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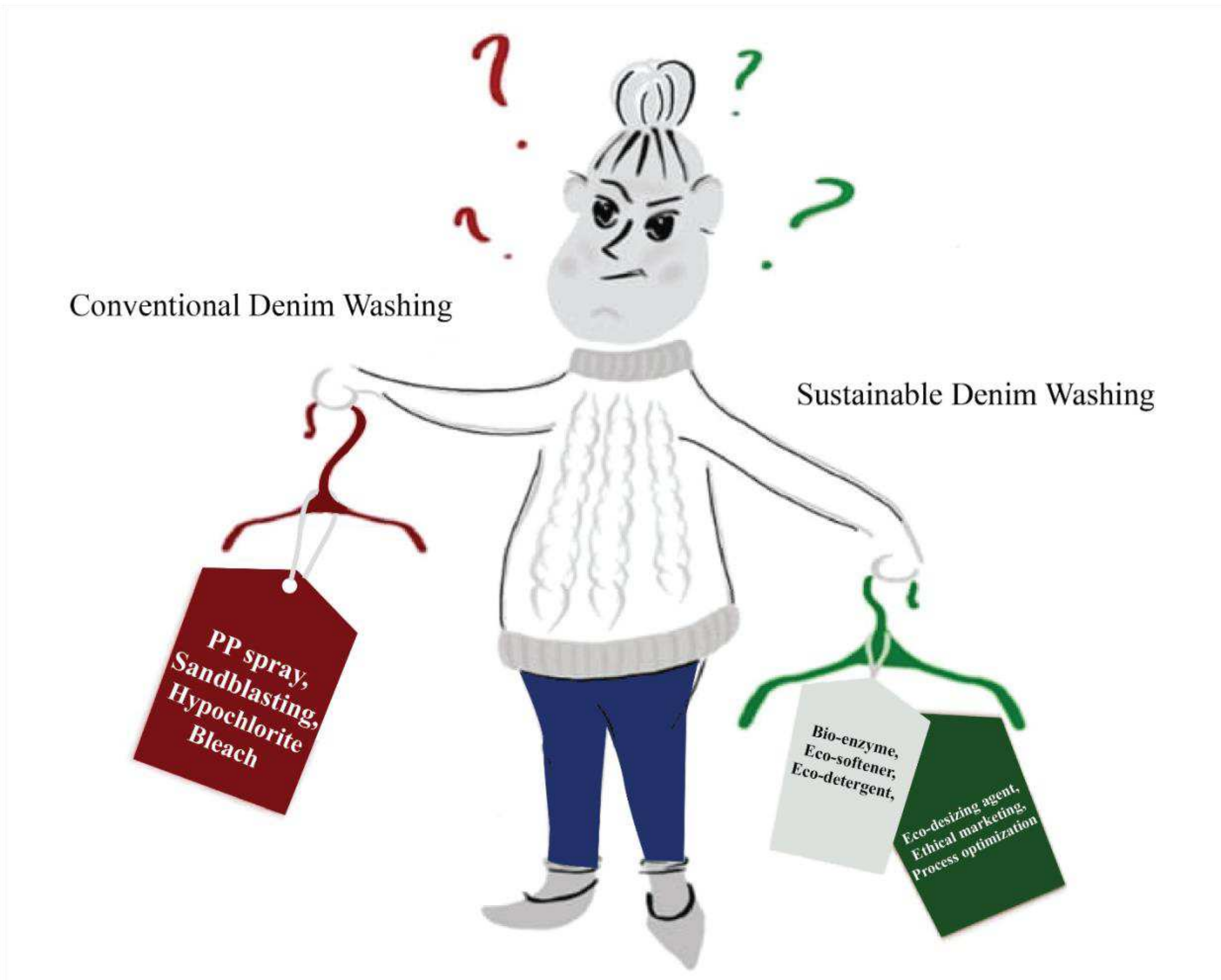
Abstract: Over the past few decades, several developments and innovations have made denim a "classic" in today's fashion cycle. Modern consumers today are concerned with clothing comfort, environmental sustainability, and aesthetic appeal. Sustainability in denim washing is a pressing concern in the fashion industry, affecting consumers' purchasing decisions. Sustainable alternatives for denim enthusiasts now include eco-friendly alternative garments dry and wet processes through nontoxic chemicals, process optimization, and washing recipe optimization. Previous research focused solely on the physical properties of denim samples following the use of hazardous conventional denim washing techniques; yet those did not adequately represent empirical assessments of the environmental impact measurement, chromatic values, and visual uniformity of vintage effects on vat-dyed denim. This research compares the three conventional washing techniques such as dark, medium, and light washes with their sustainable counterparts, analyzing their environmental impacts and chromatic evaluation. Sustainable washing techniques tend to be more efficient, saving at least 15.5-21.5 minutes per wash. While medium and dark washing save 14.44 L/kg and 19.4 L/kg of water, respectively, sustainable light washing saves 3.9 L/kg. Sustainable washes are more economical and those techniques also consume less energy and have lower chemical and energy impact scores than conventional washes. The Environmental Impact Measurement (EIM) scoring system implies 0–33 for low impact, 34–66 for medium impact, and >66 for high impact. EIM score of conventional washing methods (42 for light, 51 for medium, and 57 for dark wash) is greater than that of sustainable washing methods (8 for light, 13 for medium, and 17 for dark wash). Evaluations indicate a decline in color strength (K/S), chromaticity (C*), and hue angle (h) for light-washed denim of conventional and sustainable types. Conversely, the light-washed samples show higher color difference (ΔE), and CIE L*a*b* values in comparison to medium and dark-washed denim samples of conventional and sustainable types.

This research provides a comprehensive assessment using metrics like EIM score, color differences, color strength, chromaticity, and hue angle.

Keywords: Environmental Impact Measurement (EIM), Denim washing, Cleaner production, Garments washing, Color fading

Graphical abstract:



Introduction: Denim is one of the most worn clothing items since it suits people of different ages, genders, seasons, and occasions. It has become an essential part of modern fashion industry. Sustainability has emerged as a differentiator for some denim manufacturers in recent decades (Periyasamy & Periyasami, 2023; Srikrishnan & Jyoshitaa, 2022). Over time, consumers' awareness of the environment and its resources has increased (Ahmad et al., 2020). The denim

washing industry's top priorities now are energy conservation and emission reduction in accordance with sustainability standards. The demand for green production and consumption has increased as a result of growing consumer health consciousness and awareness of the many benefits of purchasing environmentally friendly apparel (Nahar et al., 2024; M. T. Rahaman et al., 2024). As technology has advanced and enhanced, consumer demands for denim apparel have also evolved (M. S. H. Khan et al., 2025; Md. T. Rahaman & Khan, 2024a). In addition to aesthetic appeal, consumers now incorporate comfort, functionality, and environmental sustainability. This shift has led to a rise in the demand for environmentally friendly, non-toxic, and biodegradable denim merchandise, demanding a reconsideration of textile dyeing, garments washing, and finishing processes (Md. T. Rahaman & Khan, 2024b; Zayedul Hasan, Tareque Rahaman, et al., 2021).
Denim washing is a combination of garments' dry and wet process. It reduces the amount of soluble chemicals that are present on the fabric's surface (Tareque Rahaman et al., 2021). The process of garments' dry process improves the structural properties of denim garments (Paul, 2015; Samanta et al., 2017). It includes operations such as hand sanding, sandblasting, grinding, tagging, PP (potassium permanganate) spraying, and whiskering (Fan et al., 2013; C. W. Kan, 2015; Mazumder, 1970; Zayedul Hasan, Rokonuzzaman, et al., 2021). On the other hand, the garments' wet process involves operations such as hot washing, super white washing, stone washing, acid washing, and enzyme washing (Fraj et al., 2022; Galante & Formantici, 2003; Patra et al., 2018; Rashid et al., 2020; Zayedul Hasan, K. M. Ayatullah Hosne Asif, et al., 2021). These enable surface modifications to apparel through chemical treatments. The surfaces of the denim are treated utilizing a combination of physical and chemical processes, depending on the buyer's specified quality standards and requirements (Srikrishnan & Jyoshitaa, 2022).

During the weaving process, size materials are added to the warp yarn to strengthen it. The addition of size materials increases its resistance to mechanical wear in the loom. Reducing fabric stiffness is crucial to delivering user-friendly experiences (Gandhi, 2020). To produce smooth and soft fabric surfaces, garment-washing technologists have employed a variety of effective dry and wet processes over the years (M. Hossain et al., 2017; Imran et al., 2015). In addition, the physical processes that involve hand sanding, grinding, whiskering, and the 3D crinkle effect are commonly referred to as the "garments dry process" (Choudhury, 2017; Zayedul Hasan, Tareque Rahaman, et al., 2021). It is frequently employed on unwashed garments just before the first wash. It also allows for different types of mechanical abrasions and creates a worn-out appearance on fabric surfaces (Kalaoglu & Paul, 2015). To remove impurities (size materials, dirt, and dust) from the textiles' subsequent procedures, garments are treated to wet processes such as enzyme washing, super white washing, acid washing, and stone washing in addition to the dry process (He et al., 2018; Jassal et al., 2024; C. Kan et al., 2017; Md. T. Rahaman et al., 2024). As a result, it gives a fresh, soft, smooth, and worn-out look compared to unwashed garments. Consumers are being encouraged by sustainable fashion trends to purchase reasonably priced, high-quality clothing products made of sustainable materials (Irmak et al., 2024; Kang et al., 2013; Kim & Hall, 2015; Mezarcıöz et al., 2022; Periyasamy & Militky, 2017a; Pranta et al., 2024; Pranta & Rahaman, 2024; Sobuj et al., 2021; Tanner & Kast, 2003).

In order to fulfill consumer demands for worn-out, vintage-looking effects and consistent color fading with the aim of achieving fashionable designs, the denim industry mostly depends on the dry process (Md. T. Rahaman et al., 2024). The conventional methods of hand sanding, sandblasting, whiskering, PP (potassium permanganate) spraying, and grinding are examples of these dry techniques (Sarkar & Rasel, 2019). In addition to adding value, these methods remove the insoluble contaminants and unfixed chemical compounds from the fabric's surface. Pollution of the environment has been greatly influenced by these conventional dry processes. Conventional dry processes including sandblasting and potassium permanganate spraying pose concerns related to fabric tensile strength loss and respiratory problems from silica dust exposure (Barnes et al., 2019; Hobbs et al., 2006; Zayedul Hasan, Rokonuzzaman, et al., 2021). Additionally, the labor-intensive, human-dependent process of hand sanding makes large-scale manufacturing challenging and bears the risk of lowering the expectations of consumers. Sustainable denim washing technology has the potential of increasing output, lower resource usage, and improve standards in the apparel industry as a whole (Dalbaşı et al., 2019; Md. T. Rahaman et al., 2024). Sustainable alternative garment dry processes are becoming increasingly crucial as the demands of the global fashion industry keep growing. The chemical discharge of several pollutants produced during the present hazardous garment dry process, such as potassium permanganate spray, is considered to have direct environmental effects (Fan et al., 2013; Hobbs et al., 2006). This disturbs water sources and ecosystems and causes breathing issues for workers (Amutha, 2017; Md. Khalilur Rahman Khan & Jintun, 2021; Periyasamy & Militky, 2017b). Consequently, it is crucial to conduct research regarding the sustainability of the dry process used to produce denim apparel. As producers and consumers have recently placed a greater emphasis on sustainability, denim production and consumption have gained attention (Karim & Rabiul, 2024; Periyasamy & Periyasami, 2023). Since the textile business has always been profitable, the development of sustainable and environmentally friendly alternative garment dry processes can help this industry maintain its position for several decades to come (Periyasamy & Periyasami, 2023; Md. T. Rahaman et al., 2021).

The conventional methods of garments wet processing have environmental impacts. These are distinguished by their enormous energy requirements, more water consumption, and excessive chemical consumption. These operations take a lot of water, which results in excessive consumption and frequently contaminates water sources with hazardous chemicals (Periyasamy & Periyasami, 2023; Pranta et al., 2023; Siddiquee et al., 2022). Detergents, bleach, and other chemicals are commonly used in conventional wet process, and many of these are not biodegradable and can seriously contaminate water when released into aquatic environments (M. N. Hossain et al., 2023; Mukhopadhyay et al., 2022; Periyasamy & Militky, 2017b; Yao & Wei, 2012). Additionally, significant carbon emissions are released into the atmosphere as a result of the energy needed to heat the water for washing processes (Aykaç Özen et al., 2024; Karthik & Murugan, 2017). Because of these environmental concerns, the fashion industry has been looking for alternatives that are better for the environment (Ferreira et al., 2023; M. T. Hossain et al., 2024; M. T. Rahaman et al., 2024). As a result, eco-friendly and sustainable washing that reduces the harmful effects of traditional procedures can be developed and adopted (Abbate et al., 2023; C. W. Kan et al., 2011; Md. T. Rahaman et al., 2024). Moreover, denim garments washing can be classified as light wash, medium wash, and dark wash based on appearance and processing (Khondoker et al., 2024). Generally, the bleaching time of light washing is higher than the medium and dark washings and doesn't require tinting. The conventional washings have a higher water footprint, energy consumption, and carbon emission due to the separate desizing and bleaching process (Siddiquee et al., 2022). The single-bath approach is more sustainable, less time-consuming, and less water and energy-consuming where the desizing, bleaching, and even enzyme washing are done in the same bath (Imran et al., 2015; Islam et al., 2024; Maryan & Montazer, 2015). Furthermore, using modern equipment and techniques like laser treatment, contemporary eco-friendly washing processes minimize the consumption of energy while using less water and chemicals (Dalbaşı et al., 2019; Garcia, 2015; Periyasamy & Periyasami, 2023; Md. T. Rahaman

& Khan, 2024a). Water sources are more unlikely to become contaminated when sustainable garments washing is performed without utilizing hazardous chemicals. As it uses less water and doesn't require as much wastewater treatment, the eco-friendly processes are more sustainable (Md. T. Rahaman & Khan, 2024b; Senthil Kumar & Gunasundari, 2018). Additionally, using less water, energy, and chemicals while denim washing is often more environmentally friendly than using traditional washing. Despite these developments, there are still important factors to take into account and possible barriers when switching from conventional to sustainable and eco-friendly washing techniques. Understanding the financial consequences of implementing sustainable technology is essential to determining its viability from an economic standpoint (Ekins & Zenghelis, 2021; T. Rahaman & Islam, 2021). This entails evaluating not just the initial costs but also the possible long-term savings attained through decreased resource usage and environmental compliance expenses.

This research work chooses vat-dyed denim samples for conventional and sustainable denim washings for light, medium, and dark shades. Conventional denim washing requires more time and consumes extra time than the sustainable process which leads to a comparatively high amount of greenhouse gas (GHG) emission. In sustainable washing owing to the single bath approach of desizing, bleaching, and enzyme washing the overall washing time is less than the conventional washing. Additionally, this process optimization leads to lower water and energy consumption and turns out to be a much greener wet processing. Moreover, using bio-enzymes and green chemicals such as eco-friendly desizing agents, eco-friendly detergents, and eco-friendly softeners reduces the negative impact of conventional denim washing. Because of using less impact chemicals than conventional processes, the handling of the effluent is less complex.

The denim samples are alternatively treated by laser to achieve a localized faded appearance instead of sandblasting which is a very hazardous and time-consuming process. Additionally, process optimization has been ensured by adapting single-bath bio-enzyme washing with desizng and bleaching. In sustainable denim washing, color fading treatment has been performed using alkali treatment (sodium hydroxide) instead of hazardous potassium permanganate.

Research gap indicates that only one research paper analyzes the environmental impact measurement of denim washings (Khondoker et al., 2024). That latest research explores the EIM scores of vat and sulfur-dyed denim in a single research. It has been observed that there was a lack of clearity in sample development and research methodology. It didn't evaluate color fading by means of chromatic parameters of denim samples after performing light, medium, and dark washes of conventional and sustainable denim washing.

The main goal of this research is to present an in-depth understanding of the possibilities related to switching to sustainable washing methods. Its findings can be very helpful to industry stakeholders, such as manufacturers, lawmakers, and consumers, as this research emphasized the benefits and challenges of conventional and sustainable denim washing using quantitative data. The EIM software was used to calculate the overall environmental impact. The researchers have focused on implementing the Sustainable Development Goals (SDGs) of the United Nations Organization (UNO), especially "Industry, Innovation, and Infrastructure" development (Goal number 9) and "Climate Action" (Goal number 13) employing an integrated approach of minimizing industrial wastes and environmental hazards (Khairul Akter et al., 2022; Pozo-Llorente et al., 2019).

To evaluate the impact of color fading on sustainably and conventionally treated denim apparels s, the research uses a wide range of measurements, such as color strength (K/S), hue angle (h), and CIELAB color space.

2. Materials:

2.1 Denim: The research was conducted using a vat-dyed denim apparel, sourced from Express Washing and Dyeing Limited (Ha-meem Group), located in Ashulia, Dhaka, Bangladesh. The composition of the denim apparel includes a fabric of 3/1 "Z" twill construction. The fabric is composed of 3.75% spandex and 96.25% cotton. The GSM of the unwashed denim fabric was 353. The maximum width of the fabric was 54 inches. Before washing, the shrinkage rate for both length and width is between 3% and 5% to accommodate for fabric contraction. pH between 4.5 and 5.5 after the first washing. The unwashed and raw denim apparel has been indicated in **Figure 1**.

Figure 1. Unwashed denim

2.2 Necessary apparatus: There are a few essential equipment and chemicals needed for the dry processing of denim apparel. Heat presses are used to set permanent textures of 3D crinkles (Zayedul Hasan, Tareque Rahaman, et al., 2021). Abrasive brushes and leaser machines are used to create distressed, worn areas. After 1st washing, the samples require hydro extraction, which is performed by a hydro extractor as shown in **Figure 2** (Mondal & Khan, 2014). It spins at high speed to pull water out of the fabric using centrifugal force. This stage cuts down the drying time considerably and gets the denim ready for the next drying stage. After the denim has been hydro extracted, garment dryers are used to finish drying the fabric. It designates that industrial dryers, like tumble dryers, are made to handle big loads and frequently have temperature and drying time settings that can be adjusted to guarantee the denim dries to the right consistency without causing any damage to the fabric.

Figure 2. Denim washing machineries

2.3 Required chemicals:

2.3.1 Desizing agent: For the conventional process, Nicosist-TFL is used as a desizing agent with the combination of detergent and lycra protector. It is an effective desizing and scouring agent designed to remove synthetic sizing agents typically used in various sizing formulations. It remains stable under high temperatures and alkaline conditions. Moreover, it leaves the treated fabric with an exceptionally soft feel. Desizing is a preparatory process of garments washing which removes the sizing materials which was applied to the warp yarns to withstand the weaving load. It provides a soft hand feel and improves the wettability (C. W. Kan & Yuen, 2012). In the case of the sustainable process as an eco-friendly desizing agent, DENIMCOL WASH-RGN was used for which no additional lycra protector is needed. Instead of regular detergent, eco-friendly detergent Sodasan is used.

2.3.2 Bleaching agent: For conventional process Calcium hypochlorite ($Ca(ClO)_2$) bleach is used with Sosa ash (Na_2CO_3). In contrast, for the sustainable process, Hydrogen peroxide (H_2O_2) bleach is used with Sosa ash (Na_2CO_3).

Bleaching reduces the color of vat-dyed denim and provides a light wash-out color. It can be done as an individual process or in a single bath with desizing and enzyme wash (Zayedul Hasan, Tareque Rahaman, et al., 2021; Zhang et al., 2023).

2.3.3 Enzyme: Enzymes, like cellulase, are applied to soften the fabric and enhance the worn appearance, and detergents are used to clean and prepare clothes for the 1^{st} wash or also can be used in a single batch with desizing and bleaching (Korsa et al., 2023; Patra et al., 2018).

In sustainable process Conzyme N-6000 enzyme is used in the same bath of desizing and bleaching for a sustainable color fading and better hand feel.

2.3.4 Neutralizing agent: In conventional washing acidic Sodium metabisulfite ($Na_2S_2O_5$) is used to neutralize the denim after bleaching and Potassium Permanganate/PP ($KMnO_4$) worn-out effect. In case of sustainable washing Acetic acid (CH_3COOH) is used after the single bath 1^{st} washing as a neutralizing agent and after alkali treatment (alternative to PP spray).

2.3.5 PP: Potassium Permanganate/PP ($KMnO_4$) is used in denim washing to provide it a vintage worn-out look through oxidization. It also damages and softens the hard denim fabric (Khalil, 2015; Zayedul Hasan, Rokonuzzaman, et al., 2021). However, it has adverse health effects, so cautious handling is required during washing (Periyasamy & Militky, 2017b).

2.3.6 Alkali: As a sustainable alternative to PP washing Sodium hydroxide (NaOH) is applied to the first washed denim. It provides denim garments with a sustainable color-fading effect by changing their chromatic parameters (Md. T. Rahaman et al., 2024).

2.3.7 Softening agent: Bel. OET. TR is used as a softening agent with citric acid ($C_6H_8O_7$) in conventional washing to improve the overall hand feel of the denim. However, in sustainable washing Ecosoft P-300 is used as an alternative to conventional softening agents.

2.3.8 Tinting agent: Direct Yellow 106 is used as a tinting agent with Glauber salt ($Na_2SO_4.10\ H_2O$). Tinting is an over-dyeing process that changes the tone of the garments and provides a dark worn-out look which can be done by direct dyes, reactive dyes, and pigments.

3. Research Methodology: Denim washing is a color-fading process to get a vintage outlook. It is nothing but a combination of garments' dry and wet processes (Zayedul Hasan, Tareque

Rahaman, et al., 2021). Both the dry and wet processes of denim washing differ depending on the conventional and sustainable washing processes. In sustainable denim washing, the hazardous and time-consuming sandblasting process is eliminated by utilizing a green process like computerized laser treatment. This approach is adapted to achieve a worn-out appearance. It is a localized fading effect that is priorly designed through Photoshop or Illustrator. It is a less time-consuming and eco-friendly operation (Ahmed et al., 2022; Juciene et al., 2018; Nayak et al., 2022; Ortiz-Morales et al., 2003; Razy, 2023). In Sustainable washing, a single-bath approach is followed for the 1st washed denim garments, which is an optimized technique in comparison to the conventional and separately treated double-bath desizing and bleaching process as indicated in **Figure 3** (Islam et al., 2024). The alkali treatment has been performed using sodium hydroxide, which is a sustainable alternative to PP spray that is frequently used for color fading. PP spraying approach provides a pale outlook with minimum degradation of the cellulosic fabric (Md. T. Rahaman et al., 2024). Additionally, in the case of medium and dark denim washing tinting has been utilized to obtain a slightly darker vintage appearance. Sustainable denim washings have competitive advantages in terms of time consumption, power consumption, water consumption, reduced carbon footprint, and overall environmental impacts in comparison to their conventional counterparts.

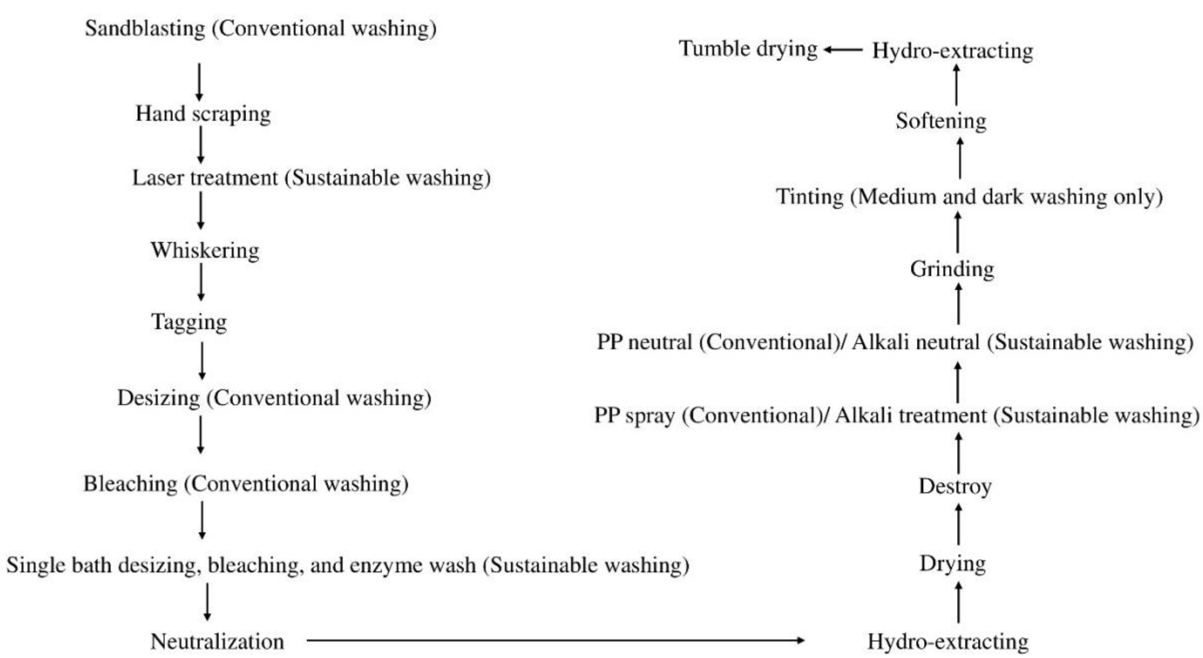


Figure 3. Experimental layout of conventional and sustainable denim washing

3.1 Experimental section

3.1.1 Evaluation of chromatic parameters: Colorimetric analysis of the samples was conducted under D-65 illumination with a 10° observer angle using a Data Color 650® spectrophotometer (USA). Measurements included color strength represented by the K/S value, as well as reflectance percentage (r%) and CIELAB parameters such as L*, a*, b*, chroma (C*), and hue angle (h).

3.1.1.1 Testing conditions: The instrument has been set to a 10° observer angle, which refers to the CIE 1964 color space standards (Akgun et al., 2008; Ohno, 2000).

3.1.2 Environmental Impact Measurement (EIM): The EIM is a specialized software designed by Jeanologia that assesses the environmental impact of textile processing and manufacturing based on water, chemical, power, and worker impact (Md. T. Rahaman et al., 2024). It is a clear and transparent tool that breakdowns to total processing and provides reliable measures to help identify where the impact is greatest and determine efficient action plans to improve overall textile processing and manufacturing. By means of EIM analysis an ecological, ethical, efficient, and disruptive manufacturing process can be established (Martínez-Climent et al., 2024).

3.1.2.1 Testing conditions: According to the EIM software a score between 0-33 shows a low environmental impact, while a score from 34-66 indicates a medium environmental impact, and >66 indicates a high environmental impact (Nahid-Ull-islam et al., 2024).

3.2 Conventional denim process: There are three variants of the conventional denim washing process such as light wash, medium wash, and dark wash. **Table 1** indicates the washing recipe and process variable of conventional light, medium, and dark wash of denim samples. Conventional denim washing requires more time and consumes extra time than the sustainable process which leads to a comparatively high amount of GHG emission (Khondoker et al., 2024). The overall water footprint of conventional washing is also higher than the sustainable process which also increases the load on water treatment and effluent treatment plants (Nahid-Ull-islam et al., 2024). The generated effluents in the conventional process require special handling as the chemicals used in the washing process are toxic to human and aquatic environments and may not be biodegradable.

Table 1. Process summary of conventional denim washings (Siddiquee et al., 2022; Sultana et al., 2019; Zayedul Hasan, Tareque Rahaman, et al., 2021)

SL	Operation	Status (Applicable/ Not applicable)	Chemicals/Equipment	Dossing in grams	Water Consumption in Liter	Material: Liquor	pH	Process cost in dollar ($)	Temperature (°C)	Time (min)	Process
1	Sand blasting	Applicable	Sand gun					0.20		2	Light wash
		Applicable	Sand gun					0.20		2	Medium wash
		Applicable	Sand gun					0.20		2	Dark wash
2	Hand scrapping	Applicable	Emery paper					0.20		3	Light wash
		Applicable	Emery paper					0.20		3	Medium wash
		Applicable	Emery paper					0.20		3	Dark wash
3	Whiskering	Applicable	Finer abrasive paper					0.47		3	Light wash

			(600 grit)								
		Applicable	Medium abrasive paper (400 grit					0.40		3	Medium wash
		Applicable	Coarser abrasive paper (300 grit)					0.35		3	Dark wash
4	Tagging	Applicable	Tag gun and tag pin					0.15		3	Light wash
		Applicable	Tag gun and tag pin					0.15		3	Medium wash
		Applicable	Tag gun and tag pin					0.15		3	Dark wash

5	Desizing	Applicable	Desizing agent, detergent, lycra protector	80	80	1:8		0.20	60°C	8	Light wash
		Applicable	Desizing agent, detergent, lycra protector					0.20	60°C	8	Medium wash
		Applicable	Desizing agent, detergent, lycra protector					0.20	60°C	8	Dark wash
6	Rinse (2	Applicable						0.05	25°C	10	Light wash

	times)	Applicable						0.05	25°C	10	Medium wash
		Applicable						0.05	25°C	10	Dark wash
7	Bleaching	Applicable	$Ca(ClO)_2$ bleach, Soda ash (Na_2CO_3)	1300	80	1:10	11	0.27	60°C	12	Light wash
		Applicable	$Ca(ClO)_2$ bleach, Soda ash (Na_2CO_3)					0.23	60°C	8	Medium wash
		Applicable	$Ca(ClO)_2$ bleach, Soda ash (Na_2CO_3)					0.23	50°C	8	Dark wash
8	Rinse (2	Applicable						0.05	25°C	10	Light wash

	times)	Applicable						0.05	25°C	10	Medium wash
		Applicable						0.05	25°C	10	Dark wash
9	Neutralization	Applicable	Sodium metabisulfite ($Na_2S_2O_5$)	120	90	1:8	5.3	0.10	25°C	12	Light wash
		Applicable	Sodium metabisulfite ($Na_2S_2O_5$)					0.10	25°C	12	Medium wash
		Applicable	Sodium metabisulfite ($Na_2S_2O_5$)					0.10	25°C	12	Dark wash
10	Rinse (2	Applicable						0.05	25°C	6	Light wash

	times)	Applicable						0.05	25°C	6	Medium wash
		Applicable						0.05	25°C	6	Dark wash
11	Hydro extraction and drying	Applicable	Hydro extractor and dryer					0.45		4	Light wash
		Applicable	Hydro extractor and dryer					0.45		4	Medium wash
		Applicable	Hydro extractor and dryer					0.45		4	Dark wash
12	Destroy	Applicable	Different size stones, Knife, and needle					0.20		1.5	Light wash
		Applicable	Different size stones,					0.20		1.5	Medium wash

			Knife, and needle								
		Applicable	Different size stones, Knife, and needle					0.20		1.5	Dark wash
13	PP spray	Applicable	Potassium permanganate ($KMnO_4$)					0.35		0.5	Light wash
		Applicable	Potassium permanganate ($KMnO_4$)					0.35		0.5	Medium wash
		Applicable	Potassium permanganate					0.35		0.5	Dark wash

			($KMnO_4$)								
14	PP neutral	Applicable	Sodium metabisulfite ($Na_2S_2O_5$)	120	90	1:10	5.3	0.10	25℃	5	Light wash
		Applicable	Sodium metabisulfite ($Na_2S_2O_5$)					0.10	25℃	5	Medium wash
		Applicable	Sodium metabisulfite ($Na_2S_2O_5$)					0.10	25℃	5	Dark wash
15	Grinding	Applicable	Denim grinder					0.10		2	Light wash
		Applicable	Denim grinder					0.10		2	Medium wash

		Applicable	Denim grinder					0.10		2	Dark wash
16	Tinting	Not applicable	Direct dyes, Glauber salt ($Na_2SO_4.10H_2O$)	0.5 gm direct dyes, 100 gm glauber salt	120						Light wash
		Applicable	Direct dyes, Glauber salt ($Na_2SO_4.10H_2O$)					0.10	45°C	10	Medium wash
		Applicable	Direct dyes, Glauber salt ($Na_2SO_4.10H_2O$)					0.10	45°C	10	Dark wash
17	Rinse (2	Applicable						0.05	25°C	6	Light wash

	times)	Applicable						0.05	25°C	6	Medium wash
		Applicable						0.05	25°C	6	Dark wash
18	Softening	Applicable	Softener, Citric acid ($C_6H_8O_7$)	180	90		5.3	0.15	25°C	10	Light wash
		Applicable	Softener, Citric acid ($C_6H_8O_7$)					0.15	25°C	10	Medium wash
		Applicable	Softener, Citric acid ($C_6H_8O_7$)					0.15	25°C	10	Dark wash
19	Hydro	Applicable	Hydro extractor					0.15		7	Light wash

	extraction	Applicable	Hydro extractor					0.15		6	Medium wash
		Applicable	Hydro extractor					0.15		5	Dark wash
20	Tumble drying	Applicable	Tumble dryer					0.15	70°C	30	Light wash
		Applicable	Tumble dryer					0.15	70°C	30	Medium wash
		Applicable	Tumble dryer					0.15	70°C	30	Dark wash
	Total							3.44 dollars		135 minutes	Light wash
								3.47 dollars		138 minutes	Medium wash
								3.42 dollars		139 minutes	Dark wash

3.3 Sustainable denim process: There are three variants of sustainable denim process such as light wash, medium wash, and dark wash. **Table 2** indicates the washing recipe and process variable of sustainable light, medium, and dark wash of denim samples. In sustainable denim washing owing to the single-bath approach of desizing, bleaching, and enzyme washing the overall washing time is less than the conventional counterparts. Besides, this process optimization leads to lower water and energy consumption. Moreover, using bio-enzymes and eco-friendly chemicals such as eco-friendly desizing agents, eco-friendly detergents, and eco-friendly softeners reduces the negative impact of conventional denim washing (Zayedul Hasan, Tareque Rahaman, et al., 2021). Because of using less impact chemicals than conventional processes, the handling of the effluent is less complex.

Table 2. Process summary of sustainable denim washings

SL	Operation	Status (Applicable/ Not applicable)	Chemicals/Equipment	Dossing in grams	Water Consumption in Liter	Material : Liquor	pH	Process cost in dollar ($)	Temperature (℃)	Time (min)	Process
1	Hand scraping	Applicable	Emery paper					0.20		2	Light wash
		Applicable	Emery paper					0.20		2	Medium wash
		Applicable	Emery paper					0.20		2	Dark wash
2	Laser treatment	Applicable	Computerized laser box					0.35		0.5	Light wash
		Applicable	Computerized					0.35		0.5	Medium wash

			laser box								
		Applicable	Computerized laser box					0.35		0.5	Dark wash
3	Whiskering	Applicable	Finer abrasive paper (600 grit)					0.47		2	Light wash
		Applicable	Medium abrasive paper (400 grit					0.40		2	Medium wash
		Applicable	Coarser abrasive paper (300 grit)					0.35		2	Dark wash
4	Tagging	Applicable	Tag gun and tag pin					0.15		3	Light wash

		Appli cable	Tag gun and tag pin					0.15		3	Mediu m wash
		Appli cable	Tag gun and tag pin					0.15		3	Dark wash
5	Desizi ng+ Enzy me+ Bleach ing	Appli cable	Eco-friendly desizin g agent, Eco-friendly deterge nt, Conzy me N-6000, Hydrog en peroxid e, Sosa ash	80	80	1:8	11	0.40	70℃	30	Light wash
		Appli cable	Eco-friendly desizin g agent, Eco-friendly					0.35	70℃	25	Mediu m wash

			detergent, Conzyme N-6000, Hydrogen peroxide, Sosa ash								
		Applicable	Eco-friendly desizing agent, Eco-friendly detergent, Conzyme N-6000, Hydrogen peroxide, Sosa ash					0.30	70℃	20	Dark wash

6	Rinse (2 times)	Applicable						0.05	25°C	10	Light wash
		Applicable						0.05	25°C	10	Medium wash
		Applicable						0.05	25°C	10	Dark wash
7	Neutralization	Applicable	Acetic acid (CH_3COOH)	120	90	1:8	5.3	0.10	25°C	10	Light wash
		Applicable	Acetic acid (CH_3COOH)					0.10	25°C	10	Medium wash
		Applicable	Acetic acid (CH_3COOH)					0.10	25°C	10	Dark wash
8	Rinse (2 times)	Applicable						0.05	25°C	6	Light wash
		Applicable						0.05	25°C	6	Medium wash
		Applicable						0.05	25°C	6	Dark wash

9	Hydro extraction and drying	Applicable	Hydro extractor and dryer					0.45		4	Light wash
		Applicable	Hydro extractor and dryer					0.45		4	Medium wash
		Applicable	Hydro extractor and dryer					0.45		4	Dark wash
10	Destroy	Applicable	Different size stones, Knife, and needle					0.20		1.5	Light wash
		Applicable	Different size stones, Knife, and needle					0.20		1.5	Medium wash
		Applicable	Different size stones, Knife,					0.20		1.5	Dark wash

			and needle								
11	Alkali treatment	Applicable	Sodium hydroxide (NaOH)					0.25		0.5	Light wash
		Applicable	Sodium hydroxide (NaOH)					0.25		0.5	Medium wash
		Applicable	Sodium hydroxide (NaOH)					0.25		0.5	Dark wash
12	Alkali neutral	Applicable	Acetic acid (CH_3COOH)	120	90	1:10	5.5	0.10	25°C	5	Light wash
		Applicable	Acetic acid (CH_3COOH)					0.10	25°C	5	Medium wash

		Appli cable	Acetic acid (CH_3COOH)					0.10	25°C	5	Dark wash
13	Grinding	Appli cable	Denim grinder					0.10		2	Light wash
		Appli cable	Denim grinder					0.10		2	Medium wash
		Appli cable	Denim grinder					0.10		2	Dark wash
14	Tinting	Not applicable	Direct dyes, Glauber salt ($Na_2SO_4.10H_2O$)	0.5 gm direct dyes, 100 gm glauber salt	120						Light wash
		Appli cable	Direct dyes, Glauber salt ($Na_2SO_4.10H_2O$)					0.10	45°C	10	Medium wash
		Appli cable	Direct dyes, Glauber salt					0.10	45°C	10	Dark wash

			($Na_2SO_4.10H_2O$)								
15	Rinse (2 times)	Applicable						0.05	25℃	6	Light wash
		Applicable						0.05	25℃	6	Medium wash
		Applicable						0.05	25℃	6	Dark wash
16	Softening	Applicable	EcoSoft P-300, Citric acid ($C_6H_8O_7$)	180	90		5.3	0.15	25℃	10	Light wash
		Applicable	EcoSoft P-300, Citric acid ($C_6H_8O_7$)					0.15	25℃	10	Medium wash
		Applicable	EcoSoft P-300, Citric acid ($C_6H_8O_7$)					0.15	25℃	10	Dark wash

17	Hydro extraction	Applicable	Hydro extractor					0.15		7	Light wash
		Applicable	Hydro extractor					0.15		6	Medium wash
		Applicable	Hydro extractor					0.15		5	Dark wash
18	Tumble drying	Applicable	Tumble dryer					0.15	70°C	20	Light wash
		Applicable	Tumble dryer					0.15	70°C	20	Medium wash
		Applicable	Tumble dryer					0.15	70°C	20	Dark wash
	Total time							3.37 dollars		119.5 minutes	Light wash
								3.35 dollars		123.5 minutes	Medium wash
								3.25 dollars		117.5	Dark wash

										minutes	

4. Results and Discussions

4.1 Visual appearances of treated samples: Figure 4 illustrates the generally apparent visual differences between sustainable denim washing and conventional denim washing. A typical sample of conventional denim washing has a rich blue hue and a firm structure, both of which are signs of the outdated and ecologically hazardous techniques used to wash and finish garments (Md. Khalilur Rahman Khan & Jintun, 2021). On the other hand, denim treated sustainably tends to have a more variegated, natural look with softer, milder hues when eco-friendly washing and treatment methods are applied. The use of organic materials and less chemically intensive production techniques are highlighted in this type of denim, which also possesses unique, customized characteristics like tiny color or texture variations (M. N. Hossain et al., 2023; Ibrahim et al., 2018; Periyasamy et al., 2019; M. T. Rahaman et al., 2024). A vintage or worn-out appearance that is in line with ecologically aware fashion practices is achieved by the sustainable version, which seems more naturally faded and worn out.

Figure 4. Treated denim prototypes

4.2 EIM score: Environmental Impact Measurement (EIM) is designed by Jeanologia to measure and evaluate the environmental impact of textile manufacturing and processing operations based on water footprint, chemical use, power consumption, and worker impact (Martínez-Climent et al., 2024). The Environmental Impact Measurement software assigns a number between 0-33 to indicate a low environmental impact. A medium effect is indicated by the score, which ranges from 34-66. High impacts are indicated with a score >66 (Khondoker et al., 2024; Md. T. Rahaman et al., 2024). Based on the denim washing recipe of the treated samples, **Figure 5** shows that the EIM software produced evaluations of 8, 13, and 17 for light, mid, and dark wash, respectively, for the sustainable wash. These all fall under the sustainable category and have little to no environmental impact. On the other hand, the EIM evaluations derived using the conventional washing method are substantially greater, with light wash scoring 42, medium wash scoring 51, and dark wash scoring 57. According to the numerical statistics, each sustainable wash is likely to have a low environmental impact score. On the other hand, each conventional wash has a medium to high environmental impact score.

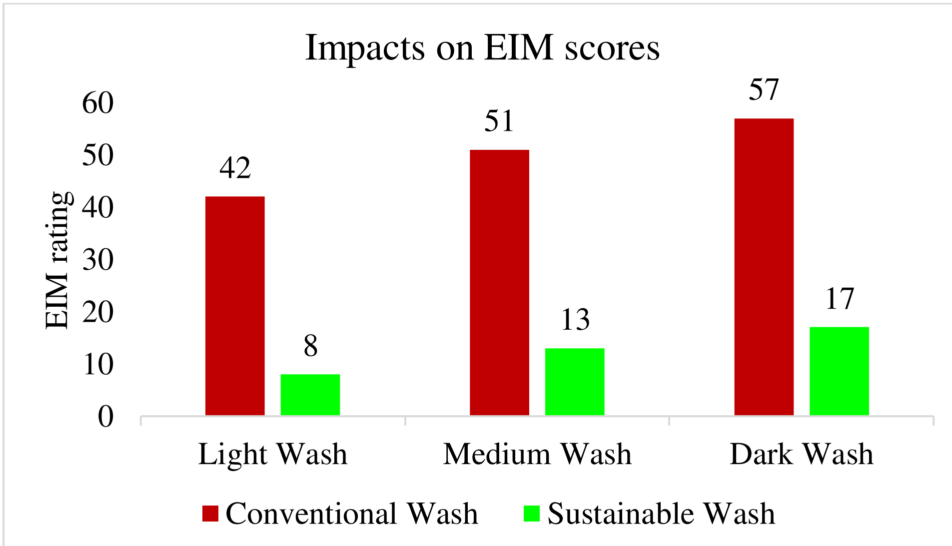


Figure 5. EIM score of different types of denim washing

4.3 Chemical impact: A score between 0-33 denotes a low impact, a score between 34-66 denotes a medium impact, and a score >66 denotes an extreme effect, following standard ranges for chemical impacts. The treated samples from conventional washings have chemical impact scores of 39, 51, and 55 in that sequence, as shown in **Figure 6**. On the other hand, light, medium, and dark washes for sustainable washing contain 9, 17, and 23, respectively. Overall, the EIM values are lower than those of samples treated with conventional washes. This is because sustainable denim washing decreases environmental ratings by promoting eco-friendly enzymes, detergents, and lycra protectors (Sheikh & Bramhecha, 2019). The garment is washed in an environmentally friendly and sustainable manner, avoiding hazardous dry processes including sandblasting, hand sanding, and potassium permanganate spray, which reduces the health and ecological impact of washing (Barnes et al., 2019; Fan et al., 2013; Periyasamy & Militky, 2017b). Sustainable washing avoids wet procedures such as regular bleach and acid washing to preserve the environment.

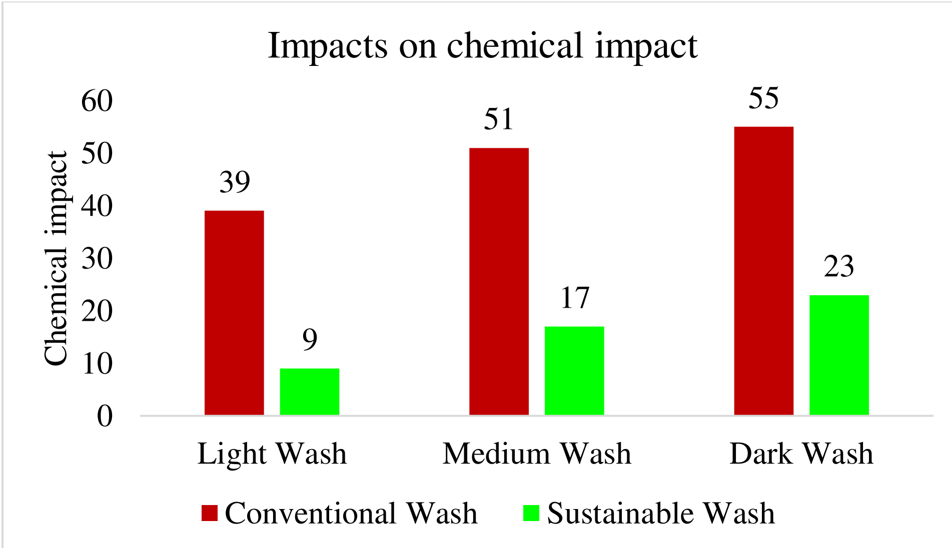


Figure 6. Chemical impacts of conventional and sustainable denim washings

4.4 Water impact: Compared to conventional methods, eco-friendly and sustainable denim washing uses less water. In order to satisfy consumer demands for fashionable designs and styles, the main objective of both the dry and wet procedures in denim washing is to produce vintage effects on the denim surface (C. W. Kan, 2015). By using techniques such as enzyme treatment, tinting, and laser fading to improve the comfort, worn-out effects, and aesthetics of denim garments, sustainable washing reduces the extensive use of hazardous processes such as desizing, bleach washing, and acid washing. In addition, the material-to-liquor (M:L) ratio is lower for sustainable washing than for conventional washing. Consumption of water of 0-45 L/kg, 46-90 L/kg, and >90 L/kg, respectively, indicate low impact, medium effect, and high impact, based on the standard score upheld by the EIM software (Martínez-Climent et al., 2024). **Table 3** demonstrates that the use of sustainable denim washing for light, medium, and dark washes saves 3.9 L/kg, 14.44 L/kg, and 19.4 L/kg of water when compared to their conventional counterparts.

Table 3. Water consumption comparison in L/kg garments among different washing

Washing Type	**Water consumption in Conventional**	**Water Consumption in Sustainable**	**Reduction in water**

	Wash (L/kg garments)	Wash (L/kg garments)	consumption (L/kg garments)
Light wash	12.1 L/kg	8.2 L/kg	3.9 L/kg
Medium wash	36.6 L/kg	22.2 L/kg	14.44 L/kg
Dark wash	47.3 L/kg	27.9 L/kg	19.4 L/kg

4.5 Worker impact: It is crucial to assess the effects that conventional and sustainable denim washing practices, such as the use of chemicals and toxic effluents, have on workers. These include a number of benefits, such as improved health and safety due to reduced pollution levels and modifications to labor practices mandated by environmental laws due to the use of sustainable technologies. Data that falls into one of three categories, such as high effect (> 29), medium impact (14–29), and low impact (0–13), are addressed by the EIM software (Martínez-Climent et al., 2024). **Table 4** demonstrates that sustainable methods can save more labor hours per garment than conventional methods, with light, medium, and dark washes requiring 8, 11, and 14 hours, respectively.

Table 4. Comparison of worker impact/ garment among different washes

Washing Type	Conventional wash	Sustainable wash	Manpower save/ garment
Light wash	10	2	8
Medium wash	18	7	11
Dark wash	25	11	14

4.6 Energy impact: The EIM software analyzes greenhouse gas emissions associated with energy use and displays the application of energy-efficient technologies or practices. It evaluates the possibility of energy savings as well. By analyzing these variables, businesses can identify opportunities to reduce their carbon footprint, reduce operating costs, and increase overall sustainability, thereby reducing their environmental impact and supporting broader environmental objectives (Khondoker et al., 2024). The EIM software is used to calculate the energy impact of clothing in kwh/kg. Low impact is indicated by a score between 0-2.5 kwh/kg, medium impact by a score between 2.5-3.6 kwh/kg, and high effect by a score >3.6 kwh/kg (Martínez-Climent et al., 2024). When compared to conventional washes, sustainable denim washing of light, medium, and dark variants has a low energy impact score, as shown in **Figure 7**. It merely shows that sustainable practices of denim washing greatly satisfy the more general goal.

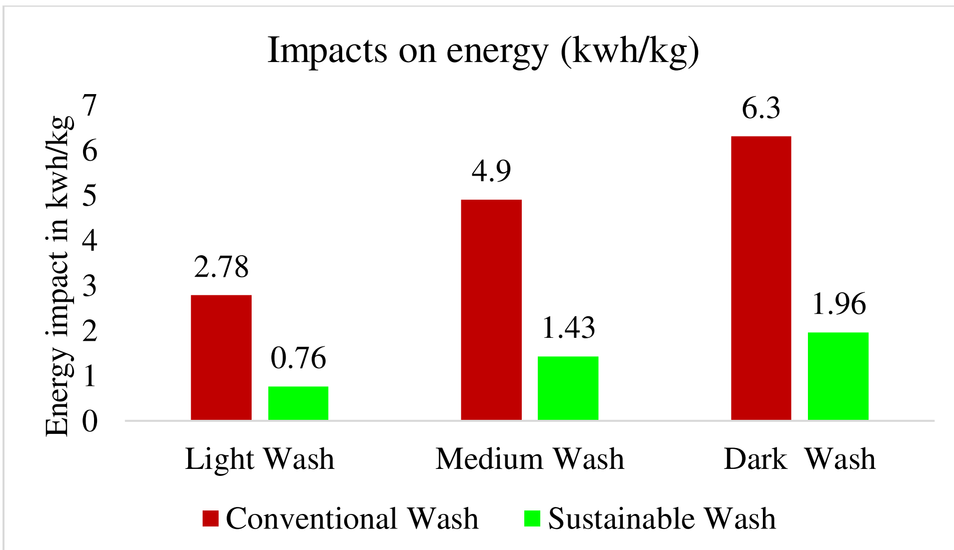


Figure 7. Energy impacts of conventional and sustainable denim washings

4.7 Washing time consideration: Sustainable denim washing techniques are more effective and require fewer chemicals. As **Table 5** demonstrates, these typically require less time than conventional methods. Conventional denim washing includes a number of processes, including pre-washing, additional chemical treatments, and water treatments. which all require a lot of processing time and careful supervision. However, by removing or minimizing these processes, sustainable techniques such as laser treatments create the required levels of color fading and accelerate the process (Ortiz-Morales et al., 2003; Razy, 2023). It reduces the amount of time needed for chemical applications. Without requiring extensive water washes, it can produce uniform color fading rapidly. In addition, sustainable washing reduces the amount of time spent on the garments' wet process by combining several preparatory steps, like enzyme treatment and desizing, into a single step.

Table 5. Comparison time of time consuming between conventional and sustainable washing

Washing type	**Conventional wash (minutes)**	**Sustainable wash (minutes)**	**Time saving (minutes)**
Light wash	135	119.5	15.5
Medium wash	138	123.5	14.5
Dark wash	139	117.5	21.5

4.8 Washing cost: As **Figure 8** illustrates, sustainable washing processes are more cost-effective than conventional denim washing methods due to their focus on recipe optimization and minimized resource consumption. Conventional denim washing methods typically use excessive amounts of electricity, water, and hazardous chemicals, all of which increase operational expenses. Conversely, sustainable practices such as operational step optimization, avoiding unnecessary steps, and using eco-friendly chemicals can improve resource efficiency and reduce waste.

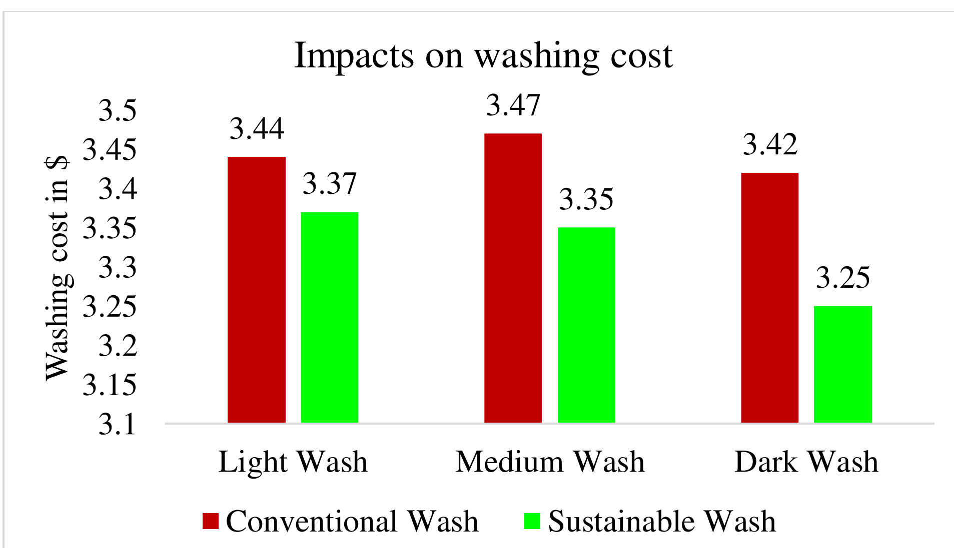


Figure 8. Washing cost comparison of conventional and sustainable denim washings

4.9 Color differences (ΔE): A meticulous color matching to ensure quality control in textile coloration and color fading processes is made feasible by the ability to determine the color differences (ΔE) across samples by assessing the chromatic values received from the spectrophotometer (Moula et al., 2022). Moreover, to evaluate the intensity of a color, it is standard practice to calculate the color difference (ΔE) between the treated sample and the reference standard (Mangat et al., 2014; Md. T. Rahaman et al., 2024). **Figure 9** indicates that the color difference (ΔE) increases from dark to light wash in conventional and sustainable washing due to prolonged bleaching and enzymatic wash time. Unlike sustainable processes, enzyme washing is not performed in conventional processes resulting in lower color fading as a result the color difference (ΔE) is lower. Hence in the sustainable process desired color fading effect requires less time, saves energy, and overall generates less GHG.

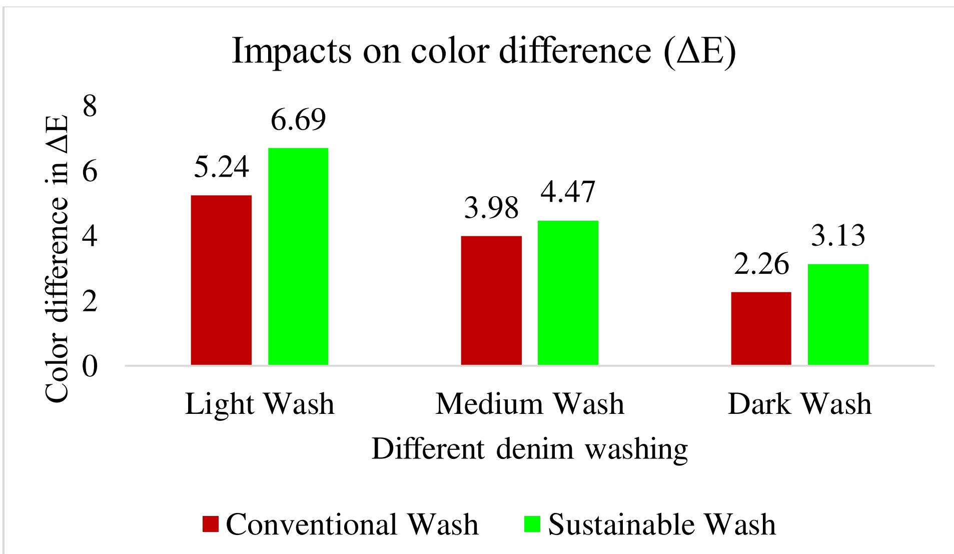


Figure 9. Color difference (ΔE) for conventional and sustainable denim washings

4.10 Color strength (K/S), hue angle (h), and chromaticity (C*): The impacts of light, medium, and dark washing of sustainable and conventional processes on color strength (K/S), hue angle (h), and chromaticity (C*) are illustrated in **Figure 10 (a) to (c)**. A visible increasing trend is observed in color strength (K/S), hue angle (h), and Chromaticity (C*) from light to dark wash in both sustainable and conventional denim washing. A lower color strength (K/S) indicates a higher color fading and a shift toward light blue from dark blue resulting in a decline in hue angle (h) (Md. T. Rahaman et al., 2024). In sustainable washing, the lowest color strength is 5.32 for a light wash, which is significantly lower than the conventional light wash, recorded at 7.3. It was observed that the hue angles of sustainable washings are lower than those of conventional washing. It indicates that due to the single-bath approach of desizing, bleaching, and enzyme wash the color fading in the sustainable process is higher (Islam et al., 2024). Henceforth, a lower processed time of sustainable washing is compatible with the higher processed time of conventional washing and can result in optimized lead time, lower consumption of energy, and reduced carbon emission. Chromaticity (C*) refers to the hue, chroma, and brightness of denim fabric color, with higher 'Chroma' indicating more vibrancy, while a lower hue signifies a warmer color (Chao et al., 2017; Cheng et al., 2024). The alteration in chromaticity (C*) is associated with color fading, which is a result of denim washing.

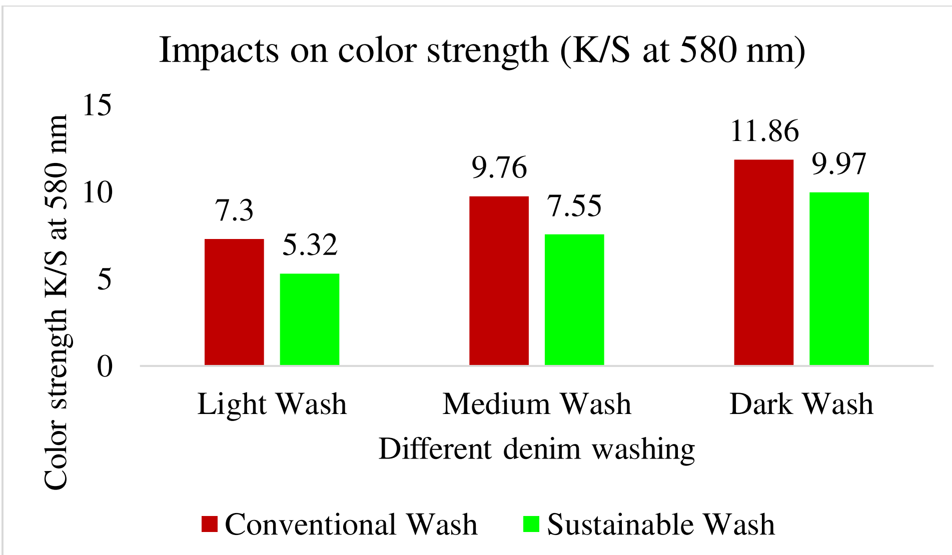


Figure 10 (a). Color strength (K/S) for conventional and sustainable denim washings

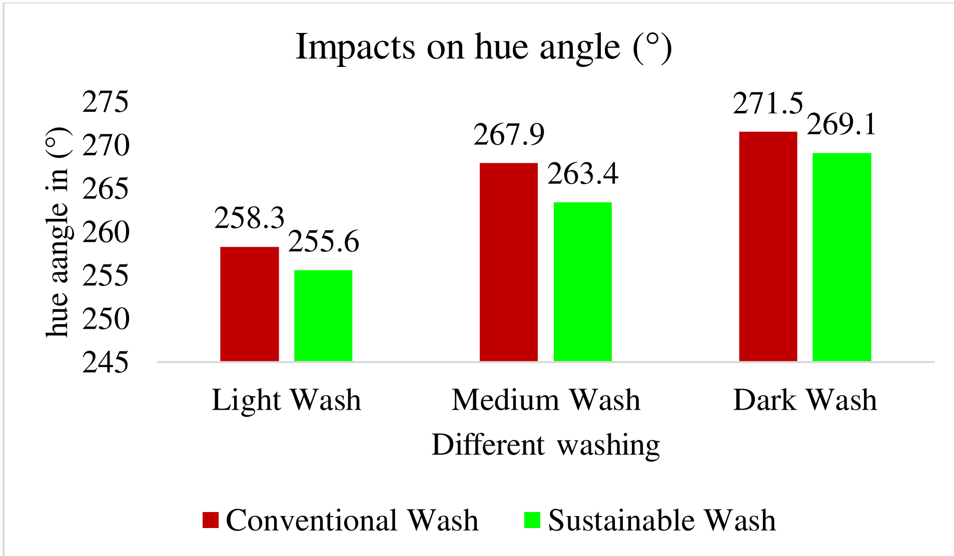


Figure 10 (b). Hue angle (°) for conventional and sustainable denim washings

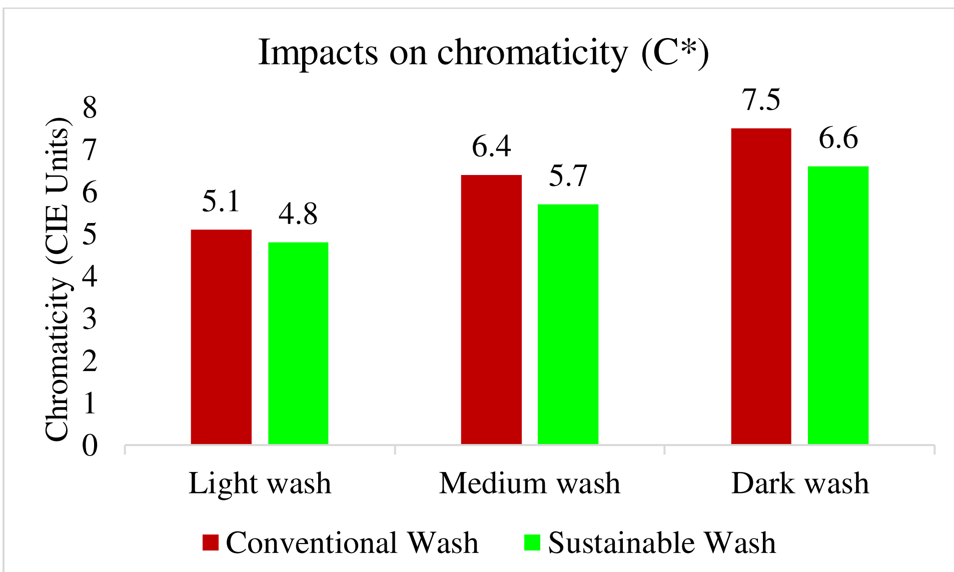


Figure 10 (c). Chromaticity (C*) for conventional and sustainable denim washings

4.11 L*, a*, and b* values: The influence of sustainable and conventional denim washings on chromatic parameters such as L*, a*, and b* is illustrated in **Figure 11 (a) to (c)**. The "L*" value delineates a color's lightness or brightness, measured on a scale from 0 to 100, where 0 corresponds to absolute black and 100 refers to absolute white (Ly et al., 2020). In CIELAB color space "a*" and "b*" can be either positive or negative, where the "a*" represents the red-green color component and "b*" regards the yellow-blue color component. Furthermore, the positive "a*" is associated with a higher proportion of red than green, and conversely the negative “a” represents a shift towards green hue (Gangakhedkar, 2010). Moreover, the positive “b*” value indicates a more yellowish color and the negative value shows a blue shift in the hue (Giusti et al., 2024; Gupta et al., 2005). The evaluation indicates that a declining trend is found in L*, a*, and b* values for both sustainable and conventional washing from light to dark wash. However, in the case of sustainable washing owing to higher color fading, the whiteness of the washed fabric is more than that of conventional washing as it represents a lower L* value. Moreover, the red shift of the hue of sustainable washing is higher than that of corresponding conventional washing which signifies a much warmer color and worn-out appearance. Additionally, dark washing shows the highest negative value of b* which is -8.72 for sustainable and -7.25 for conventional as the intensity of indigo vat dye is higher in dark wash than in medium and light washes.

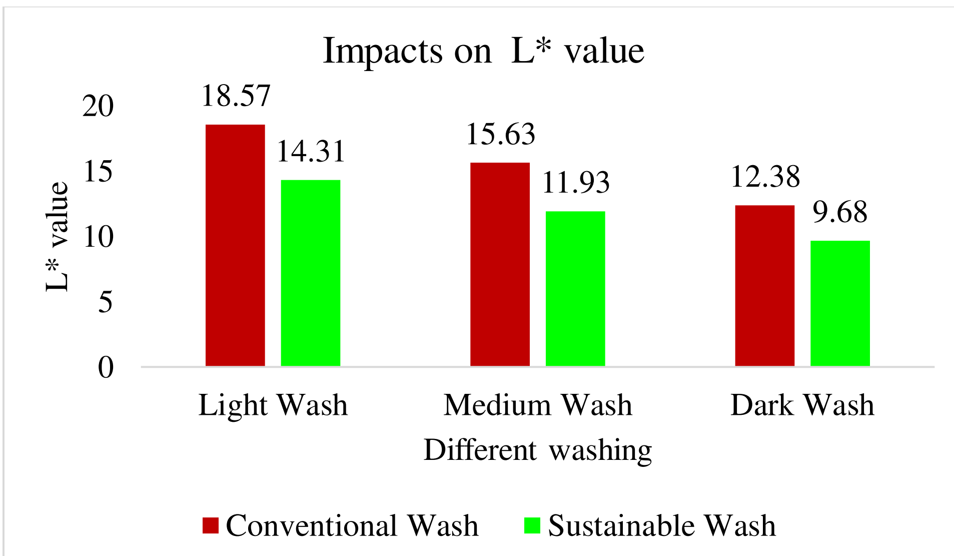


Figure 11 (a). L* value for conventional and sustainable denim washings

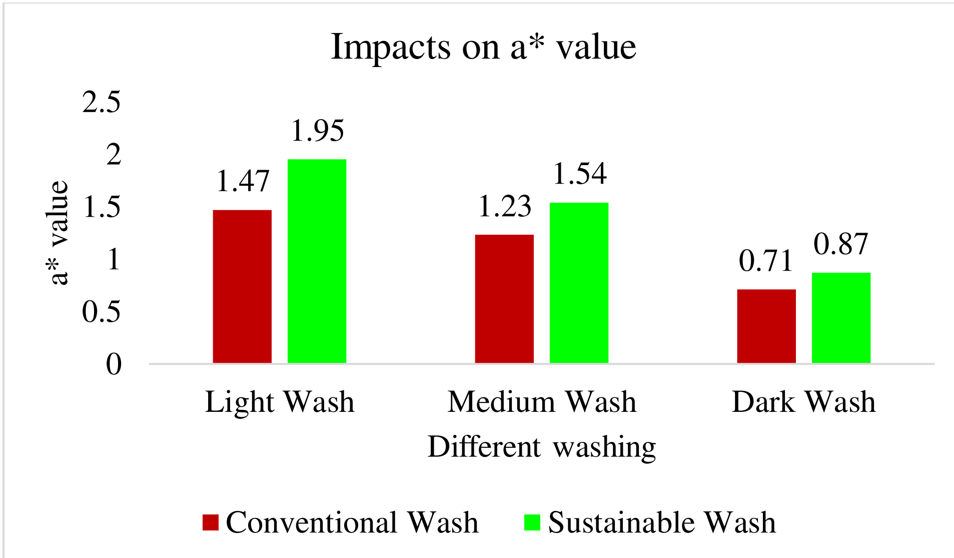


Figure 11 (b). a* value for conventional and sustainable denim washings

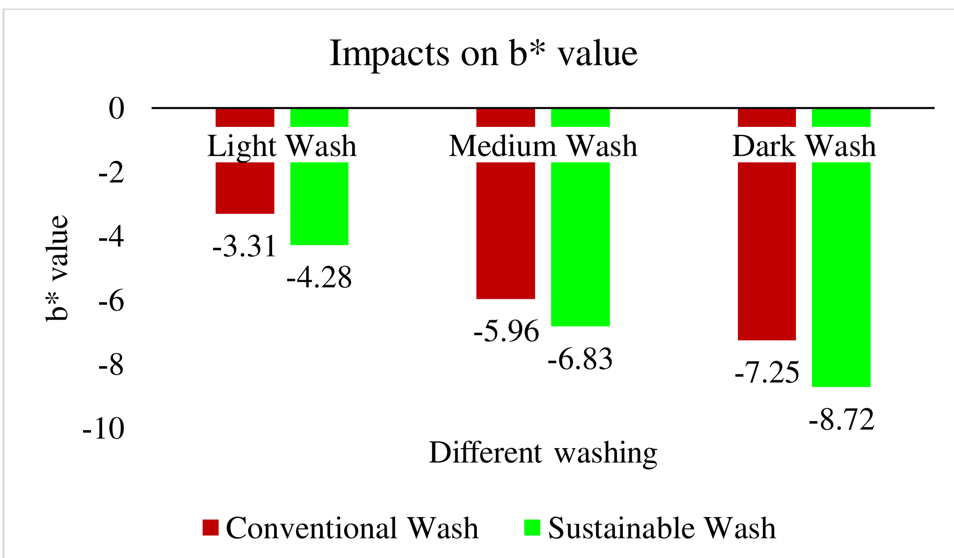


Figure 11 (c). b* value for conventional and sustainable denim washings

5. Conclusions: Conventional denim washing frequently uses excessive amounts of water, power, and hazardous chemicals, all of which increase carbon emissions, pollution, and resource depletion. Aquatic ecosystems and biodiversity are harmed by these practices, which discharge synthetic microfibers and hazardous dyes into bodies of water. On the other hand, sustainable denim washing methods use less water and energy to reduce their negative effects on the environment. These also place a high priority on reducing the use of chemicals, which lowers the risk of soil and water contamination and ensures safer working conditions for textile industry workers. Evaluating the chromatic parameters, and environmental impacts of conventional and sustainable washings is the progressive aspect of this research. According to the EIM assessment system, low environmental impact is denoted by scores 0–33, medium environmental impact by scores 34–66, and high environmental impact by scores >66. Conventional washing techniques expressed a higher EIM score (42 for light, 51 for medium, and 57 for dark wash) than sustainable techniques (8 for light, 13 for medium, and 17 for dark wash). For both conventional and sustainable varieties of light-washed denim, evaluations show declining trends in color difference (ΔE), and CIE L* a* b* values. On the other hand, compared to medium and dark-washed denim samples of conventional and sustainable materials, the light-washed samples exhibit lower color strength (K/S), chromaticity (C*), and hue angle (h). According to data from Jeanologia, this research simply revealed that denim apparel treated with sustainable denim washing has a lower chemical and environmental impact than denim treated with conventional denim washing methods. The amount of water and energy used is minimal when using sustainable practices making it possible for the washing industry to accomplish the maximum chromatic values (a*, b*, and L*) and color strength (K/S). As a result, sodium hydroxide spray (sustainable alternative garments dry process) is an environmentally friendly alternative to sandblasting, PP spray, sandblasting, and numerous other hazardous processes used in the conventional dry process of garments. Compared to the sustainable approach, conventional denim washing requires much more time and uses more energy, which results in a relatively significant amount of greenhouse gas emissions. Conventional washing also uses more water overall than the sustainable method, which puts greater pressure on water treatment facilities. Because the chemicals employed in the washing process are hazardous to both individuals and aquatic habitats and might not be biodegradable. The effluents produced by the conventional technique need to be handled carefully. The single bath method of desizing, bleaching, and enzyme washing in sustainable washing reduces the overall denim washing time compared to conventional washing. This process optimization also results in a decrease in water and energy consumption, making the garment wet processing much more environmentally sustainable. Additionally, the harmful effects of conventional washing are mitigated in sustainable denim washing by bio-enzymes and environmentally friendly chemicals like eco-friendly softeners, detergents, and desizing agents. The management of effluent is less complicated because fewer hazardous compounds are used than conventional approaches. Sustainable denim washing methods assist manufacturers, technologists, consumers, and the business itself by allowing the industry to reach the best color fading performance with minimal environmental effects. Circularity approaches in denim washing might be further investigated by digital technologies such as blockchain for supply chain transparency and artificial intelligence (AI) for inventory management and optimization. In order to ensure a sincere dedication to sustainability, denim merchandising strategies need to be transparent and authentic. It is very much possible for brands, suppliers, and regulatory bodies to accelerate the achievement of sustainability goals and promote an environment that is more favorable to eco-friendly denim merchandising.

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