clean technologies

Review

Sustainability Assessment of Cotton-Based Textile Wet Processing

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Abstract: The textile and fashion industries account for a significant part of global business. Textile wet processing (TWP) is a crucial stage in textile manufacturing. It imparts aesthetics as well as functional appeal on the textile fabric and ultimate products. Nevertheless, it is considered as one of the most polluting industries and threatens sustainability. There have been different approaches to transform this polluting industry to a sustainable industry. Many researchers have found this challenging, as sustainable, eco-friendly, green or cleaner wet processing might not be always applicable and relevant from the perspective of industrial applications. The present work helps us understand the current state of research of cotton-based textile processes including proposed sustainable approaches. It also examines the achievement of the degree of sustainability of those proposed processes with the lens of the triple bottom line (TBL) framework, identifies existing limitations, and suggests future research scopes that might pave ways for young researchers to learn and undertake new experimental and theoretical research.

Keywords: sustainability; textile wet processing; triple bottom line (TBL); environment; economy; society

1. Introduction

Textile production is the result of long manufacturing and wet-processing stages. These manufacturing stages involve yarn, fabric and garments manufacturing and wet processing [1]. The textile wet-processing (TWP) industry is based on various pre-processing (pre-treatment), processing (dyeing and printing) and post-processing (finishing) stages that consume a significant amount of water, dyes, chemicals and energy. All these treatments are crucial to ensure optimal performance and desired visual effects [2]. Color is a strong tool for design and aesthetics in textiles. Dyeing and printing make a significant contribution to these coloration process [3]. However, these processes generate enormous amounts of effluent. These effluents contain different types of chemicals that are harmful for the environment and human body. The processes involving TWP use large amounts of water: 80 to 150 L of water along with other chemicals for processing 1 kg of fabric [4]. China, the biggest textile manufacturer in the world produces around 54% of total textiles manufactured in the world. Every year they produce more than 25,000 million tons of wastewater. The effluents in the wastewater are required to be treated before discharging into environment. TWP necessitates a significant amount of pernicious chemicals of different kinds, high temperature (up to 220 °C), and high electric and thermal energy to process the fabric [3]. It emits a huge amount of greenhouse gases that is one of the contributing factors to global warming. In addition, exposure of these chemicals has long-term detrimental effects on human health, and biotic and abiotic components of the environment. Also, these processes consume high energy to supply heat during various processes such as, scouring, bleaching, and dyeing. In developing countries, most of the energy plants are based on fossil fuels that will eventually deplete renewable energy sources [5,6]. The global urge of saving the environment and making a green world has pushed researchers, technologists and manufacturers to introduce different sustainable manufacturing procedures that could reduce the burden of these processes on the environment [7,8].

In the present review, published research works in the context of sustainable cotton-based textile processes have been introduced and critically reviewed. Furthermore, learning from this review was utilized to evaluate TWP using the triple bottom line (TBL) framework. The concept of sustainability used for this framework involved economic, social and environmental factors. The proposed framework in this paper contributes to our understanding of the comparisons among existing sustainable research approaches and their merits to achieve those three pillars of TBL framework as well as pointing out the research gap in TWP for future consideration.

2. Conceptual Framework: Triple Bottom Line (TBL)

Sustainability has become a prime concern around the world. Consumers' growing concern about environment pollution and human safety has encouraged both fashion manufacturers and retailers to adopt various sustainable or green or eco-friendly manufacturing approaches. As a result, textile technologists and researchers have also been conducting various research projects on sustainable textile and apparel manufacturing over the past decades [9]. The term 'sustainability' was first used by Carlowitz in 1713 in his book regarding forest science to emphasize the significance of wood, as we need our daily food. Later, the definition was formally documented in 1987 by Gro Harlem Brundtland of the World Commission on Environment and Development (WCED) as "sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs" [10]. The concept was defined more clearly by the TBL approach of sustainability incorporating some specific aspects-environmental, economic and social, which are the pillars of sustainability. The TBL framework was developed by Elkington in 1998 that mainly emphasized keeping a balance among environmental, social and economic aspects from the perspective of business strategy. Although in the past sustainability was only referred to as green manufacturing approaches, now it is evaluated based on all of these three aspects [11,12].

According to the TBL framework illustrated in Figure 1 with a view to achieving sustainability, any entity should make proper balance among economic, environmental and societal requirements. Therefore, when designing a project or any approach, stakeholders must consider environmental and societal betterment along with financial concern [13]. Any idea having the ability to meet all these conditions is considered fully sustainable. The TBL framework have been adopted as a scale by many profit and non-profit business organizations and government institutions. These institutions assessed their projects and strategies from the perspective of achieving feasible as well as long-term sustainable development. However, the incorporation of TBL to set a proper balance among these three pillars is still challenging [11]. Research on developing TBL-based supply chains demonstrated how sustainability could be maintained throughout fashion production, retailing and consumption processes [14].

The environmental aspect of TBL is based on the requirements of reduced use and wastage of natural resources as well as prevention of environmental degradation [14]. This dimension of TBL can be evaluated by measuring various standards; for instance, evaluation of the carbon footprint, eco-friendliness, NO_2 and CO_2 emissions, values of molecules present in wastewater and material retrieval rate. Researchers and practitioners have been extensively analyzing the extent of the carbon footprint over the last few years, as it could be directly related to the amount of CO_2 emitted throughout the lifecycle of a garment [14].

Figure 1. Triple bottom line (TBL) framework of sustainability [12].

The economic dimension of sustainability is referred to as an effective economy that can be sustained for a longer period, and at the same time it acknowledges the significance of ensuring secure and long-term employment [15]. While evaluating the economic dimension of sustainability, researchers also concentrated on other crucial factors such as utilization of sustainable raw materials for production, total cost of ownership, reduced inventory level, reuse and reduced consumption [14].

The social dimension is the third crucial aspect of sustainability that can be referred to as conforming social welfare of community and gender or race indiscrimination [15]. Multiple stakeholders may adopt multifaceted initiatives while examining and solving any problem related to social issues. However, it is challenging to evaluate all social dimensions during solving a single decision-making problem. Therefore, it is required to develop a set of standards that can be implemented into any form of social responsibility. The International Standard Organization (ISO) has provided a standard framework named as International Standard ISO-26000, which has classified the social issues into different groups. According to this, the most relevant social standards that need to be considered for integrating social sustainability to the supply chain are safety, firmness of work conditions and community development [14].

3. Textile Wet Processing (TWP)

Textile material goes through various wet processes before dyeing and finishing. Sizing ingredients applied during weaving operations, organic and inorganic impurities present in fibers and dirt or dust incorporated during knitting operations need to be removed in fabric preparatory processes. The subsequent processes include dyeing and finishing are based on the types of fibers and end-use requirements [6]. The flowchart of these stages including the wastewater flow path have been demonstrated in the following Figure 2.

The textile industry is identified as one of the high water-consuming industries [4]; on the other hand, the scarcity of water is the number one risk of the world based on its impact on society [17]. High water consumption for textile processing is itself a big concern for the scientific community. A significant portion of biotic components of the aquatic biome are facing the reality of a paucity of fresh water. The situation faces even greater deterioration by discharging the textile wastewater containing noxious chemicals which have both tangible and intangible impacts on all the basic abiotic components of environment such as hydrosphere, lithosphere and atmosphere [18]. Therefore, it is mandatory to ensure that the application of dyes, chemicals, and other reagents meet the environmental criteria. Besides, it is imperative for wet processors to facilitate an effective discharge and treatment of effluent or wastewater, so that it cannot possess any adverse impact on any living organism [19]. Various kinds of chemicals such as dyes, pigments, thickeners, formaldehydes, acids, alkalis, oxidizing, and reducing agents are used in all processes from pre-treatment to finishing in wet-processing unit. These chemicals not only harmful for health but also severely pollute water as shown in Table 1. Therefore, discharging this wastewater untreated is life threatening for all components of the environment. Roy, et al. [20] characterized combined textile wastewater discharged from a cotton processing industry in Bangladesh, compared to standard water qualities and discussed how they jeopardize the environment.

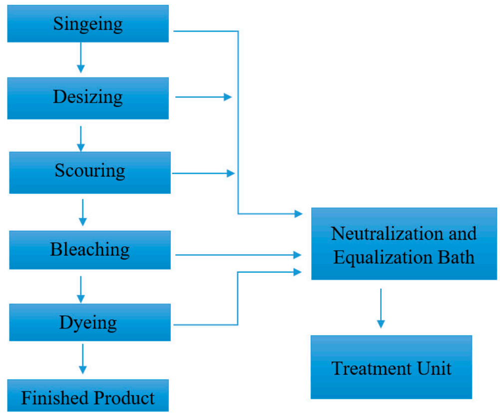

Figure 2. Flow process diagram of cotton textile wet-processing (TWP) [16]. Reproduced with permission from [Taylor & Francis Group], Sahoo, C.; Gupta, A.K.; Pillai, I.M.S., *J. Environ. Sci. Health Part A*, Taylor & Francis Group, 2012.

Depletion of dissolved oxygen in water due to hydrosulfites and blocking the passage of sunlight due to thick concentration of colors endanger aquatic lives. The soil becomes impotent and futile because of the salt which is used as an electrolyte during dyeing and printing. Textile industries mostly use low-cost synthetic dyes, most of which are not biodegradable. Moreover, dyes containing chlorine carry carcinogens and mutagens which are health hazardous. Due to chemical evaporation, these carcinogens, heavy metals, and other chemicals are exposed to the air and are absorbed by the body, which, in the long run, cause physiological and biochemical malfunctioning of body's organs [21].

Table 1. Effluents generated in different textile processes [22]. Reproduced with permission from [2015 Elsevier Inc], Patel, H.; Vashi, R. Characterization and Treatment of Textile Wastewater; Elsevier Inc., 2015.

Processes	Reagents/Chemicals Used	Effluents Generated
Sizing	Starch, waxes, carboxymethyl, cellulose (CMC), polyvinyl alcohol (PVA), wetting agents	High in biological oxygen demand (BOD), Chemical oxygen demand (COD)
Desizing	Starch, CMC, PVA, fats, waxes, Pectin	High in BOD, COD, suspended solid (SS), Dissolved Solid (DS)
Bleaching	Sodium hypochlorite, Cl2, NaOH, H2O2, acids, surfactant, NaSiO3, sodium phosphate, cotton fiber	High alkalinity, high SS
Mercerizing	Sodium hydroxide, cotton wax	High pH, low BOD, high DS
Dyeing	Dyestuffs urea, reducing agents, oxidizing agents, acetic acid, detergents, wetting agents	Strong colored, high BOD, high DS, low SS, low heavy metals, high salinity, electric conductivity

4. Environmental Aspects of TWP

The first process in wet processing is desizing, which is to remove the size material used in weaving preparatory process such as modified starch from corn and/or potato, carboxymethyl, cellulose (CMC) and polyvinyl alcohol (PVA). Conventionally, acid or oxidizing agents are used for the removal of size coating that eventually increase the oxygen-demanding agents significantly [23,24]. As a sustainable attempt, use of enzymes are suggested that hydrolyze starch materials at the surface [25,26], but negatively affect the strength of cotton by degrading cellulose [27]. Cold pad-batch process based on oxidative desizing or employing hydrogen peroxide along with persulphate can produce a harsh fabric surface, although it is the most efficient desizing process compared to other desizing methods. On the other hand, application of hot water to remove synthetic size components and then the subsequent recovering process of these components from the bath by applying an ultrafiltration technique can be a cost competitive and environmentally friendly desizing option [6,24,25].

Impurities present in cotton fiber like oil, wax, fat, protein and pectins etc., which are highly responsible for poor absorbency are removed through scouring [28,29]. The subsequent process removes the protoplasmic residues of protein and flavones pigments of cotton, which is called bleaching. This process makes the cotton pure and permanent white. As a result, fabric dyed with light color can be manifested easily [30]. Traditionally, sodium hydroxide (NaOH) and hydrogen peroxide (H_2O_2) along with detergent and wetting agents are used for scouring and bleaching [31]. In contrast, the use of these chemicals in pre-treatment has very harsh consequences especially in terms of high amount of chemical oxygen demand (COD), biological oxygen demand (BOD), pH and toxicity [31,32]. Later, applications of some less harsh chemicals like ozone, some environmentally compatible biocatalysts and enzymes have been found with acceptable results for scouring and bleaching [33,34]. Ozone is successful as a pre-treatment agent in terms of performance, complete removal of size materials, increased fabric absorbency, and improved whiteness index. This process also involves less water and energy consumption and is ecofriendly. However, ozone generation through oxidation process are very complex and costly that limit its commercial use [34]. Also, it has failed to attract industrial professionals due to its poor whiteness index and expensive production process [35].

Recently, some advanced technologies have been introduced for textile preparation such as activators [36], radiation [37], and sonication [38]. The common essence of all these processes are energy and time saving. None of these technologies perform whole scouring and bleaching alone. They actually assist traditional or enzymatic scouring-bleaching process to make the process faster at low temperature. There have been found some trials to substitute strong alkali, NaOH using moderately strong alkali, Na_2CO_3. Peroxide bleaching (even organically produced peroxide such as glucose oxidase) requires alkali, and always needs to be followed by peroxide killing and neutralization, as it would otherwise create problems during dyeing by decelerating dye hydrolysis. The neutralization of this alkaline wastewater generates a huge amount of wastewater containing salt and other chemicals such as thiosulphate to remove the residual bleaching components from the textile material [25,39]. Besides, wetting agents and detergents containing nonylphenol ethoxylates and octylphenol ethoxylates used in scouring and bleaching are non-biodegradable and toxic and thus complicate wastewater treatment process and the lives of aquatic organisms [40]. In consequence, peroxide bleaching also worsens fabric strength [30,36,37]. Hannan, et al. [41,42] investigated scouring and bleaching of cotton knit fabric using high temperature water at 120 °C without any chemical involvement and found satisfactory dyeing performance for medium and dark shades. At high temperature, water molecules break and generate some H^+ ions lowering pH from 7, thereby scouring and bleaching cotton by the acid hydrolysis mechanism.

As an ecofriendly and environmentally benign approach, various attempts to treat cotton fiber with enzymes such as pectinase, protease, lipases, cellulase and endo-pectate lyase for scouring and laccase, peroxidase and peracidsglucose oxidase for bleaching are available [43,44]. However, the bio scouring of enzymes requires comparatively less temperature than the traditional process [43], the application of enzymes is narrow in case of bleaching, and provides a poor result [45]. It is also found that cellulose, pectinase and peracetic acid (PAA) indirectly prepared from tetraacetylethylenediamine (TAED) and sodium perborate, suffer from poor insolubility [46]. A combined desizing-scouring-bleaching process was developed by using alkylated carbonyl butyrates anhydride triglyceride fluid (ACBAT), sodium hydroxide and hydrogen peroxide [35]. However, successful bio-desized samples require further treatment of scouring and bleaching, where NaOH is precursor [47]. Seemingly, a substitute of NaOH in scouring and peroxide bleaching by enzymes for textile preparation is still questionable [48].

Coloration is an ancient concept, recently, a study by Splitstoser, et al. [49] provides evidence that cotton and indigo blue have been maintaining a long-term relationship even before the idea of blue jeans. They identified that the history of dyeing cotton with indigo dye started 7600 years ago in Peru. Nowadays, synthetic dyes lead the dyeing industry because of low manufacturing cost, brilliant shade, and variety of colors [50]. At the same time, they are condemned for their detrimental effects to the environment [6]. The dye residual present in wastewater is responsible for generating highly colored effluents and deleterious for the aquatic ecosystems. Table 2 shows the proportion of unfixed dye left in the dyebath after the dyeing of different textile fibers.

Table 2. Percentages of unfixed dyes after dyeing for cotton fibers [6]. Reproduced with permission from [Springer Science], Saxena, S.; Raja, A., Textiles and Clothing Sustainability; Springer Science., 2017.

Dye Type	Unfixed Dye %
Azoic dyes	5–10
Reactive dyes	20–50
Direct dyes	5–20
Pigment	1
Vat dyes	5–20
Sulphur dyes	30–40

These unfixed dye particles affect the photosynthesis of plants by hindering the access of light to aquatic environment. Moreover, the dyes and their by-products are toxic and carcinogenic [51]. For instance, Germany and many European countries banned Azo dyes as it was extracted from a specific aromatic amine that is considered carcinogenic. Most of the synthetic dyes do not get degraded even after being treated in effluent treatment plant (ETP). As a result, when the solid sludge containing these dyes are sent to landfills, this spreads contamination across land and surface water. The huge amount of salt used during dyeing also contributes to increasing the total dissolved solid proportion in the resultant effluent, which is harmful for both humans and the environment. Moreover, the complete removal of TDS is expensive and difficult. Synthetic dyes may contain different active ingredients and heavy metals [52]. The use of potassium dichromate in the oxidation of vat or sulphur dyes generates Cr^{6+} in the wastewater, which is also carcinogenic in nature. It is very difficult to bring down the values of these metal contents to the required level compatible for the environment. Besides, different auxiliaries used in dyeing also do not get degraded and cannot be recycled. Thus, they also contribute to high BOD and COD values of the effluent. Reducing agents such as sodium hydrosulfite used in vat and sulphur dyeing cause the discharge of sulphide content, which creates a problem in waste disposal. This discharged sulphide could be converted further into sulphuric acid due to bacterial oxidation. Consequently, due to the growing global environmental awareness, the idea has flipped back to the natural dyeing process, a sustainable approach for textile coloration.

Nowadays, considerable attention is being paid to natural dyeing processes of textile materials so that negative environment impact could be alleviated [53] along with their functional value addition such as, antimicrobial, ultraviolet (UV) ray blocking, deodorizing [54]. Natural dyeing of cotton involves many extra preparations such as dye preparation and extraction and mordanting. Cellulose of cotton fibers exhibit poor affinity to natural colorants. Mordanting is a crucial stage that grows an affinity between functional groups of dyes and fibers. Mordanting can be accomplished at various stages of the dyeing process; for instance, pre-mordanting, meta-mordanting, post-mordanting are performed before, during, and after dyeing respectively based on the performance and process parameters [55,56]. To perform mordanting, different metal salts including heavy metals; for example, ammonia alum, chrome alum, potash alum, soda alum, potassium dichromate, copper acetate, cuprous chloride, zinc tetrafluoroborate, lanthanum oxide [56] are used, which are themselves more pernicious to the environment than many other synthetic dyes.

A significant number of attempts have been made to search and apply natural mordants while dyeing with natural colorants [57]. Samanta and Agarwal in their review article mention the applications of natural mordants for some natural textile fibers like wool, silk, jute and cotton. Recently, a number of trials have also found on applying natural colorants and pigments for synthetic dyes with poor to acceptable performance. Although protein fibers provide good to excellent dyeing results, the performance of cotton dying is not much encouraging. Moreover, Samanta and Agarwal along with Räisänen, et al. [58] describe some satisfactory outcomes without using any mordants especially for silk, wool, polyester and polyamide fiber dyeing. However, the practice of natural dyeing of cellulosic fibers, especially cotton, without mordant is hardly found. Vankar, et al. [59] show natural dyeing of cotton and silk using enzymes instead of mordants with favorable output. Chairat, et al. [60] dye cotton yarn with *Combretum latifolium*, Blume stems using chitosan and *Memecylon scutellatum* Naud as biomordants with close to acceptable performance. Mohammad [61] realize natural dyeing of cotton has not been able to fully overcome its limitations.

5. Economic Aspects of TWP

Processing cost is one of the major dominant factors of a product's retail price; it often surpasses manufacturing and material cost, thereby, an economic processing is a one of the prime focuses. The generated wastewater due to the use of chemicals needs treatment before discharging to the environment, which also raises the process cost. China alone discharges more than 2.5 billion tons of wastewater every year causing the contamination of natural water, which threatens the sustainability of textile production [6]. Although the use of natural products instead of harmful chemicals is appreciable, but it consumes several times more water than the traditional processes that ultimately influence greater energy consumption [62]. Also, natural products including biocatalyst are very costly to prepare and require compatibility assessment [48]. Additionally, the enzymatic process is followed by a subsequent neutralizing step either by temperature or pH increases or the addition of other reagents leading to rise process cost [63]. Combination of multiples processes or reduction of process steps (single-stage desizing-scouring-bleaching) favors economic production; which is often practiced in the industries using traditional textile chemicals. In contrast, this is not possible in enzymatic process, as enzyme activation requires specific environmental conditions.

The natural dyeing process is different from the conventional synthetic dyeing process, and the performance of naturally dyed fabric is relatively poor concerning color strength, color fastness [58]. The cost and complexity of dye extraction involves a lot of stages, even though the ratio of use of natural products used versus the color pigment obtained is very negligible, thereby practically it is not viable in terms of cost and scalability. For instance, 5000 kg leaves cultivated from one-acre land produce 50 kg indigo blue dye, so the color yield from madder is 150 kg from 3–5 tons of plant per hector land. Besides, the extraction process involves a lot of other resources such as water, chemicals, and power, which altogether contribute to the price concern. The cost of mordanting also needs to be considered in the case of natural dyeing [55]. There are also some mentionable research works on the technological development like, super critical dyeing, plasma dyeing, foam dyeing, but these are associated with high investment and maintenance costs [6,64]. Surface modification using those technologies can significantly reduce water, energy, chemical and time consumptions. For instance, plasma and UV photons can be applied for surface modification instead of using water as a processing medium [65], but requirements of gas pressure and high energy is drawback of this process [66]. As a result, the use of synthetic dyes is unavoidable.

6. Social Aspects of TWP

Social sustainability is the third main pillar in the TBL framework. Social sustainability ensures a healthy future by building proper framework without compromising the current requirements of the society [67]. By definition, social sustainability deals with the approach of meeting the current necessities of the society without creating any harm of potential risks for the generation to come [68]. To make this happen, social sustainability comprises a number of elements such as social values, human rights, group improvement, social capital, social homogeneity, social obligations, human adjustments, equality and many more [67,69]. TWP should ensure all these elements to achieve social sustainability.

Achieving social sustainability is the responsibility of both the supply and demand sides of a society. The supply side, the manufacturers, and the demand side, the consumers, both should work hand in hand in practicing corporate social responsibility (CSR) and creating sustainability awareness [64]. Textile processing industries deal with some mechanical, chemical and biological hazards [67,70]. One of the mechanical hazards in wet processing industry is excess heat. In wet processing, the workers work under relatively high temperatures leading to fatigue and dehydration [71]. A lot of flammable chemicals are used in the manufacturing process, which entail safe storage to avoid any spillage [70]. Chemical hazards are very susceptible to other hazards in the wet-processing industry. Workers are exposed to dyes, solvents, formaldehydes, optical brighteners, fixatives, which are very toxic and carcinogenic in the wet-processing unit [72].

Annapoorani [67] in his paper identified the illnesses that the workers in wet-processing industries suffer from such as nasal, laryngeal, bladder tumor, asthma, respiratory trouble, colorectal growth, thyroid disease, nasal tumor and many more. According to Singh and Chadha [73], TWP workers handle toxic chemicals including dyes that can cause different forms of cancer in the long run [74]. Handling of direct, acid, reactive and disperse dyes from benzedine-derivatives can result in bladder cancer [72,75]. Wynder, et al. [76] also found the same notion of bladder cancer among the workers in the aniline dyeing industry. Women in the dyeing industry have a strong chance of suffering from nasopharyngeal cancer (NPC) and colorectal cancer, which is a big occupational risk [77,78]. Workers who handle reactive dye, gain increased level of serum IgE in their health [15,79] triggering nasal disorders and respiratory problems [80]. US dyeing and finishing workers were found to be suffering from skin diseases reported by Soni and Sherertz [81]. Based on the level of the chemical exposure, different health difficulties might occur such as depression, allergy, headache and insomnia [82]. Sudha and Meenaxi [70] identified impacts of chlorine bleaching, which might result in skin and eye irritation; corrosive alkalis and acids cause potential burns and scalds; and organic solvents can result dermatitis or skin vulnerability. Moreover, workers exposed to reactive dye suffer from eczema, uticaria and asthma. Upadhyay and Pandey [83] found as high as 51% of dyeing workers suffering from occupational contact dermatitis in Jaipur, India. Sweating, pressure and friction have resulted in dermatoses among wet-processing workers. Some biological hazards (i.e., enzymes) can cause allergies, skin sores and other infections to the workers [70,71].

The TWP is very much a labor-intensive sector. Workers need to handle heavy textile materials for prolonged period of time relentlessly [83]. Lifting heavy materials, holing those in position, bringing materials down, pulling and pushing textile materials are their usual duties, cause pain in different parts of body known as musculoskeletal disorders (MSDs) [67,83,84]. Biswas, et al. [85] conducted a study on yarn-dyeing workers where they applied Ovako Working Posture Analysis System (OWAS) and found that workers experienced pain in shoulder, neck and lower back because of maintaining awkward postures during work.

In addition, TWP contains a number of psycho-social hazards such as varying work load, harassment, discrimination, physical/mental mistreatment, lack or flexibility, societal considerations and many more. Despite strong embargoes, as many as 250 million child laborers aging from 5 to 14 years of age are directly and indirectly working in the industries, 61% are from Asian countries [86]. Woolf [86] in his study have identified a number of those child laborers working in TWP industries handling toxic chemicals, dyes and pigments.

A number of research works have been conducted on the poor compliance issues in textiles. Those studies cover poor working condition [87], wage issues [88], child labor [89], gender discrimination [90], labor unions [91], workers' rights [92] and other relevant issues. Most of the studies have been focused to composite textiles or apparel industries. A handful of studies were conducted concerning wet-processing industries. Although research on mitigating the environmental impacts (environmental sustainability) of the wet-processing industry have frequently been found, social perspective of sustainability has not yet been explored with the same emphasis, which outlines future research consideration.

The counterpart of social sustainability deals with the consumer's mindset. Consumers around the world are aware about sustainability [93,94]. However, sustainable tagging and labeling [6,95], consumers' knowledge regarding sustainable products [96,97], willingness to buy sustainable products [98,99] and green marketing [100] are questionable concerns. Eco-labels such as health, environmental, organic and social labels help consumers identify a sustainably made product [95]. One of the obvious research gaps is the practice of eco-labeling for textiles and apparel products, although its wide application is found in other sectors such as the food and mosaic industries [101]. These practices govern consumers' purchase decision making [102]. Unfortunately, consumers' understanding of eco-labels for textile products is perplexing, thereby requiring future exploration. It was found that millennials have a willingness to buy sustainable products compared to other ages, since they are more conscious [98]. Some consumers learn to compromise sustainability in exchange for price [99]. Consequently, cheaper products are popular in market that pushes companies to look for cheaper manufacturing processes even though they might not be sustainable. This evidence necessitates green marketing that will educate consumers about the importance of sustainable practices in textiles including wet processing [100].

A possible solution for reducing these existing social sustainability issues is the practice of CSR activities by the industries. In last couple of decades, the textile industries have been shifted from the developed countries to the developing countries such as Bangladesh, India, China, Pakistan, Vietnam, Cambodia. In these countries, compliance issues, labor laws and rights, employees' safety and satisfaction are not that well established [103]. Taking these opportunities, companies operating in this region focus more on profit maximization rather than rights of employees [104]. So, the corporate ethics and culture are disrupted, which can be redeemed by the increasing practice of CSR activities. Nonetheless, CSR activities can contribute a lot to the reputation of a company, since CSR is considered as a yardstick of corporate ethics and integrity. The companies which take part in CSR activities earn motivation for the employees to contribute more [105]. These motivated employees become more satisfied with their job and company [106], and the reputation of the company goes up as well [107,108]. These phenomena build better connections and commitments for a company with its employees and consumers [104,109]. As a result, the employees will feel enthusiastic to work hard for the success of the company. At the same time, the consumers need to show their support to buy sustainable products by raising sustainability awareness and educating themselves.

7. Technical Limitations

Apart from the aforementioned issues, there are some complexities in the current research attempts for making textile processes sustainable. For instance, the applications of natural products are very cumbersome. Their extraction processes, process parameters, and quality control processes are difficult to maintain. The use of enzymes has some limitations in terms of process conditions such as time, temperature, pH, and concentration, though it is environmentally safe. The storage system of enzyme is also a delicate issue to deal, since it losses efficiency over time [110]. In natural dying, mordanting, a surface modifying process to grow affinity between fibers and dyes, make the overall process more complex. Furthermore, harmful chemicals shockingly arise during mordanting by the use of heavy metals. The availability of natural dyes and pigments is very negligible compared to the supply chain demand. Limitations also include inability of shades, hues' variety and reproducibility. For example, reactive dyes, a type of synthetic dye, has hundreds of colors or hues. It is also possible to generate and control the shades of a particular color like pale, light, medium, semi-dark and dark. However, natural dyeing, often called sustainable dyeing, for instance, dyeing with henna, has only one color with limited shades (it is also very difficult to maintain the exact shade). Dyeing with natural colorants combing different shade effects is another cumbersome issue to deal and hence future research should be considered. Also, the serviceability of the fabric is poor; for instance, the color is not brilliant with poor fastness properties, the dye effects are poorly reproducible, and they lack consistency. Finally, the evidence of dyeing of synthetic fibers with natural colorant is limited due to poor affinity and substantive property [111].

8. Recommendations on Using Advanced Technologies to Reduce Environmental Impacts

Researchers and technologists have made various attempts to improve the effluent treatment process, reduce the load of pre-processing, processing and post-processing chemicals, and thus ensure sustainable textile manufacturing processes. Some of the attempts have been described below based on the mentioned three criteria of sustainability.

8.1. Use of BIO-Based Materials

The use of bio or nature-based materials is highly recommended in the wet-processing operations, as these materials are safe, biodegradable and create less pollutant compared to synthetic chemical and auxiliaries. Bio-polishing, enzymatic desizing and bio-scouring should be used extensively in the wet-processing industries. These processes require less energy and time. Hence, this reduces production cost [6]. Primarily manufacturers can combine a small proportion of synthetic dyes with a large proportion of natural dyes to ensure an environmentally sustainable yet economically viable dyeing operation. However, technologists, researchers and manufacturers should conduct extensive researches on how to get exact fabric shade by applying natural plant-based dyes and associated additives. Thus, this will prevent the use of synthetic dyes. Researchers can also explore natural plant-based bleaching operations similar to that of plant based scouring process to reduce these environmental burdens [6,55,65,112].

8.2. Use of Advanced Dyeing Machinery and Technologies

There have been many developments in the recent years in designing dyeing machines and formulating dyeing technologies. The advanced machines require less water, energy, dyes and chemicals. One of the biggest developments is the formulation of lower material and liquor ratio that have been possible because of using these advanced machines. Technologies like continuous bleaching and dyeing ranges facilitates quick, continuous and automatic dosing systems, which also reduce effluent volume. Wet processors should widely adopt plasma technology, supercritical fluid technology, ultra violate (UV) technology and foam dyeing are the latest waterless technologies being popular in textile manufacturing countries. The main advantage of using these technologies is that these could be applied for dyeing both hydrophilic and hydrophobic fabrics. Moreover, stakeholders should implant energy efficient machineries to reduce excessive energy usages, and CFC chillers and refrigerators to reduce ozone depletion [6,55,65].

8.3. Use of Recycled Process Input and Waste

There have been recent technological developments in the recycling of process input and waste, which would reduce manufacturing cost as well as environmental impact. One of the common wastes for recycling is the use of the alkali containing mercerized liquor in scouring and bleaching operations. Wet processing industries can apply various membrane filtration methods such as microfiltration, nanofiltration, electrochemical process, advanced oxidation process and an ion exchange process for the recovery of size materials used in sizing and unfixed dye particles present in the residual dye liquor. Water is one of the most important components in wet processing and makes up a large part of the total cost of dyeing and finishing. Therefore, it is crucial to recycle the wastewater, so that it could be reused. Different industries have set up an advanced effluent treatment plant that can convert the wastewater into clean drinking water [5,55,112,113].

9. Conclusions

Complete sustainability considering all components of the TBL framework is really very challenging. Available literature shows partial success; if any of the components is availed, other components are hampered or sometimes a part of the process might ensure all components but not throughout the whole process. Even though some processes are claimed to be sustainable; actually, they are not fully sustainable and contain many technical complications that limit their practical implications. The cost of sustainability is too high to achieve. Again, consumption of sustainable products is not popular due to customers' lack of environmental knowledge and awareness. However, low cost bio-based textile processes using advanced technology and machinery might lead to next-generation sustainable textile processes. At the same time, it is imperative to grow sustainability concern among both customers and suppliers and to pay some extra attention to the practices of CSR.

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