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Towards sustainable denim: evaluating the dry process techniques in surface modification

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Abstract

Purpose: As an alternative to widely used denim wet washing techniques, which consume a huge amount of water and chemicals, dry washing techniques need attention. That is why this study sought to investigate and evaluate the sustainable surface modification techniques known as dry wash methods applied in industrial denim apparel washing.

Methodology/Design: A descriptive research design is followed to conduct the case studies by collecting primary data from three 100% export-oriented denim washing factories, exploring a detailed and accurate picture of the dry processes prevailing in the denim washing factories. The findings of the qualitative data of the study are reported descriptively with graphical illustration along with flow charts to convey the collected information for better understanding, along with the sustainability indicators, namely Water, chemical and energy consumption.

Findings: The study analyses water, chemicals, and energy as indicators of sustainable washing and finds zero water and chemical usage in the hand scrapping, tagging, grinding, whiskering, destroying, laser, and ozone fading, along with no or very little energy consumption in grinding (0.67%), laser (4.8%) and ozone fading (4.5%) procedures, validating environmental sustainability.

Practical and Social Implications: This paper contributes detailed information about sustainable surface modification on denim to the academic and professional literature, comprehending valuable contents like process techniques, tools, controlling points, and resource consumptions in the context of water, chemical, and energy consumption as well as help global manufacturers set benchmarks in adopting and modifying those manual processes to progress further in industrial apparel washing.

Originality: This paper provides practical field-level information on multiple dry process techniques used in denim surface modification, focusing on their sustainability in terms of water, chemical, and energy use. Case studies from three manufacturers enrich the literature with real-world manufacturing scenarios for dry wash surface modification techniques.

Keywords
Denim, surface modification, dry process, sustainable wash, environmental impact.

1 | INTRODUCTION

The aesthetic appeal, comfort, and emerging fashion trends are the primary driving factors behind the worldwide consumer demand for surface modification of denim. Blue jeans, a popular denim apparel, can offer the consumer a much smarter casual look than other casual wear (Samanta et al., 2017). Denim is the most widely embraced fabric among all other textile products and is extensively consumed by individuals of all ages, social classes, and genders (Paul, 2015). Surface modification of denim is functional during the various manufacturing stages in fabric production like enzymatic pre-treatment using pectinases, laccases, acid cellulases etc. (Ibrahim et al., 2018). However, the rise in popularity of

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the fading effect has been observed within the realm of apparel design concerning the ever-evolving fashion trends, particularly for blue and black jeans. Denim washing represents a substantial portion of the textile sector (Colomera & Kuilderd, 2015). It is the process to give aesthetic finish to denim apparel to enhance its appeal as well as to provide strength (Choudhury, 2017). Two types of surface finishing, especially for denim, are practised in the washing industry, comprising wet and dry washing methods to attain stylish appearances that are unique and desirable (Khalil, 2015). Applying wet surface modifying methods resulted in removing the uppermost layer of colour through a chemical process, resulting in a white exterior. However, the dye remained intact in the underlying layer of the denim, contributing to its faded appearance (Haq et al., 2014). The traditional way of denim finishing is wet washing by the application of stone, enzyme, bleach, acid etc. to achieve the desired fading look and soft handle (Tarhan & Sarıışık, 2009) but the consumption of multiple chemicals and huge amounts of water in denim wet washing has adverse environmental impacts as denim requires multiple processes for the distressed appearance which results in a repeated infusion of dangerous chemicals (Schrott & Paul, 2015). Chemical discharge and various pollutants emitted during denim washing affect water supplies. Each method of modification has inherent advantages and disadvantages. A pair of jeans consumes 150 grams of chemicals, 70 litres of water, and 1 kWh of power during traditional denim wet washing (Khan & Jintun, 2021). Substituting harmful chemicals with ecologically sound substances, lessening wastewater, and developing novel design and production methodologies in denim washing have become crucial (Unal et al., 2020).

Several progressive, sustainable approaches, such as the laser fading, ozone fading, destroy, whiskering, etc. mainly known as dry processes in the apparel washing factory, embraced for denim modifications to alleviate the environmental impact of conventional wet washing techniques (Sakib, 2023) but detailed about those processes, parameters, tools, resource consumption and chemical usages to identify ecological implications for proven environmental sustainability are still lacking in this research domain. Reducing water, chemicals, and energy consumption is regarded as a significant factor at the industrial level to attain a sustainable process in denim washing (Senthil Kumar et al., 2021). This research endeavour aims to assess the prevailing patterns of dry processes applied to modify denim surface, chemical substances (if required), essential equipment, apparatus, and controlling factors for achieving the intended faded aesthetic look on denim apparel, as well as the ecological implications of these procedures to explore the environmental sustainability. The study will provide practical insights into innovative approaches pertaining to both traditional and advanced surface modifications of denim apparel. It will shed light on detailed sustainable dry processes in the context of water, chemical, and energy consumption and help global manufacturers set benchmarks in adopting and modifying those manual processes to progress further in industrial apparel washing and meet the increasing global demand for worn-out denim. This study will also contribute to the academic and professional literature, enhancing the collective knowledge base for consumers, fashion readers, and practitioners by containing valuable information on environmentally sustainable dry processes for washing denim apparel.

2 | RESEARCH METHODOLOGY

2.1| Case description and selection

A descriptive research design is followed to conduct the case studies in the research work, exploring a detailed and accurate picture of the dry processes prevailing in the denim washing factories. Three case factories were selected for the study to describe the dry processes in apparel washing accurately and systematically. The factories are selected based on the criteria of a 100% export-oriented denim washing factory with orders of dry processes on denim apparel, including the current trends of the fashion market. Such purposive, theoretical sampling was selected for this study due to the qualitative nature of the study. Choosing only three factories was the optimum for maximising the insights relevant to the central research objectives under the scope of this study.

Table 1. Production capacity per day of the case factories

Factory	Production capacity per day
Case Factory 1	~80K
Case Factory 2	~120K
Case Factory 3	~60K

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Manual, semi-automatic, and automatic dry processes are directed to the washing floor. Case Factory 1 is in the Mawna Union, Sreepur, Gazipur, established in 1998, and factories 2 and 3 are both located in Tongi, Gazipur, since 1984 and 2005, respectively, as shown in Figure 1. The available processes collected from the production planning department in the case factories are selected to be observed for the research work. The collected data is sorted, evaluated and compared for the qualitative presentation. The standard operation procedure of the dry processes, chemicals (if required), controlling parameters, machines, equipment and other necessary tools are summarised in this work. The consumption of water, chemicals, and energy is also explored as indicators of the environmental impact of dry processes used to modify the denim surface.

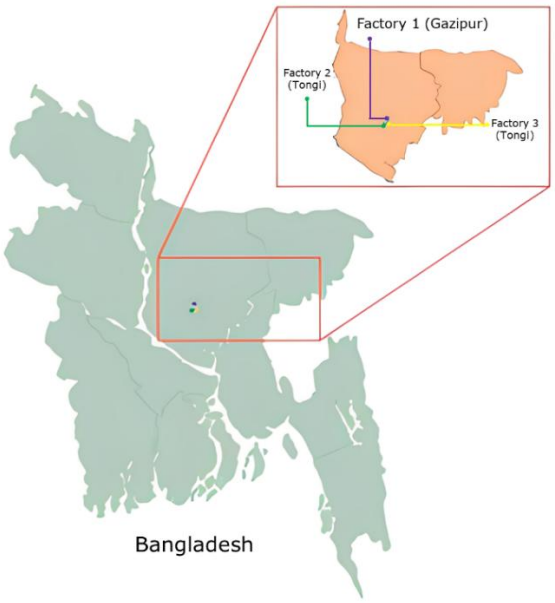


Figure 1. Location of the case factories

2.2| Data collection and data analysis:

Primary data is collected by the observational method to explore the dry processes of denim washing in the case factories. The time of the required fading effect was measured by the stopwatch, the temperature was taken from the digital screen of the machines (where applicable), and the type of fading area was measured by an observational method. The laser and ozone fading machine details were explored from the machine manual, and the operation parameters required for fading effects. The proportion of energy consumption is determined by the division of machine kilowatt-hours by the hourly output of grinding, laser and ozone modification techniques. Critical observation was conducted to identify the controlling points, operation procedures, and limitations of different surface modification techniques. Analysis of the visual changes of the surface of the denim apparel is conducted on the inspection table. Data is prepared by removing inconsistencies and irrelevant information and structuring the key findings in relation to the research objectives. The findings of the qualitative data of the study are reported descriptively with graphical illustrations along with flow charts to convey the collected information for better understanding.

3 | FINDINGS AND DISCUSSION

There are several surface modification techniques that are followed in dry processes of apparel washing in the case factories of Bangladesh, and those techniques are eco-friendly, as fading effects are produced without water and without the application of hazardous chemicals. Among those, grinding, Hand scraping, Tagging, destroying, Laser Fading, Whiskering, and ozone fading are found in the investigation. The standard operating procedures, essential equipment and chemicals (where applicable) for the surface modification to develop fading effects, process control parameters, and defects generated in the process are described in this section. A standard sequence for washing plant found in three case factories is as follows: sample development, shrinkage bits analysis, blanket/size set/ pilot run analysis, and finally going for the bulk production. Generally, in the case of factory 1, it has been found that the first step of every dry process is "sorting according to size variation" to facilitate effective inventory

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control. Then, localised areas of the denim pants are marked through chalk for treatment or design to guarantee consistency and design components in the finished product. The "Whisker" stage comes first, which is one of the popular surface modification techniques used to give the denim fabric a faded or worn-out appearance. Later, hand scraping and tagging are completed if the buyer requires those effects.

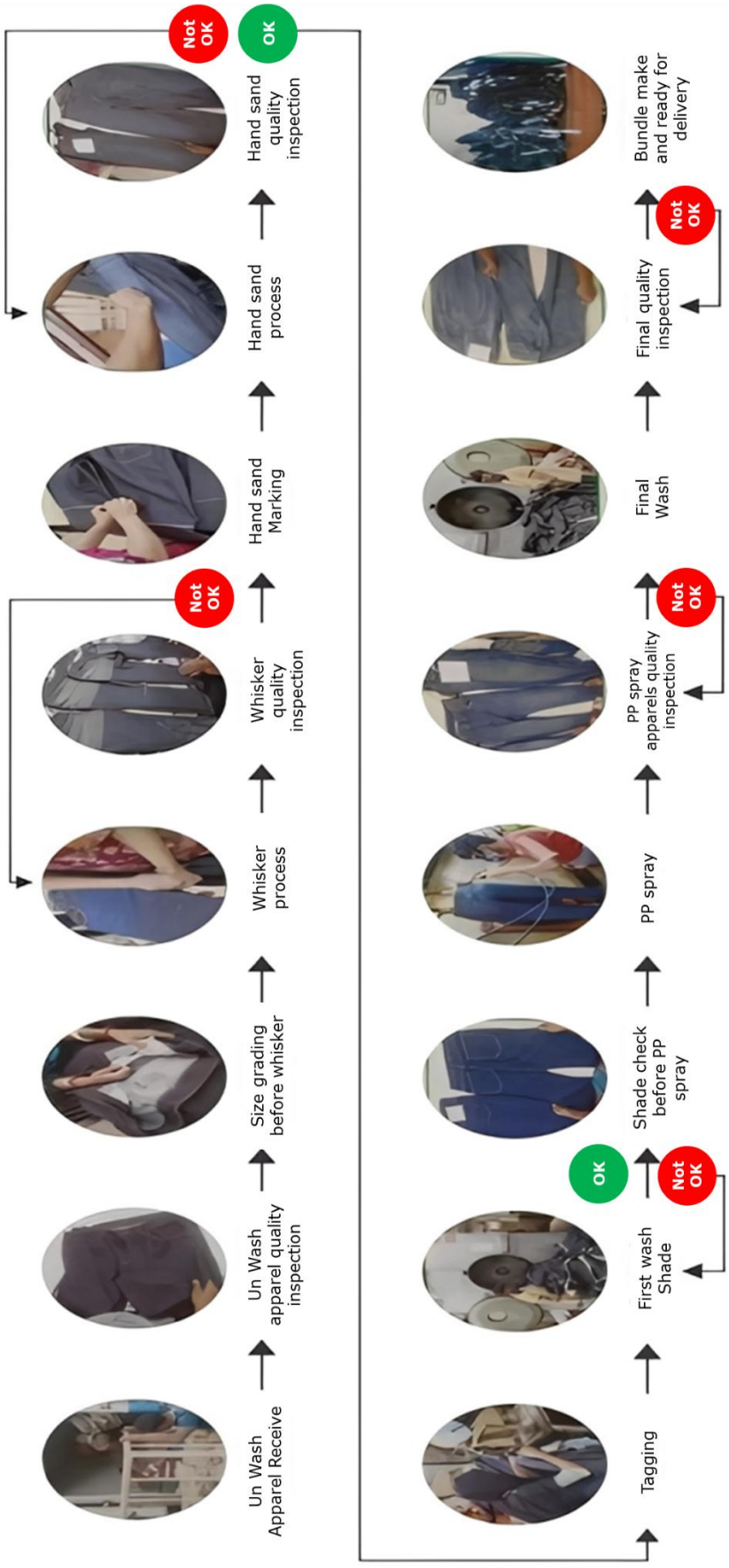


Figure 2. General sequences followed for the surface modification by dry washing techniques in case factory 1.

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After that, required wet washes are followed for the desired modification on the surface as per customer demand or fashion trend. For example, the size materials are removed with the first wash, which is also known as the Desizing process. Afterwards, the denim apparel goes through a destructive process, grinding, and is sprayed with potassium permanganate (if required), followed by neutralisation and softening processes applied to the apparel to soften it. If wrinkle or crinkling is also a required effect for those pairs, then the final process is the wrinkle or crinkle process, as no dry or wet process can be applied after those processes to maintain the desired appearance of the product. Finally, the apparels become ready to be shipped to the destination. Figure 2 shows the general sequences followed for the surface modification by the dry washing Process in the case factory 1. However, only sustainable dry processes in the context of water, chemical and energy are discussed in this part.

3.1| Surface modification by hand scraping process

"Hand scraping", a labour-intensive technique where expert craftspeople manually abrade the marked area of the fabric to create different patterns and texture effects. The hand-scraping effect usually develops on the front thigh area (Figure 3) as well as on the back thigh of the jeans. This process is a sustainable process as it is a waterless and chemical-less surface modifying technique for fashion effects development on denim apparel. Figure 4 represents the process flow diagram of hand scraping in the case factory 1. Initially, the material was scraped with a hand scraper while applying constant pressure. An air dummy was then employed, and air suction through the dummy is 25L per minute. Following that, scrapping was done by emery paper six times in total—three times in one direction and three times in the other. Colours are removed off the clothes by hand scraping. The amount of colour removed is determined on the grade of the emery paper and the hand pressure of the workers. Emery paper is usually used to scrape the garments in a particular placement & design for a more specific effect. Hand pressure depends on as per fading requirements. It is generally done in a rigid form of garments to get the distressed look. During the investigation, two types of emery papers, 600 and 800, were found in the case factory, and 800 was finer than the 600 to rub the denim. It is also found in the literature that different numbers of emery papers are available in the market, typically ranging from 40 to 600 and beyond (Agarwal, 2009). During the abrasion process, quality maintenance is a very hard-hitting task to avoid less, over, uneven, or crease marks on the final products.



Figure 3. Visual Appearance after hand scrapping

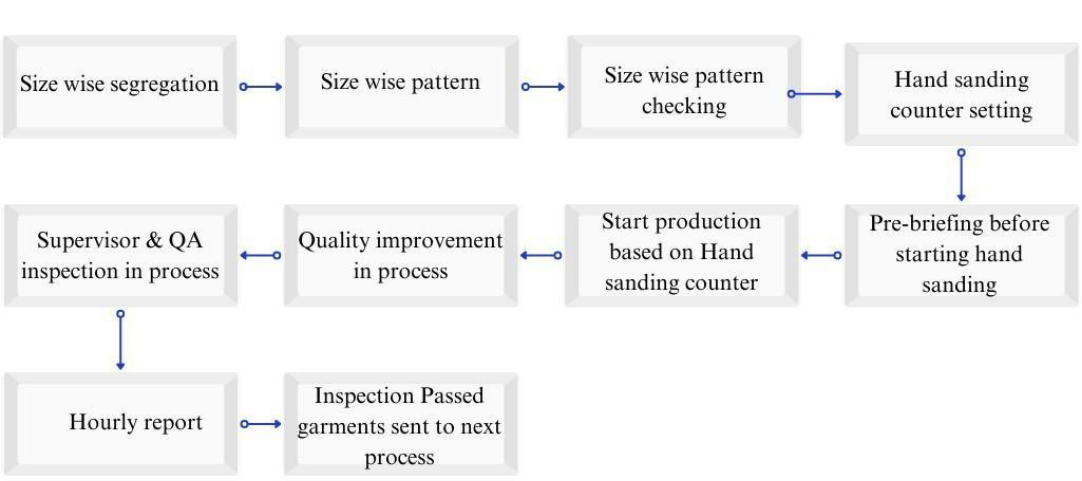


Figure 4. Process flow diagram of hand scraping process.

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3.2| Tagging process

Another environment-friendly water and chemical-free process for surface modification on denim is "Tagging", which is applied on the "raw denim", which refers to the received denim products that have not been processed. Like all other dry processes in industrial denim washing, the 'size separation' and 'area marking' are the compulsory steps before starting the tagging process. Tagging effects are developed on denim apparel before the wet washing process, applying folding techniques, and stapling by tag pins. Tagging is done on apparel for fashion and value-added fashion wear. In this process, the effect is created by tag pin machines with the help of plastic or nylon tag pins in a rigid form of apparel. The item is folded on the required areas and tacked through the folds. The number of folds can be two to four or five. Usually, the inner of the fold is dark due to less exposure to rubbing and chemicals. The faded effect comes on the folded parts. The practice of tagging clothes is carried out while they are still unwashed (Zayedul Hasan et al., 2021). Figure 5 shows how the apparel is tagged in the dry process of apparel washing.



Figure 5. Tagging in denim apparel

3.3| Grinding process

The grinding process is applied to basically jeans items to provide a worn-out look in the grinded areas (Zayedul Hasan et al., 2021). It is a water and hazardous chemical-free surface modification process, and is done with a pen or roller grinder machine, consuming very little energy per item. Hence, it is also designated as environment-friendly dry process. The process is conducted after the wet wash on items. Usually, a pen grinding tool for small and non-edge areas of apparel is used in the semi-automatic process, and quality depends on the skill of operators. Figure 6(a) shows the outlook after the pen grinding process of the apparel.

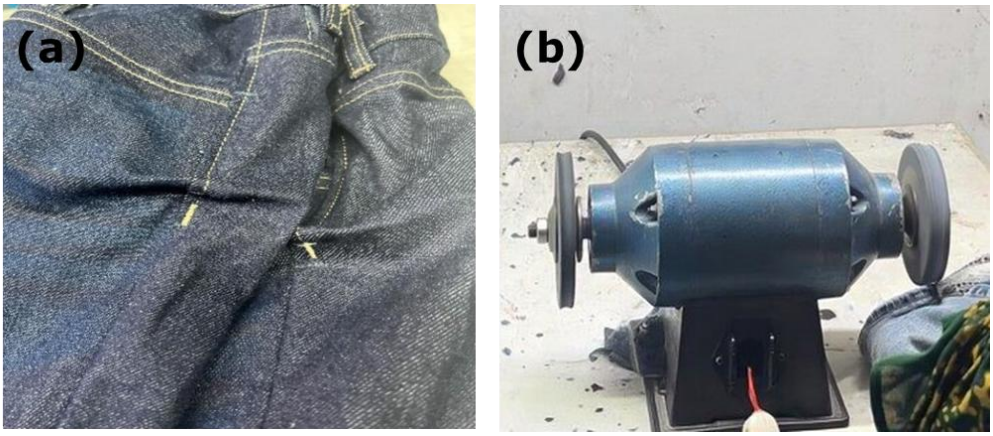


Figure 6. (a) Surface modification through the pen grinding process, (b) Roller grinding machine

Another type of grinding process is the automatic process through a roller grinding machine, applied to a large area or the edge of the apparel (Figure 6(b)). Generally, Hem, pocket edge, west belt, pocket opening, and pocket plug are marked for this process, although it is completely dependent on the requirements of buyers. The result of the effects is based on the abrasion made by grinding over the garment's surface. It depends upon the friction and speed of grinding. Usually, 150 - 180 rpm is used in the grinding wheel of 5-inch diameter for the worn-out look. Abrasive stone-type wheel in the grinding machine is found to be used for the desired outcome in the denim products. The study also found that 8

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KW per hour of energy is required for 1200 pcs of apparel, revealing the minimum energy consumption of 0.67% per piece in the grinding process. The over, less or wrong placement of grinding effects are the critical considerations during the process, and skilled operators are preferred for this job.

3.4| Laser fading

One of the modern approaches of dry processes to surface modification of denim is using laser technology, which applies hot laser light at a 90-degree angle to remove surface colour from the denim apparel. It is a modern & sustainable dry process which doesn't use any water or chemicals. Laser technology acts as a thermal source that eliminates the indigo dye of denim fabrics by sublimation (solid to direct gaseous state), giving multiple faded effects such as whisker, destroy, grinding, etc. The CO_2 laser beam produced from the laser tube of the machine can be focused accurately and consistently into a particular area of the fabric surface without any unwanted harm. The laser machine emits focused laser rays that can also partially burn the denim surface to destroy the warp yarn for a worn-out look, which is called laser destroy. An air suction machine is used to remove the debris. As a result, high-quality outputs even for the complex designs have been enabled with higher productivity and less manpower. Factory 1 has a Jeanologia Flexi HS model laser fading technology machine, which is used for multidimensional design effects like laser destroy, laser whisker, etc. Generally, one or two manpower is required for the process. One is the operator of the laser machine, and sometimes a helper might be needed to assist the operator with material handling. During the investigation, the authors explored laser destruction and laser whisker effects in case factory 1. The process flow of laser destruction is shown in Figure 7. The laser intensity is measured for the proper effect. The automatic control panel maintains the control parameters (time, laser wavelength, laser intensity), although the design should be pre-set in the monitor. The grading of destroy is checked and set before the bulk production is started, to maintain the quality of the product. Marking time in the required areas was 5 to 7 seconds, and the average time needed to complete a product for the destroy effect, as shown in Figure 9(a), was 20 seconds, although the time varied depending on the number of destroy areas. The usual productivity per hour of the machine for laser destroy is between 200 and 250. The destroy effect is developed on the upper thigh corner after all wet washes. Figure 9 presents destroy effect in bleach washed jeans.

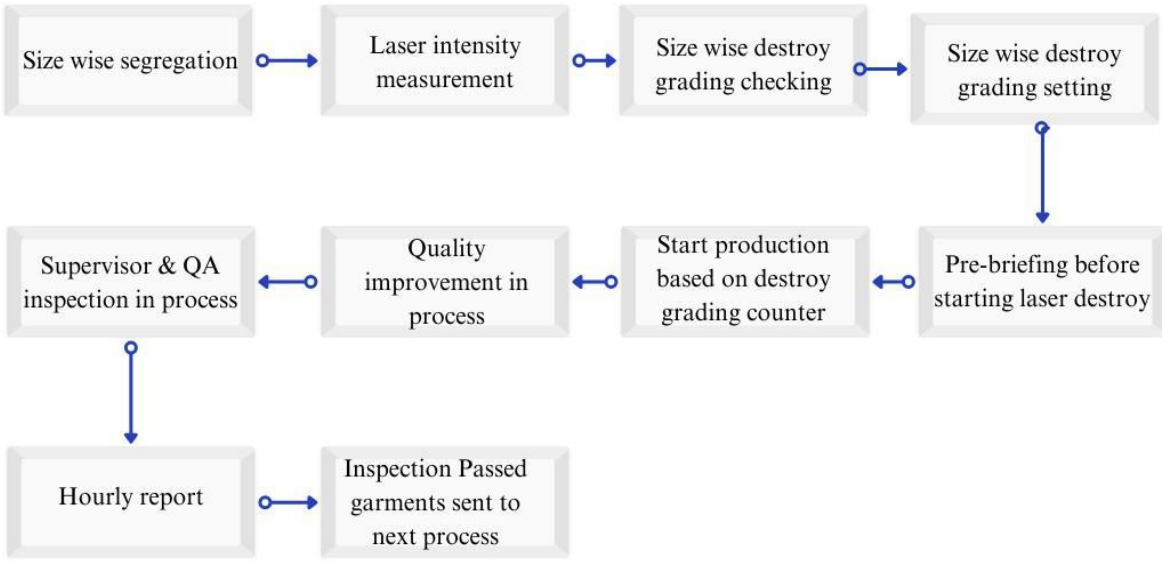


Figure 7. Process flow diagram of laser destroy

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Figure 8. (a) Laser destroy, (b) Laser Whisker and (c) Final Whiskering effect

Any form of vintage effects, whisker pattern, intentional holes, and tears for ripped jeans, complex designs, and images can be developed through laser fading technology. The preparatory processes for laser whisker are similar to laser destroy but the only difference is the time required for the laser whiskering effect. It requires an average of 30 seconds for both panels (Figure 8b). Unlike laser destroy, the laser whisker effect is developed on the jeans' surface before other wet washes and the final effect is worn-out vintage denim pants (Figure 8c). To enhance the value of the product, laser fading does not require consuming water and harsh chemicals, which justifies that laser fading is an environmentally sustainable denim washing technique supporting green manufacturing. This study found that the laser machine consumes 12.2 kW of power per hour. Literature also suggests that the laser technology has impacted the denim washing business by enhancing quality and reducing the use of water, chemicals and power. This can save 85% of chemical products, 67% of water, and 62% of electricity when combined with an ecological washing (Khan & Jintun, 2021). Another study stated that the colour fading effect caused by the CO_2 laser in denim fabrics is more successful than the traditional cellulose treatment (Nahid et. al. 2024). It also removes the flies that are created while abrading during manual destroy, avoiding the health hazards for the workers in the factory (Nayak et al., 2022), ensuring a sustainable surface modification for denim products in the long run. However, no recycling arrangement for released carbon is found in the critical observation.

3.5| Manual destroy

The Manual Destroy is another denim surface modification technique which gives the ripped, distressed look without the consumption of water and chemicals. Earlier factories used to apply a knife to cut and pull out the warp yarns, leaving the weft yarns intact. Later, a pen grinder type with various sizes of stones is used for such destroy effect (Figure 9(a)). The abrasive stone acts as a knife to destroy the warp yarn from the fabric surface, revealing the white weft yarn. The marked area is destroyed very carefully as over destroy can cause rejection during quality inspection. Usually, it is done after several types of wet washes like bleach, enzyme, and pen grinding, but sometimes, grinding machines are also used wherever required to make the distressed look more prominent and customised, such as in the bottom hem parts of denim shown in Figure 9(b). The process starts with separating the denim according to size. Using a pen grinder for such effects takes manual labour and creates flies and torn yarns as waste. The factory reports that manual destroy takes more than twice as long as laser destroy for a similar design, but it is also practised in the factory for foreign order demand. The manual touch for a distressed look is always preferred by the global customers, although lasers can create complex designs within a very short time, as reported by the factory. An example of manual destroy on jeans is shown in Figure 9(c). where prominent destroy effects are developed, and this is done after all types of washes to maintain the quality of the product; otherwise, the designed areas will be over destroyed due to necessary steps like machine rotation for wet wash, hydro extracting for dewatering, drying speed, etc., required for other washes.

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Figure 9. (a) Manual destroy through grinding stone, (b) Bottom hem of the jeans is destroyed through grinding machine and (c) Manual destroy effect on jeans.

3.6| Manual whisker

'Whiskering' or 'whisker' terms are used interchangeably in the factory, which creates thin, lighter coloured streaks that resemble natural wear patterns, for example, along the seams and pockets. The apparel that is to be whisked is segregated according to size beforehand, which facilitates better productivity and avoids errors. Patterns are made for different sizes and checked afterwards. The process of whiskering pattern development starts with selecting a design and marking the design after a poly paper is placed upon the apparel. The marked poly paper is then placed on the rubber board so it can be engraved in the marked areas to make the whiskering pattern (Figure 10). Then the whisker counter or pattern is to be checked, and the counter is to be set for the process to start. The counter is changed every 5 to 6 hours. The pattern is inserted into the denim to scrape over the engraved area to create the whiskered design. A briefing is given before the production starts.

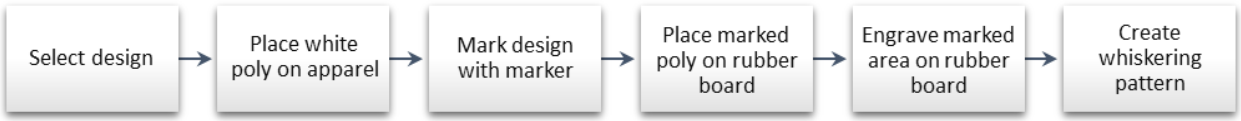


Figure 10. Whisker pattern development process

The production then starts, followed by continuous supervision, quality checks and improvements. The process flow is given in Figure 11. The average time required for each effect is 10 seconds, although it varies depending on the worker's efficiency. The number of scraps is usually between 14 and 16 per piece, but it entirely depends on the whisker intensity and the thickness of the denim. The quality of the whiskering effect depends on the three parameters: type of emery paper, scraping quality and efficiency of the worker. There are several ways to get this effect, such as sanding, grinding or chalk rubbing. The most common method for applying whiskers is to use sharp-edged emery paper that has been placed on plastic or rolled on a thin wood stick. This is used to gently scrape the apparel over the engraved pattern lines (Figure 12(a)), and a whisker effect is generated on the selected area (Figure 12(b)). The whisker paper or the emery paper grades, and the base of the pattern lines are significant for the desired outcome. Emery/Sand/Abrasive paper used for whisker and scraping processes in denim fabric is typically made from materials such as aluminium oxide or silicon carbide. Those Papers can be of different grades. Grade of Abrasive Paper refers to the number of abrasive particles (Grit) embedded per square inch area on the paper. The higher the grit number, the smaller the particles and the finer the abrasive paper. Conversely, a lower grit number indicates larger particles and a coarser abrasive paper. For example, P-800 refers to a grade of abrasive paper with a grit size of 800 per square inch. It has the smallest particles among the mentioned grades and is used for achieving a smooth finish on surfaces that require minimal sanding or material removal. P-800 was discovered in the field investigation used for the whiskering effect (Figure 12(c)) in the case factory. The efficiency of the worker is another factor of quality assurance. Additionally, rubber balloons can occasionally be found with various pattern designs on them. To simulate whiskers, apparel is inflated and positioned atop balloons.

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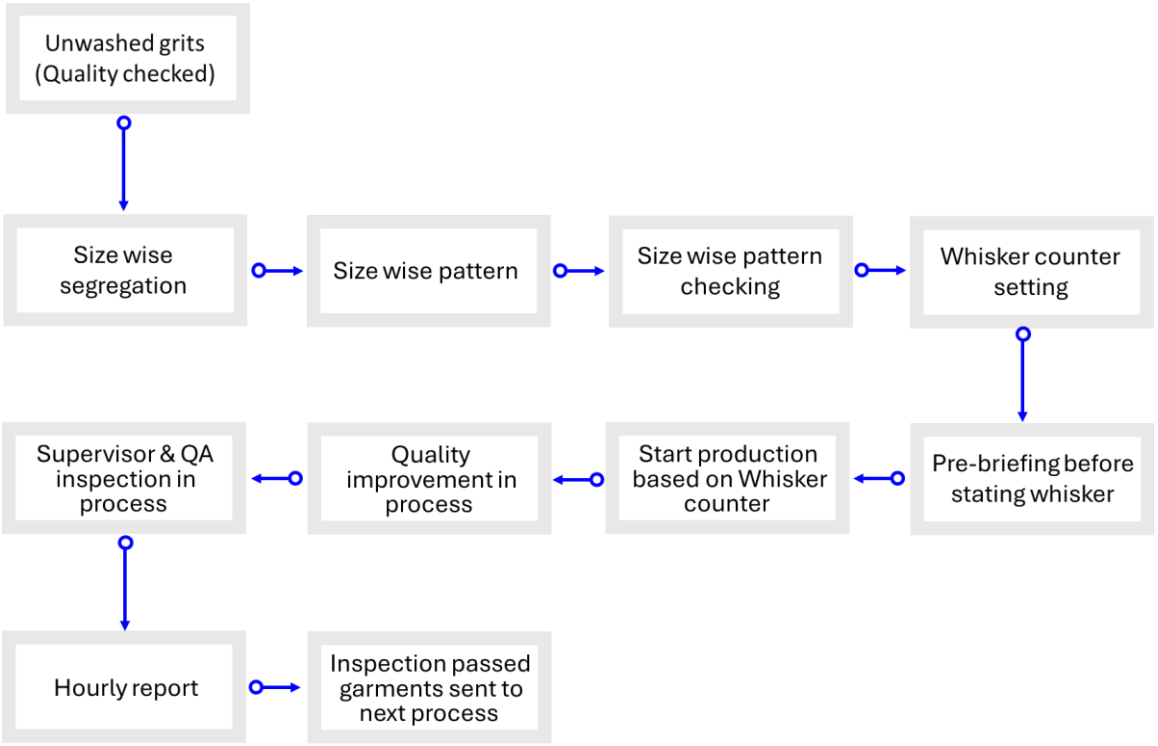


Figure 11. Process flow of bulk production of whiskering effect



Figure 12. Pattern lines for whiskering effect, (b) P-800 emery paper found in the case factory and (c) Whiskering effect through emery paper.

Chalk rubbing is another process of whisker pattern design effects on denim products found in the case factory 3, which is a very innovative process. The chalk is used instead of emery paper (Figure 13(a)), and a rubber-type hard foam board is applied as a base under the apparel. The pattern board is made by engraving the marked rubber board area of the whisker with a cutter or blade. (Figure 13(b)). The foam thickness is 1 to 2 cm. Alike emery paper whisker, chalk rubbing whisker starts with the segregation of apparel based on whisker intensity, but in this process, potassium permanganate (pp) is used in the whiskered areas for the prominent appearance. According to the whisker intense PP solution is prepared. The standard concentration of PP used here is 0.25-0.5 g/L. As before, a whisker rubbing counter is set, which is changed every 6 hours of production for quality maintenance, and it is always signed by the production manager before placing a new counter. As the PP solution is applied with chalk rubbing, it is also designated as a PP rubbing whisker in the factory. Sometimes, the factory uses denim scraps, which are soaked in a PP solution for the rubbing operation for the same whisker effect (Figure 13(c)). Whichever the factory uses, emery paper, chalk or denim scraps for whiskering effect, it is a sustainable surface modification process because the effect is generated without the consumption of water and energy. The chemical potassium permanganate required in the chalk rubbing operation requires a very minimal amount compared to conventional wet wash processes in industrial denim washing. The whiskering effect through the chalk rubbing operation is presented in Figure 13(d). Generally, less or over effect, uneven effect and sometimes crease marks occur in the production, which can cause rejection. So, continuous supervision is maintained during the bulk production to avoid rejection.

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Figure 13. (a) The chalk used in the chalk rubbing operation, (b) Rubber board of chalk whisker, (c) Denim scraps for pp rubbing and (d) Whiskering effect through chalk rubbing operation.

3.7| Ozone fading

Ozone wash is another advanced, sustainable wash technique in industrial apparel washing, which is explored in this study. Ozone fading technology applies ozone gas (O3) to the apparel instead of using traditional chemicals used in wet washing. Ozone is a strong oxidising agent, having the quality to oxidise surface dye of indigo dyed denim apparel. This quality is employed in place of enzymes, pumice stones or hypochlorite bleaching techniques to fade denim apparel (Nahid et. al. 2024). The factory uses the Jeanologia G2 Evo machine for the ozone fading technology, with a capacity of 100 to 130 kg. The energy consumption is 10.54 kWh19 (Jeanologia G2 Ozone Technology, 2023). The average total time needed to complete the process is 16 minutes, including rinsing, softening, drying and ozone fading in a sequence. The usual ozone time is 8 minutes, consisting of Pre-cycle time (1 minute), cycle time (2 minutes), recirculation (3 minutes) and air release (2 minutes). The process of rinsing, softening, and drying is done by the normal industrial standards or parameters. Pre-cycle time is used for wetting the apparel to relax the apparel, removing the crease mark & making it uniform. Ozone is generated in the cycle time by exposing high-energy ultraviolet rays to strike ordinary oxygen molecules, splitting them into atomic oxygen and combining with other oxygen molecules to form ozone. Then ozone inflicts damage to the surface of the apparel. It removes the loose indigo dye & gives a little fading effect to the denim products of the top and bottom parts. The process uses a high temperature of 306°C for high-energy UV rays (Figure 14(a)). The gas concentration range is 10% to 30%, depending on the effects. For a higher fading effect, a higher concentration is required and vice versa. The factory usually uses 8 to 12 g/Nm^3 and 24-32 g/Nm^3 for 10% and 30% concentration, respectively. It was 9.8 for 10% and 29.5 for 30% observed in the factory. Any residual ozone is neutralised before unloading the apparel during the re-circulation. It is a fixed process and always happens before unloading. Then, air is released to clean the ozone gas after neutralisation. Blue colour is the combination of yellow and green, and ozone fades the yellow part, and the effect tends to go towards the green direction. Back staining or yellow stains are also removed using the ozone fading process. Figure 14(b) shows a very slight change due to ozone fading.

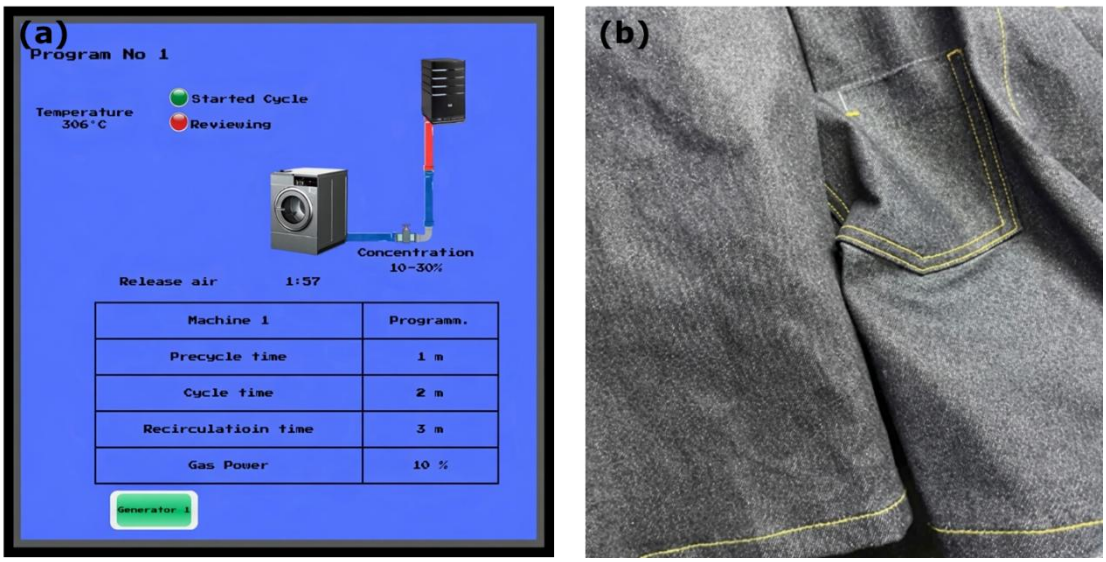


Figure 14. (a) Ozone fading process parameter, and (b) Ozone wash effect

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3.8| Sustainable surface modifications in the context of the sustainability indicators

Typically, denim products undergo several industrial washing techniques as a means of finishing, modifying the surface for customisation and a trendy look, and developing value-added products for profit margin. The factory always looks for innovations in easy and economical processes to meet the market demand, for which dry processes are very well accepted by the producers. However, the methods still need to be evaluated in terms of sustainability indicators of water, chemicals, and energy, both on the factory scale and in scientific investigation. There are several parameters to measure environmental sustainability, like energy and water conservation, chemical and waste reduction, etc. (Olafsson et.al. 2014). This work explores a comprehensive discussion about the standard operation procedure of dry processes of industrial apparel washing in the previous section to select the parameters to assess the environmental sustainability of those practises. The water, chemical and energy are identified as sustainability parameters after exploring the process techniques. It is evident from the exploration that tagging, manual whiskering, hand scrapping, and manual destruction consume no water, chemicals, or energy to modify denim surfaces, denoting them as environmentally sustainable surface modifications in industrial apparel washing. All these processes are developed manually using innovative techniques that give a natural, worn-out look widely accepted by fashion consumers, regardless of age or gender. In addition, the grinding machine consumes 8 kWh, and productivity averages 1200 pieces per hour for grinding the bottom hems and pocket corners of jeans. The energy consumption percentage in the grinding process is 0.67%, meaning 0.67 kWh of energy is consumed for every 100 pcs of jeans.

$$\text{Energy consumption percentage}=\frac{Energy\ consumption\ in\ KWh}{Productivity}\times 100 = \frac{8KWh}{1200}\times 100 = 0.67\ \text{KWh/100pcs}$$

Similarly, the Jeanologia G2 Evo ozone fading machine consumes 10.54 kWh per hour, with a productivity of 230 pieces, consuming 4.5% energy. The laser machine consumes 12.2 KWh to modify an average of 250 pieces of denim apparel surface, where the consumption is 4.8% slightly higher than ozone fading. So, the consumption order is Grinding process < Ozone fading < Laser fading, although three modification techniques do not require water or any harsh chemicals, specifying their positive environmental implications. So, the explored modification techniques do not use water or harmful chemicals, as seen in other kinds of washes like enzyme wash, which requires 34.1L water per piece for desizing, rinsing, enzyme treatment, rinsing and softening, and bleaching treatment requires 39.17L water per piece, slightly higher than enzyme for the required additional neutralisation stage (Siddiquee, et al. 2022). Both washing also necessitates higher temperatures between 55 °C and 60°C (Ahmed et al. 2021; İvedi et al. 2021), while the majority of the dry processes entail room temperature (~30 to 40°C) except the ozone fading and laser fading, which use high temperature momentarily, though without any use of liquids. Moreover, the bleach washing process is conducted by non-environment-friendly chemicals, such as oxidising or reducing bleaching agents (Ahmed et al. 2021; Haq et al., 2015). So, the techniques applied to modify the denim surface found in the case factories are sustainable considering water, chemical and energy deserting two separate cases: a very slight consumption of potassium permanganate in chalk rubbing, an innovative dry process for the whiskering effect, and the absence of any recycling setup for released carbon in the CO_2 laser machine arrangement. It requires further research to establish this modification technique as more environmentally sustainable, thus global manufacturers can embrace it unequivocally. Additionally, these processes encompass both manual and semi-automated operations, which necessitate labour, implicating health and safety considerations for workers, a crucial element of social sustainability. During inspections, workers were observed using personal protective equipment, including facemasks, gloves, goggles, and boots, to safeguard against contaminants from abrasion processes, smoke, and chemicals used in production activities. However, the authors were not allowed to photograph the production operatives for privacy reasons. These processes have been practised in Bangladesh for more than two decades, demonstrating their economic viability and alignment with economic sustainability. Dry and wet processes for denim surface modifications are distinct from each other and are applied for different types of modifications, rather than being alternatives to each other. Moreover, the combination of these processes gives the final outlook of denim fashion products. As a result, a cost comparison between each dry and wet process has no rationale from a practical point of view.

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Figure 15. Sustainable surface modification techniques for denim

5 | CONCLUSION

This research aimed to scientifically explore the dry processes and evaluate the level of sustainability with respect to the use of Chemicals, water, and energy to discover sustainable surface modification techniques for denim. Most used dry washing techniques like Hand scraping, Whiskering, Destroying, Tagging, Grinding, Laser fading and the newest ozone fading techniques were found in this investigation. The manual whiskering, hand scraping, tagging effect and destroying can be done entirely manually without requiring any chemicals, water or energy making them well sustainable processes. Though other than manual destroying process, use of laser technology is also found to be used for destroying, and this requires a very small amount of energy per product, but no water or chemicals. Laser technology is also used for laser whiskering, another surface-modifying technique, and similarly, this also does not require any water or chemicals but just very little energy. Fading is also found to be done by a newer technology other than laser, and that is the Ozone fading, which consumes no water or chemicals and a small amount of energy. Similarly, the grinding technique requires neither water nor chemicals and consumes a minimal quantity of energy, which is utilised by a small pen grinder operated by an operator or an automatic roller grinding machine. The zero use of water or chemicals and very little energy make those approaches more sustainable than other surface finishing methods that use hazardous chemicals like bleach and acid. This study followed a descriptive research design and came short of presenting statistics due to the unavailability of data or business secrecy. So, future studies can explore how to overcome such limitations and assess environmental sustainability quantitatively with precise data and calculations, using software and showing comparative analysis with other kinds of techniques. It also requires further research to establish a sustainability mapping model for traditional and advanced surface modifications.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used no generative AI or AI-assisted technologies.

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