temperature. Thermal plasma finds application in metal, electrical and materials industry but is not suitable for use in textiles as textile materials which are polymeric in nature get degraded at higher temperatures. Therefore, it is the cold plasma which is used for carrying out modifications in textiles. Energy to a gaseous medium for generation of plasma can be supplied through several means such as chemical, radiant, nuclear, thermal ionization at high temperatures, or electrical discharges by applying an electrical potential, but electrical breakdown of gaseous molecule in the presence of sufficient discharge voltage across the electrodes with high-frequency AC signal is the most popular and commonly used method for generating plasma.

Plasma can be further categorized into low-pressure or vacuum plasma and atmospheric pressure plasma (APP) depending upon the pressure inside the plasma reactor. Low-pressure plasma was developed many years ago as it is easy to ionize a gaseous molecule by electrical breakdown under low-pressure conditions. It has been extensively studied for material processing as also for textile applications. However, it has not found commercial applications in textiles and allied industries due to economic considerations as to develop and maintain low-pressure conditions in the big-size commercial reactors is costly, and moreover, being a batch process, it is not suitable for integration into the current continuous textile processing machinery. Though it is difficult to generate and stabilize the plasma at atmospheric conditions, but if it can be achieved, it can offer a cost-effective and faster processing technology, which can be easily integrated with the existing textile processes. Hence, atmospheric pressure cold plasma has received much interest among researchers as well as industry as an alternative sustainable processing technique for varied applications in textiles.

As the reactants are in gaseous form, plasma processing is a dry process, and hence, there is no effluent generation. It is also a highly energy-efficient and clean process. This leads to saving a large quantity of water, chemicals and electrical energy while avoiding the production of large volumes of effluent or hazardous by-products. The various sustainability benefits of the plasma treatment can be summarized as follows:

- Dry process, no water required for processing other than for cooling of reactor,
- Lower requirement of chemicals in comparison with conventional processing,
- No need to dry processed textile,
- Lower energy consumption,
- Faster processing speed,
- Versatile process, possibility to process different types of products using the same reactor by changing the gases used for plasma generation,
- Only surface changes and no damage to bulk.

Value-added functionalities such as water, stain and oil repellent, hydrophilic, removal of size, natural waxes and also improvements in dyeing, printing, biocompatibility and adhesion can be achieved by modifying the fibre surface at nanometre level through plasma. Surface modification with a desired functionality can be produced by selecting the appropriate plasma parameters and ratio of carrier to precursor molecules. Fragmentation of precursor molecules followed by the reaction of plasma with the textile fibres is an effective tool for nanoscale surface engineering of textiles to develop advanced, technical, apparel and home textiles. Plasma reaction at atmospheric pressure is challenging due to the presence of high-density ions, electrons, excited particles and ready availability of reaction inhibitors such as atmospheric air and oxygen.

Various uses of plasma in textiles are discussed below:

Textile preparatory processing

Plasma can be used to assist in removal of the contaminants, finishing and sizing agents from the textile materials. PVA is primarily used for slashing synthetic yarns and may be used as a secondary sizing agent to starch for cotton yarns. A complete PVA size removal is difficult and requires high energy and water consumption as it is soluble in hot water. Atmospheric plasma treatment has been found to increase the cold water solubility of PVA on cotton [112]. Plasma treatment has been reported to be used by Kan et al. [113] for removal of starch sizes from cotton and for reducing the time for cotton scouring [114]. It has been reported that plasma treatment can significantly reduce soap concentration and washing temperature in degumming process of silk [115].

Plasma treatment has been used for making the synthetic fibres such as PET and PP hydrophilic [116]. Oxygen plasma is usually suitable for such applications. It can reduce the wetting time of these substrates and increase their antistatic and adhesion property. Surface etching produced by plasma treatment greatly improves the inkjet printability of PP.

Improvement in coloration

Plasma treatment has been reported to increase the exhaustion of dyes on textiles, especially on protein fibres such as wool [117]. In the studies conducted by Teli et al. [118] on silk also, almost complete exhaustion of acid dye was achieved at a much lower temperature and in shorter time duration. This can be of much use in improving the dyeing process sustainability. However, results on cellulosic fibres are not very conclusive, and in most cases, plasma treatment has not resulted in any appreciable change in colour strength. Man et al. [119] have, however, reported an improvement in colour yield, levelness and rubbing fastness of red pigment dye on cotton with oxygen plasma treatment.

APP pretreatment has been reported to significantly increase the colour yield of the digital inkjet-printed cotton fabrics [120]. Colour fastness to washing and rubbing and outline sharpness were also improved in comparison with the control cotton fabric printed without APP pretreatment.

Applications in textile finishing

Many studies on plasma treatment to achieve antifelting properties on wool have been reported. Felting of wool occurs primarily because of the specific scalelike, hydrophobic surface of fibres. Plasma treatment induces morphological and frictional changes which reduce the felting shrinkage of wool. However, plasma treatment alone is not satisfactory in terms of durability and results in a rough handle, and therefore, subsequent treatment with a suitable polymer is necessary. The resultant product after application of polymers is machine washable, and the effect is achieved without using chlorine. Pretreatment of wool with air/oxygen plasma followed by coating with polyurethane-based resin has been found to impart good antifelting properties [121].

Another main application of plasma in textiles had been for producing water-, stain- and oil-repellent properties. These features are achieved by the use of plasma containing fluorine molecules. If a fluoroalkane such as tetrafluoromethane or hexafluoroethane is used as a process gas, fluorine gets substituted for abstracted hydrogen on the surface of the substrate, reducing its surface energy and making it oil and water repellent. This process has been carried out on varied textile substrates such as PET, nylon and cellulosic materials [122–124]. The advantage of the process is that there is no change in the comfort properties of textiles such as air permeability due to the nanoscale of the process and the process is completed in a single step. No further drying and curing is required; thus, there is a saving of energy, time and chemicals.

Plasma processing machinery

Low-pressure plasma, requiring closed, vacuum system equipment, was unsuitable for textile processing on an industrial scale as capital equipment cost as also the operational and maintenance costs would be high. APP offers an alternative, attractive, low-cost, environmentally friendly route for textile manufacturing, with improved quality and performance. Though plasma processing of textiles is still in an experimental stage and a number of issues need to be addressed before it becomes a commercial alternative, a number of manufacturers have developed pilot- to commercial-scale machinery for plasma treatment of textiles for various applications, and some of these manufacturers are listed in Table 5.

Table 5 Plasma machinery manufacturers

Manufacturer	Application
Acxys, France	Wettability, water repellent (www.acxys.com)
Apjet, USA	Water and stain repellency (www.apjet.com)
Arioli, Italy	Water repellent (www.arioli.biz)
Diener, Germany	Cleaning, etching, activation, polymerization [125]
Dow corning corporation	Surface modification and coating [126]
Europlasma, Belgium	Surface coating, water repellent (www.europlasma.be)
Grinp, Italy	Surface modification and coating (www.grinp.com)
Plasmatreat, USA	Self-cleaning, flame retardancy *(*www.plasmatreat.com*)*
Sigma, USA	Surface modification and coating [127]
Softal, Germany	Water repellent, wettability (www.softol.de)
Vito, Belgium	Cleaning, activating, coating (www.vitoplasma.com)

7 Role of Eco-standards and Environmental Regulations in Promoting Sustainability

Eco-labels by governmental or independent bodies aim to set environmental standards for products. Concern about the environment among consumers especially in EU countries has been growing in recent years, and more and more people are interested in buying green alternatives to regular products. However, just by looking at a textile product, it is not possible to know whether it is eco-friendly. An eco-label identifies the general environmental performance of a product spanning its entire textile supply chain and contributes to consumer safety and reducing the environmental impact, thereby supporting sustainable textile consumption patterns. Government, industry, commercial associations, retailers, companies and consumers are all major participants in the scheme. Eco-labels were first introduced during the last decade of the twentieth century after the German ban on azo dyes derived from amines suspected to be carcinogenic, and today, a number of regional as well as global eco-labels are in existence. These labels cater to environment conscious customers by ensuring the quality and performance of products as well as usage of materials that are safe for human health and environment during their manufacturing. Manufacturers must meet certain requirements before their products can be classified to be ‘green’. Participation in an eco-label scheme is voluntary; companies submit their products for third-party compliance testing and/or verification to obtain an eco-label for specific products that meet detailed established environmental guidance criteria. That eco-label may be then displayed on the products that meet these requirements. Widely recognized eco-labels are helpful guidelines for consumers who want to buy eco-friendly sustainable products.

These labels promote the communication of authentic and verifiable information on environmental aspects of products and services, encourage the demand and supply of products and services that cause less strain on the environment and boost market-driven efforts for sustainable manufacturing. When a product is approved by an eco-label, permission to use the scheme’s distinctive eco-label or symbol is granted for a specified period. The award is periodically reviewed to ensure that they comply with the evolving criteria, technological developments and market advances. Some examples of the criteria specified by these labels are as follows: textile products should contain limited amounts of substances harmful to health and the environment and should be processed with reduced use of water and air pollution. Laundry detergents should not contain certain substances considered to be harmful to the environment or which promote the growth of algae in water bodies; be mostly biodegradable; and include ecological washing instructions. The Oeko-Tex 100 (product certification), Oeko-Tex 1000 (factory certification) and the Bluesign® International Standards are examples of eco-labels that attempt to provide clear information on the impact of textile products on people and the environment. The Bluesign® system requires the entire textile supply chain to jointly reduce its impact as its five principles, viz. resource productivity, consumer safety, water emission, air emissions and occupational health and safety cover the entire value chain.

REACH standing for Registration, Evaluation, Authorization and Restriction of Chemicals is a regulation of the European Union which came into force in 2007. By mandating the registry of details of chemicals manufactured or imported into EU in amounts exceeding the prescribed limit, it aims to improve the protection of human health and the environment from the risks posed by chemicals across various sectors. The use of registered chemicals is authorized or restricted according to their hazard and risk data.

The OEKO-TEX® Association has recently introduced the new ECO PASSPORT certification for sustainable textile chemicals. It is a two-step verification procedure for textile processing chemicals, colourants and auxiliaries which enables the manufacturers to confirm that their products meet the specific criteria for environmentally responsible textile production [128]. EU official label for green textiles—EU Flower limits the amount of toxic residues in textile materials, limits the level of metallic impurities in dyes and pigments, prohibits the use of azo dyes that cleave to a list of aromatic amines or dyes classified as carcinogenic, mutagenic and toxic for reproduction and also specifies the pH and temperature and COD content of the textile wastewaters.

The latest 4.0 version of the Global Organic Textile Standard (GOTS) introduced in March 2014 sets requirements from the harvesting of raw materials to manufacturing and labelling to assure the consumers of the organic status of textiles. However, it takes into consideration that industrial-scale production of textiles is not possible without the use of chemicals. Hence, at each manufacturing stage, a list of materials is provided which are safe and allowed and which are not allowed for use. Minimum impact on the environment, minimum hazard and toxicity are the criteria for allowing the use of a material. Therefore, natural dyes and other chemicals from endangered plant species are not permitted, but synthetic dyes which can meet toxicity and hazardous substance criteria are allowed. Minimum colour fastness requirements have also been specified. The objective is to ensure good-quality textile products not containing harmful substances which are produced in an environmentally and socially responsible manner, thus ensuring sustainability.

Almost all the eco-labels have set the limits for the harmful substances such as heavy metals, banned carcinogenic amines, brominated and chlorinated flame retardants, APEO and formaldehyde release in the finished textile products and put emphasis on the sustainable manufacturing process while ensuring the minimum social requirements.

8 Social and Economic Issues

Social and economic aspects are an integral part of sustainability of any process. Textile processing has to be economically competitive, but at the same time, social issues also need to be considered. As the long textile value chain involves a number of players from diverse sectors such as textile fibre growers, spinners, chemical suppliers, processors, garment makers, transporters, retailers and consumers, these issues are of concern for each of them and every sector is responsible in ensuring sustainability of textile manufacturing. Regarding the chemical processing sector, as discussed in the previous section, many voluntary eco-labels introduced for textiles look at a product in a holistic way and are concerned about its production process as well which should have low environmental impact. They look for consumer safety as also the occupational safety of workers during manufacturing and insist upon payment of fair wages and thus are contributing to the promotion of sustainable textile production. The low-impact sustainable textile manufacturing processes need wider adoption as the environmental impact caused by these processes are endangering the water resources in many developing and undeveloped countries and thereby the well-being and livelihoods of communities residing in surrounding areas dependent on in these resources. Many textile industries in these countries are not willing to adopt sustainable chemical processing options as they are interested in quick profits and also lack the required financial and technical resources to implement the low-impact technologies. It would require investment and initial costs would be higher for adopting sustainable technologies, but in the long run, savings in energy, chemicals and process water consumption would result in lower costs. These would appear still more attractive if the environmental damage and cost of restoring it are taken into account. Governments and law makers therefore have to contribute by putting stricter regulations and their proper implementation for the protection of environment. At the same time, they should also offer incentives and support to processors for adoption of low-impact technologies. Big brands and companies buying these textiles as also the consumers have a social responsibility to minimize the damage to environment and should be ready to pay extra if required to promote sustainable textile production. Environmental issues are of concern to society at large as greenhouse gas emissions, and the resultant climate change would affect everyone. Also the air and water pollutants can affect much larger population by spreading through wind, rain and consumption of contaminated food products. Therefore, all stakeholders in the sector need to come together and contribute to ensure sustainability. Further research efforts from chemical manufacturers, machinery manufacturers and researchers should continue to further develop low-cost low-environmental-impact products for minimizing the adverse social and economic implications of textile wet processing.

9 Future Outlook and Conclusion

As discussed in this chapter, quite a number of solutions are available for various textile wet processing operations which can significantly reduce the detrimental impact on the environment. However, there are still many challenges and many promising technologies such as plasma and supercritical CO_2 processing need further development and refinement to make them a viable alternative. Similarly, efforts are needed for developments in the field of biodegradable dyes, chemicals and auxiliaries as also enzyme assisted processing in view of the environmental advantages. It is the responsibility of the concerned industry and researchers to further develop viable, minimum environmental impact options.

Adoption of the available best practices for sustainable textile wet processing has been poor as most of the operations are located in developing and undeveloped countries in decentralized sector and these units lack the resources to install and follow state-of-the-art facilities and practices. Governments therefore have two roles to play in such scenario. First, they need to put stricter regulations and ensure their proper implementation in order to promote sustainable textile production and to ensure clean environment and livelihoods for the people. Secondly, along with investors, they should provide financial support to help in modernizing the sector and reducing its environmental footprints. Voluntary eco-labels and certification schemes have contributed towards achieving these objectives in a limited way.

Each player across the sector has to work towards ensuring sustainability. Certain non-profit and trade organizations such as Textile Exchange and Sustainable Apparel Coalition involving all stakeholders are now working to reduce the environmental and social impacts of textile production around the world. The sector as a whole has to aim towards achieving zero discharge of hazardous chemicals and draw a road map to reach this goal. This is urgently needed to prevent the further contamination of water bodies with hazardous substances and the resultant build-up in people and animals. Toxic pollution has to be dealt with in all countries as otherwise the pollution of water resources along with global warming caused due to the release of greenhouse gases and associated climate change would threaten our livelihoods and our future. Brands, retailers and consumers on their part need to be environment conscious and be ready and willing to pay more for the products which do not harm people and the environment.

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