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Md. Khalilur Rahman Khan, Sayedatunnesa Jintun

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Sustainability Issues of Various Denim Washing Methods

Md. Khalilur Rahman KHAN*, Sayedatunnesa JINTUN

Department of Textile Engineering, Faculty of Engineering and Applied Sciences, Bangladesh University of Business and Technology (BUBT), Dhaka, Bangladesh

*khalilbutex@gmail.com

Review

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ABSTRACT

Denim washing is increasingly joining the list of indispensable processes of meeting the demands of the world's shifting fashion industry. Other than this, there is a rising trend in the sustainability perception among both producers and customers in the modern world. However, denim washing is considered to have direct impacts on the environment because of its chemical discharge and many other pollutants emitted during the process which affect water supplies. In the process, the denim industry encounters challenges at every level. Therefore, there is need for studying sustainable problems associated with denim washing. The unseen soul of the denim industry is technology, as nothing can be transformed without technological advancement. Sustainability problems of conventional washing have been addressed in this paper (i.e. pp spray washing, bleaching washing, stone washing, sand blasting etc.). Furthermore, the paper describes how sustainability can be achieved through the most recent washing techniques, such as laser, waterjet, nanobubble, ozone, NoStone, potassium permanganate alternatives etc. The introduction of new technologies has triggered a dramatic shift in the denim washing industry in terms of water usage, electricity and chemicals as well as improved quality. Consequently, it is undoubtful that the recent technologies in denim washing are crucial in making the industry sustainable. Moreover, the paper describes the idea of digitally printed denim and the available software for measuring sustainability in the process of denim washing.

KEYWORDS

Denim, Washing methods, Sustainability, Enzyme, Ozone, Water jet fading

INTRODUCTION

Overall, the textile industry, and specifically the denim industry, has always been a valuable industry, thus its extension expands its centrality in decades to come. Among all the existing textile products, no other kind of fabric has attracted such an acknowledgment as denim. Denim has been used extensively by different generations of people, sexual orientations and classes [1,2]. On the basis of all-time fashion, denim may be considered a fabric and can be exceptionally a stylish fabric. For the sustainment during the fast-changing fashion, denim has undergone consistent advancement [3]. There is a high developing denim demand from the youth, linked to reasons such as denim's higher quality, strength, comfort level, low maintenance, and simple accessibility. Worldwide, the showcase of denim is expected to rise profusely in the coming years. Denim washing stands out as a part of the essential production processes needed to meet the rapidly rising and changing fashion market's demands [2].

Brundtland (once known as the World Commission on Environment and Development) defines the buzzword, sustainability, as “improvement that meets the present desires without relinquishing future generations’ capacity” [4]. Literally, sustainability refers to the act of preserving scarce and vital natural resources for future generations. Sustainability, in most manufacturing industries, is a primary motive. Sustainable practices explain the involvement beyond the customers and business, while the environment and community are essential [5]. Currently, all are enthused to engage sustainability in the design and manufacturing processes in the continuously changing fashion trends [6]. Sustainability can be identified through three components: environmental, social and financial sustainability.

There is a close association between textiles and governance, social and environmental problems. However, the rising awareness of the social and environmental problems affecting the textile sector is the reason behind the increase in sustainability measures’ implementation over the past few years. The crucial consequences of sustainability in the textile industry pertain to denim manufacture as well. In the phase of manufacturing, sustainability is among the key challenges in the denim industry. In the industry, there exists a huge desire to ensure every phase of production is sustainable [7].

However, during the selection of denim garments, customers are influenced by factors such as fashion, attractiveness, and aesthetics. Denim clothing, in the primary process, does not inherit the customer’s desired properties. However, it becomes effective after washing due to its new strength, comfort, softness, look and low cost, leading to the customer’s total satisfaction [8]. Washing is considered an essence of finished denim and is the final stage of denim manufacture. However, different techniques of denim washing are employed to achieve denim’s fading effect, softness, as well as relaxed feeling [9,10]. Besides, the industrial processes are linked to various environmental implications, mainly surrounding the heavy chemical usage and the extensive use of energy and water resources, effective wastewater treatment etc. Jeans or denim are also considered the world’s highest pollutant textile products, as a result of their indigo dyeing, the amount of water required to achieve excellent washes as well as chemicals used [11]. In terms of achieving sustainability in the denim industry, every kind of washing technique has their own merits and demerits. In the past few years, various washing results have become prominent. Advanced materials, the latest technology and environment friendly washing techniques are establishing the sustainable production of denim. Therefore, a denim producer must be conscious, versatile, effective, and technologically aware of sustainability. Bangladesh’s denim industry’s future set-up will certainly affect the perception of modern technologies of washing. From this perspective, this study aims at expounding on the recent developments in sustainability achievement during denim washing.

METHODS FOR ACHIEVING SUSTAINABILITY IN DENIM WASHING

The denim industry discharges vast quantities of wastewater into surrounding streams and bodies of water, thus leaving a large water footprint [2]. With traditional washing recipes, every jean consumes 150 grams of chemicals, 70 litres of water and 1 kWh of power during the stage of denim washing [12,13]. The old-fashioned and time-consuming techniques are, therefore, not ideal for denim mass production and the manufacturing cost also increases [14]. Because of the high costs of manufacturing resulting from energy, chemicals and water usage, an industrial-scale installation is viewed as a big concern for the achievement of a sustainable process. However, sustainability issues in denim washing may be categorized as follows:

- i) Less water consumption for the blue planet.
- ii) Elimination of wastewater.
- iii) Reuse of water.

- iv) Less chemicals for sustainable future.
- v) Use of environmentally friendly chemicals and materials.
- vi) Less energy for efficient manufacturing.
- vii) The protection of human health.
- viii) Shorter process.
- ix) Process optimization in terms of time, temperatures and raw materials.
- x) Quality improvement.
- xi) Increasing productivity.
- xii) Longevity of washing equipment.

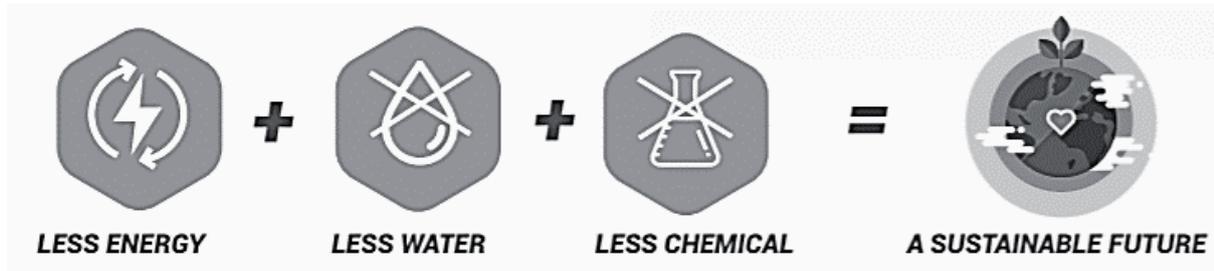


Figure 1. Significant parameters for sustainable denim washing [15]

SUSTAINABILITY ISSUES OF CONVENTIONAL DENIM WASHING

Sandblasting

Sandblasting treatment method washes the denim surface by using rough, high-speed impelling materials. Despite being banned in most countries, it is still employed in some parts of the world, mainly through radar, because it provides an inexpensive and simple technology of generating the anticipated effect on denim [16]. Several brands, attempting to end the fatal method, prohibit the economically favoured sandblasting. If sandblasting is carried out without adequate protective equipment, it can be extremely hazardous to employees' health. The process produces vast quantities of silica dust that can be inhaled by workers, posing a great risk for a lethal pulmonary disease called silicosis. In an attempt to achieve a worn look, the use of brush or sandpaper strategy exposes workers to work-related asthma hazards because of the dust [17].

Stone Washing

For a long period of time, pumice stone has been used in the denim industry in creating an abrasion effect on the denim fabric. The denim style is characterized by a vintage, mildly distressed look. Despite several downsides attached to the use of stones, the abrasion effect remains the best solution. Stones, for instance, could subject denim to wear and tear, specifically on the waistbands and hems. In washing machines, everything is abraded, including the jeans' rivets and metal buttons. Since the stones are disposed of, the process leads to the challenge of waste from the grit. By washing the denim repeatedly, the stones are supposed to be entirely removed [18]. The use of pumice stones by machinery to abrade denim clothing is harmful. The crucial step of unloading the batch to remove stones incurs a time consuming, laborious process. To avoid stones remaining in the pockets, which can ruin the garments in later steps, the garment must be checked by the operator one by one. Dumping of waste stones is another environmental concern as it needs appropriate landfilling procedures. Stone inventories' management needs are an additional burden for factories occupying valuable areas of land. Pumice stones are made up of fragments of ferrous and heavy metals

that should eventually be separated from the garments with repeated washes [19]. Material-based stone washing other than pumice stones leads to serious risks to the health of workers [17].

Bleaching Wash

The denim bleach strategy can be utilized in decolorizing indigo from denim, a process that involves a strong oxidative agent. The foremost commonly used chemicals utilized within the industry amid washing, with or without the expansion of stone include potassium permanganate, hydrogen peroxide, calcium hypochlorite, and sodium hypochlorite. The resulting decolorization is largely more apparent, depending on the treatment time, temperature and the intensity of the amount of the bleach liquor. The commonly used technique of denim bleaching is chlorine bleaching through sodium hypochlorite (NaOCl). Monitoring this process is difficult i.e. the same degree of bleaching may not be easily achieved in repeated runs [20]. However, the release of hypochlorous acid and chlorine is environmentally harmful, as it threatens living organisms and harms the environment. Moreover, since it acidifies, it may cause pulmonary complications like the acute respiratory syndrome (ARDS), due to aspiration that may turn fatal. Despite its success in bleaching itself, it often produces an unpleasant scent in the resultant garment. Notably, sodium hypochlorite is an extreme irritant and can potentially impose substantial chemical burns on workers. After the bleaching process, the remaining hypochlorite should be expelled from the denim. Reducing agent treatment may be used in eliminating residual chlorine, also known as residual hypochlorite, in a process called antichlor process. As a reducing agent, thiosulphate or sodium metabisulfite is used in denim. When mixed with water, it discharges a sharp and unpleasantly smelling gas and SO_2^- , which harms the ecosystem and spoils water [2]. There is a common problem of yellowing, resulting from the residual chlorine from the process of washing in this case. Therefore, chlorine and manganese, which is a heavy metal, should be evaded for the sake of the environment. Traditional hypochlorite bleaching has been recognized to harm the stretch fibres and potentially leads to complaints [21]. Hydrogen peroxide stands out as the cheapest method of bleaching. Also, during its storage, it has a high degree of whiteness and is difficult to be yellowed. However, it is disadvantageous in that, under alkaline conditions, high temperature bleaching requires energy efficiency improvement and may lead to substantial fibre damage [22].

Potassium Permanganate (PP) Spray Washing

Potassium permanganate (PP) is an oxidizing agent used for denim's local bleaching and finishing. Besides, PP spray is used on jeans for lightening a particular area as well as creating whisker effects on denim. However, potassium permanganate (PP) spray is the most hazardous procedure for staff's safety and health. When using a spray-gun to convert chemicals to micro-particles, workers performing this strategy absorb the micro-particles, which causes lung problems, despite the implementation of various protective precautions [23]. In this method, washing and neutralization consumes huge water volumes. Failure to effectively neutralize leads to yellowing. PP sprays have adverse impacts on laborers, as coming into contact with it bothers and burns the eyes and skin. Therefore, factory staff dealing with this chemical without safety equipment and proper ventilation systems may be at risk of long-term and short-term health problems [24].

Enzymatic Stoning Wash (Bio-stoning)

There has been a rise in the global awareness on enzyme use in textile processing aimed at minimizing pollution during textile production resulting from their eco-friendly and toxicity characteristics [25]. For the enhancement of fabrics' quality and comfort, enzymatic treatment is more effective than a variety of

chemical and mechanical operations. The enzymatic stonewashing technique employing chemicals like cellulase is useful in the production of denim's stonewash look. The invention of bio-stoning or enzymatic stonewashing entirely or partly replaced stonewashing. With the immense-looking market for distressed jeans' garments, there is an increase in the use of enzymatic stonewashing. Bio-stone washing has increased the range of available finishes, opening up new opportunities of denim finishing. A small number of enzymes may replace large quantities of pumice stones [26]. The enzymatic stonewashing increases the jean load by up to 50% as well as producing a softer finish and a perfect look [27,28]. This technique improves both the clothing's contrast and the abrasion effect. With partial or no use of stone, a fancy colour-fenced surface is produced. After the enzyme treatment, its rinsing process is lower than pumice stonewashing. Moreover, it has a lower stonewashing cost [29]. Jeans stonewashed through this process have more durability. Besides, it ensures equal outcome under minimum volume, time, waste, water and machine damage. However, bio-stoning involves the release of water and chemicals into the effluent, thus the process is not friendly to the environment [30]. Cellulase denim washing is highly precise and effective; with high resulting reproducibility, consistency, and fading effects' precision, as in the case of productivity [31]. While the outcomes in acidic cellulase are quicker, too much back staining decreases the indigo colour and affects the fabrics' strength. The best stonewashing choice is the neutral cellulase due to lesser back staining, wider pH profile, and lesser strength loss than the acidic cellulase. It therefore lowers the need for rigid pH control producing a more reproducible wash-to-wash finish [27]. Other cellulase applications in the textile industry include the bio-polishing of garments. Cellulase has the capability to hydrolyse microfibrils that protrude from the garments' cotton surface. The microfibrils, after being damaged, appear to break away from the main body of the fibre leaving a smoother yarn's surface [32]. Besides the enzymatic treatment making the fibres' surface "polished", it decreases not only the fibres' flexural rigidity, but also the strength of breaking due to the fibre structure's degradation [33]. Gokarneshan et al. suggested that, to achieve a desired effect, both stonewashing and biopolishing should be combined, which saves at least 30-50 litres of water per kilogram of denim garments [34].

SUSTAINABILITY ISSUES OF LATEST DENIM WASHING

Enzymatic Bleaching Wash (Bio-bleaching)

Enzymes have gained popularity as a substitute for chemicals used in shading/bleaching and are definitely advantageous in terms of wastewater treatment and the use of resources.

Laccases

Laccases are essential enzymes in the achievement of eco-friendly blue denim bleaching process. They are a part of the enzyme type of oxidoreductase. Generally, laccases do not work independently, but require a chemical mediator to be applied between the enzyme and the indigo. The enzyme is oxidized in the presence of an aqueous medium where it attacks the mediator and converts it to free radicals. Ultimately, the free radicals attack the indigo converting it into oxidized products [2]. Moreover, the primarily used mediators are harmful. However, this enzyme's benefit is the specific indigo dyes' treatment and not in the fibre itself. The enzyme breaks down the indigo molecule without affecting other dyes like sulphur, direct or reactive dyes [35].

DeniLite® Cold

DeniLite® Cold is the new cold bleaching solution from Novozymes. The current method is based on enzymes named peroxidases, and operates without extra oxygen from either water or air. This new peroxidase has a high reaction speed, with 90% of the reaction ending in 10 minutes. Based on the gentle bleaching conditions, the cold bleaching technology enhances denim fabric longevity. The enzymatic conditions acting on the fabric's indigo dye are tremendously precise. This ensures that the fabric's elasticity and strength, unlike in tougher bleaching chemicals, remains unchanged [36].

Combined Washing Concept

Denim washing has substantially reshaped denim fashion's sales demands and potential. Denim clothing industry's significant breakthrough lies in the shades and results obtained, beginning from stonewashing to the recent enzyme washing processes and bio-polishing concepts [37]. The rubbing of denim clothing pieces is done through a combination of pumice stones and enzymes, or the utilization of chemicals. Novozymes Denimax® Core, a recent wash processing plan from Novozymes, empowers the handling of the scrubbed area that goes on prior to the combined desizing process. While the conventional process has two rinses and two baths, the combined process has one rinse and one bath, reducing the water usage for more than 50%. As a result of reduced procedures, heat savings may be achieved by shifting from any of the conventional methods procedures to the combined process [38].

NOSTONE®+

NoStone®+, in conjunction with Levi Strauss & Co., is the newly revamped system of denim washing, developed by Tonello. The system is developed to overcome the environmental, mechanical, and economic constraints of stonewashing process. NoStone®+ framework's premise is the stainless-steel rough drum, which is linked to the washing machine cylinder. The drum is handled in a special way to make it more or less abrasive, depending on the intensity of the desired effect or the needed treatment. The process's nature is mechanical rather than chemical. The outcomes of NoStone®+ are similar to those of stonewashing, while also reducing the carbon footprint produced from the use of pumice stones. NoStone®+ also minimizes manual labour, preparing time, emissions, generation costs, and water usage. More so, it does not produce sludge nor dust, does not harm the system, and according to Tonello, it produces a uniform effect in both sampling and production [39]. In conjunction to the NoStone® technology, enzymes may also be utilized in the accentuation of NoStone® process's impact [24].

Potassium Permanganate Alternatives

Spray treatment with potassium permanganate is the most conventional and economical method [40]. Despite being an effective technique, it has a high aquatic toxicity, thus imposing risks on health and the environment. Many countries have a duty or stringent rules to offer proof of preventing such misuse [41]. Other developing chemical systems recently developed do not emit manganese into the atmosphere, as it is a heavy, non-biodegradable metal [24].

OrganIQ Product

The organIQ bleaching technique, a proprietary of CHT Group, is the first fully biodegradable and purely organic denim bleaching agent that achieves sustainable, remarkable results. Application of this technique

does not require extra neutralization and does not pollute wastewater with hazardous contaminants, when properly used. Under a combination of organIQ bleaching agent and organIQ biopower, there will be no need to use chlorine, potassium permanganate, or stones. Moreover, the really fluffy products become perfectly smooth and develop a precious character [42]. Modern techniques' combination, such as organIQ + fog application, produces fully effective ecological washing results, and ensures resource protection [43].

Nearbleach Sky White

Nearbleach Sky White, designed for localized bleaching, is applied in brush and spray technique, in combination with hydrogen peroxide and the catalyst, Katalin Sky White, to achieve a controlled and quick bleaching for denim garments of high whiteness. In this process, time and water is saved. After application, there is need for only a simple washing step, with no neutralization [44].

Acticell Technology Solution

Acticell technology solution is designed to produce bleaching effects, just like potassium permanganate bleach. It also works best as an alternative product in achieving localized bleaching results (Acticell RT, Acticell B3). The desired outcome can also be achieved at any temperature, e.g. 60°C or room temperature. The bleaching effect takes place during a heating operation. The product has been certified by GOTS [45].

Garmon Avol Oxy White

Garmon Avol Oxy White is free from all drawbacks associated to potassium permanganate toxicology, including toxicity to aquatic creatures. Moreover, workers' health is secured. It provides simple application, handling protection, and a stunning consistency. Tumble drying or curing must be avoided as it is inappropriate and results in tensile loss and cotton tearing [46].

Peristal BLI Eco

Alternatively, Peristal BLI Eco system is used instead of oxidative spray bleaching, which also ensures sustainability and effectiveness when dealing with denim jeans that are indigo-dyed. This method is effective as it does not contain any heavy metals nor chlorine, thus conforming to most environmental requirements, like bluesign® and ZDHC. Moreover, the products are odourless and free from alkylphenol, formaldehyde, ammonia, and heavy metals' ethoxylates. Additionally, their oxidizing reactivity is very high. For the workers' safety and security, there should be strict adherence to the crucial safety measures in the industry [47].

Ozone Washing

Ozone washing is an innovative waterless technology. The ozone imposes crucial effects on clothing as well as the environment [48. 49]. The ozone is a triatomic molecule with three oxygen atoms. One of the artificial methods of producing the ozone is corona discharge. The gas fades dyed textile fabrics by rupturing the chromophores of natural or synthetic fibres. Due to the high oxidation ability of the ozone ($E=2.07$ eV), it can easily decompose complex aromatic rings of dyes, resulting in decolorization. In order to generate ozone (a strong oxidant gas), only air and electric energy is used [11]. On treated products, the ozone does not leave secondary derivative products, because it is chemically unstable. The garment may be bleached through this technique. During denim garment bleaching, the ozone is dissolved in the water in the washing machine. Moreover, denim garment bleaching and fading may be done via the use of the ozone gas in closed

chambers. When compared to other oxidizing bleaching agents, the use of the ozone gas is much faster, as it only takes 15 minutes, while conventional bleaching takes 30-50 minutes [2]. While the ozone finishing uses two to three washes and rinses, stonewashing or chemical bleaching uses six to seven. Despite the inability of the ozone to eliminate water use during jeans finishing, it greatly lowers water consumption. By decreasing the temperature needed and the amount of water that should be heated for wet finishing, it decreases energy consumption. Besides the reduction of chemical and water consumption from 85% to 95%, and energy from 70% to 80%, Jeanologia's G2 Dynamic technology is designed to guarantee a detoxed and sustainable fabric. For instance, if 15 to 20 litres of water are required per kilogram of fabric, the whole process will only require 0.5 to 3 litres of water per kilogram with G2 Dynamic [50]. G2 technology, by using ambient air, develops the garments "sun-washed" effect with the real look of outdoor use. In addition, using the ozone instead of some conventional finishing eliminates the effluent as well as the generation of sludge from the pumice stones. This technique is simple and friendly to the environment, because after laundering, the UV radiation may deozone the ozonized water [18]. Additionally, the ozone is applicable beyond shading, such as in stonewashing, to replicate other processes of denim finishing. This approach is sustainable due to its high quality, comparably better performance, long-lasting effects of the operation, low maintenance costs, simple installation, minimal bleaching production costs, and high production capacity and efficiency. Nonetheless, safety procedures and features should be key in the avoidance of workers' deadly or dangerous accidental exposure to the ozone gas. Since it runs in dry conditions, the system enhances whiteness and eradicates the jeans pockets' back staining as well as other potential organic spots [51].

Nanobubble e-Flow Technology

Nanobubble e-Flow technology can handle raw clothing and apply different chemicals, move the clothing with the use of micro-nanobubbles (MNB) as the chemical product vehicle capable of directly getting inside the fibres [52]. The process involves injection of atmospheric air into the electro-flow reactor and then subjecting it to an electromechanical shock to generate wet air flow and nanobubbles [53]. Different chemical products such as dyes, antimicrobials, liquid repellents, wrinkle-free resins, softeners etc. are used to pass functional properties to the denim. Through the application of this modern technology, the revolutionary feature is that certain items get into contact with garments with minimum water amount [54]. The nanobubbles' skin has a duty to transport the chemicals to the garments [12]. Water and chemicals are homogeneously blended with the help of microbubbles and spread on the garment [55]. Nanobubble technology boasts of significant success such as 86% water use reduction, 97% wastewater reduction, extremely low liquor ratio of 1:1, the recycling of steam/water, energy use reduction up to 80%, 50% chemical products saving, related chemical wastage reduction, reduction of the washing and drying process, as well as necessary temperature reduction and reduction in CO₂ emissions [54,56]. The method is, therefore, cost effective. It can create a washed look by laser as well as the wet ozone process creates a bleached look over the denim [56]. The e-Flow process provides pre-shrinkage of the fabric, thus avoiding high shrinkage during washing at home. Moreover, it improves the colour fastness to rubbing properties [53]. If the surface of the fabric is meant to achieve a stonewashed effect by enduring a high degree of abrasion, the e-Flow technology, on the basis of aesthetics and sustainability, is a commercially viable choice. However, it is important to consider the productivity factor. Chemical suppliers have produced cellulase enzymes usable in e-Flow, such as the DyStar's Lava[®] Cell NEF [57].

Water Jet Fading

Conventionally, the jeans' abrasion and whitening processes are done either with manual brushing or permanganate sprays, whereby the two techniques are harmful to the respiratory system, skin and the eyes. By using water during whitening, Tonello's Water Brush tackles the above disadvantages [58]. Hydro jet treatment often needs hydro jet nozzles' contact to the one or both surfaces of fabric. There is much relationship between the degree of colour washout, pattern clarity, resulting fabric softness and the nature of the dye in the fabric and the manner and degree of fluid impact energy added to the fabric. Blue indigo dyed denim produces exceptionally essential outcomes [18]. Fascinatingly, Tonello's water brush uses water, but does not absorb it. The water used in garment whitening is gathered by a large tank under the spray robot. The tank filters the water then recycles it back to the robot. Again, the highlights include its zero influence on the workers and the ecosystem, and the reduction of resource use [58]. Tonello has an aim of replacing the manual and permanganate brushing techniques with highly pressurized water through Water Brush incorporation in finishing processes to create the same worn effect without applying heavy chemicals. The chemicals not only pollute the environment but also pose risks to the workers involved in the process.

Laser Technology

To avoid some of the shortcomings of the traditional technologies, a new revolutionary approach has been established under laser technology's advent in the textile industry [59]. It is another sustainable option in the denim washing field. This is the fastest growing and approved technology of the denim industry, and has made denims go green [13]. Laser finishing is referred to as denim spray painting. Lasers are employed during laser engraving as well as laser marking. The method is often used to replace environmentally disadvantageous and potentially hazardous typical dry techniques, such as grinding, destroying, hand sanding, sand blasting etc. [59]. Via this technique, the dye on the surface is decomposed by the laser beam and the subsequent components are converted to vapour and expelled away. The efficiency of fading is dependent on the wavelength of the laser beam, pulse duration and power density [3]. Laser technology provides infinite exploration and innovation possibilities for designers. This technique creates patterns carried out by computer-managed processes, such as even images, text, lines and dots [13]. Therefore, it can be used in creating personalized patterns and designs or generating worn-out effects like rips, abrasions and whiskers. It is also capable of providing detailed duplicability of the applied results. Moreover, laser engraving is useful in fabrics' burning and colour fading to generate embroidered designs in the cloth. Lasers are preferred for low-cost sealed CO₂ and laser engraving [60]. There is a possibility of pre-programming the laser with designs that may exactly replicate the anticipated look obtained through manual sandblasting and sanding with considerably minimal labour and physical hazards. To produce a variety of denim looks, it requires less water, chemicals and electricity. For an enhanced laser effect to mimic heavier bleaching applications, an addition of laser boosters to the fabric may be effective [24]. Furthermore, it reduces production costs and saves time. According to experts, these technologies have led to 500% production increase per workplace and 50% fabric strength loss [13]. Moreover, the software, such as E-Mark and CarbonLaze, increases industrial efficiency, gives room for more innovation, simplifies design, and decreases steps of pre-production process. In conjunction to an eco-washing system, laser technology for finishing jeans has led to outstanding environmental benefits. This new technology saves 85% of chemical products, 67% of water, and 62% of electricity [13]. The most complex issue associated to laser processes is the inaccuracy of the laser beam magnitude. When low, it is difficult to obtain the effect, and on high laser strength, it may destroy the fibre bonds, leading to tearing and chemical damage [1]. Furthermore, the fading process is linked to a high eye

damage potential [3]. It was hard to operate and maintain the early laser systems. However, the current laser systems are easier in terms of service and maintenance [60].

Plasma Treatment

With a wide range of sustainable technologies, many would consider the plasma treatment as an effective way of replacing traditional chemical processes, because it facilitates the achievement of the desired outcome using an appropriate reactive gas, and it is a dry process as well. Avoiding chemical waste is the key attraction of plasma in industrial operations. Saving vast amounts of water, chemicals and electricity is another benefit [61]. The plasma is an incompletely ionized gas, and is often referred to as the fourth state of matter. Upon the exposure of a substance to the plasma, a number of plasma particles (neutrals, radicals, ions, and electrons), as well as UV photons reaching the surface with various energies' distribution, bombard the surface. A number of these active species are energetic enough to detach chemical bonds and prompt fibre surface reactions [62]. The RF and Corona's low-pressure treatments resulted in an improvement in denim lightness, implying elimination of indigo dye from the fabric surface. To achieve a worn look for indigo-dyed denim fabric, corona treatments and low-pressure plasma may serve as a viable alternative to the traditional bio-stoning. However, further research is required in order to prevent harsh fabric handle emergence and the upsurge of yellowness [63].

Sustainability Issues of Digitally Printed Denim

On its sustainability journey, the textile industry is gradually inclining towards digitalization [64]. Digitally printed denim uses a mechanism that can bring denim to a new level, by using textile inkjet printing as an artistic method [65]. Digital printing can create precise image data, with the use of millions of colours in infinite motif format. Under this technology, it is possible to create visually convincing design specifics that mimic the real thing, like abrasion areas, whiskers, and yarn slubs [66]. Digi Denim is a completely 'waterless' kind of denim. Among the traditional washing processes are pre-treatments, enzyme washing, bleaching, and neutralizing. Every step in this process requires a significant amount of water. The digitization of denim industry contributes to sustainable practices. Without any natural resource or material waste, digital design can create countless pairs of jeans, thus lowering waste levels and the environmental impact. Digi Denim provides a huge cost decrease and the overall lead time. It is a sustainable and cost-effective option as opposed to the traditional denim finishing and colouring techniques [1].

SOFTWARE FOR MEASURING SUSTAINABILITY IN WASHING

The control of the cost of energy, chemicals, and water in the production process is aimed at developing an ethical, productive and environmentally friendly denim washing system. Through the evaluation of the current impacts, the defining interventions and areas of change are easily recognizable, and can thus be tracked for sustainability.

Environmental Impact Measuring (EIM) Software

EIM software is used in the assessment of the environmental impact of finishing processes for garments in categories such as: the use of water, the use of energy, the use of chemical products and health of the workers. With regard to water, a low-impact process is defined by the EIM as consuming less than 35 litres of water per garment. The EIM takes a product's toxicology into consideration. It penalizes the use of more

chemicals for contaminants, regardless of the amount of the substance used. The environmental effect of a complete finishing process can also be calculated by the EIM. The individual can clearly see the key cause of the environmental hazards with this tool, giving them the requisite data to move towards a more environmentally friendly process. The EIM also enables the consumer to compare various processes and determine their resulting outcomes in terms of sustainability issues [67].

Environmental Score (eScore) Software

VAV Technology developed the eScore Software for denim manufacturing industries that calculate and compare the quantities of chemical, electricity, and energy reference values, as consumed by the machines based on the prescriptions. It provides data on the lower and upper limits to protect the environmental and human health, data on the system effort and utilization of ability. Based on each company's water and chemical consumption, eScore Software ranks the companies and categorizes their scores as follows: i) 0-33 Score: Environment-Friendly Production, ii) 33-66 Score: Acceptable Production, iii) 66-99 Score: Limit Value, iv) 100 and more: Non-Environment-Friendly Production [68].

CONCLUSION

Different kinds of mechanical or dry-washing processes and chemical or wet-washing processes create a lucrative outlook for the denim washing system. Relating to sustainability concerns, the traditional washing methods are linked to tremendous health and environmental risks. However, with new technologies and approaches to denim washing, sustainable and attainable solutions are currently available, capable of supporting the environment, the consumer and the company. Following the denim industries' adoption of new technologies in the manufacturing process, there has been a drastic decrease in the use of energy, chemicals and water during the washing of denim fabrics. It is worth stating that these new technologies, including waterjet, ozone, and laser technologies, have presented themselves as excellent options for denim washing regarding the expense, time, durability, consistency, and efficiency. As a result, the denim industry will soon experience dramatic changes following the new developments. However, there is need for further advancement in denim washing techniques to enhance sustainability of the industry.

Author Contributions

Conceptualization – M.K.R.K.; methodology – S.J.; resources - M.K.R.K. and S.J.; writing-original draft preparation – M.K.R.K. and S.J.; writing-review and editing – M.K.R.K. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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