# EFFECTS OF INDUSTRIAL WASHING TECHNIQUES ON THE PHYSICAL AND COLOR FASTNESS PROPERTIES OF DENIM FABRICS

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**Abstract:** *Denim, as one of the most widely consumed fabrics in the global apparel industry, undergoes various industrial washing processes to enhance its physical comfort and aesthetic appeal. Industrial washing techniques such as bleach wash, stone enzyme wash, and acid wash are widely adopted to meet the demands of contemporary fashion trends. However, these treatments can significantly alter the fabric's structural integrity and surface characteristics, which directly influence product quality and consumer satisfaction. The present study investigates the effects of selected washing methods on the physical and aesthetic properties of raw denim fabric. Standardized ISO test methods were applied to evaluate tensile strength, elongation, and tear resistance, changes in areal density, while color fastness to wash and rubbing was assessed to determine resistance to fading. Findings from this study aim to highlight the trade-offs between durability and aesthetics across different washing techniques, thereby providing valuable insights for textile manufacturers. The research also suggests optimal washing processes that maintain fabric quality while satisfying fashion-driven market requirements.*

**Keywords:** Denim, Enzyme, Enzyme Wash, Stone Enzyme Wash, Multifiber, Tear Strength, Bursting Strength.

# UTICAJ INDUSTRIJSKIH TEHNIKA PRANJA NA FIZIČKA SVOJSTVA I POSTOJANOST BOJE DENIM TKANINA

**Apstrakt:** *Denim, kao jedna od najrasprostranjenijih tkanina u globalnoj industriji odeće, prolazi kroz različite industrijske procese pranja kako bi se poboljšala njegova fizička udobnost i estetski izgled. Industrijske tehnike pranja kao što su izbeljivanje (bleach wash), stone enzyme pranje i kiselo pranje (acid wash) široko se primenjuju kako bi se zadovoljili zahtevi savremenih modnih trendova. Međutim, ovi tretmani mogu značajno izmeniti strukturni integritet i površinske karakteristike tkanine, što direktno utiče na kvalitet proizvoda i zadovoljstvo potrošača. Ova studija ispituje uticaj odabranih metoda pranja na fizička i estetska svojstva sirovog denim materijala. Standardizovane ISO metode ispitivanja primenjene su za evaluaciju zatezne čvrstoće, istezanja i otpornosti na cepanje, kao* *i promena površinske mase, dok je postojanost boje na pranje i trljanje analizirana radi utvrđivanja otpornosti na bledenje. Rezultati ove studije imaju za cilj da istaknu kompromis između trajnosti i estetike kod različitih tehnika pranja, pružajući vredne uvide proizvođačima tekstila. Istraživanje takođe predlaže optimalne procese pranja koji održavaju kvalitet tkanine uz istovremeno zadovoljenje zahteva tržišta vođenog modnim trendovima.*

**Ključne reči:** Denim, enzim, enzimsko pranje, stone enzyme pranje, multifiber, čvrstoća na cepanje, otpornost na pucanje.

# 1. INTRODUCTION

## 1.1 Introduction

One of the oldest textiles in the world, denim is most frequently connected to jeans [1]. Regardless of a person's gender, culture, climate, season, or social occasion, denim jeans are among the most popular apparel products in the world today [1]. Denim is a woven fabric that is incredibly durable, stiff, and robust [2]. In order to satisfy the expectations of the rapidly evolving global fashion business, denim cleaning is becoming an increasingly necessary procedure [3]. Made from cotton twill with a colorful warp and white weft yarn, denim is a robust and long-lasting woven fabric that is frequently used for jeans, workwear, and casual attire.Industrial garment washing is essential to the textile industry [4]. It improves the garment's look to meet fashion standards in addition to aiding in the removal of dust, filth, and dangerous materials [1]. Washing, which includes treatments like enzyme wash, bleach wash, and acid wash, is a crucial step in the finishing of clothing. These treatments add value to stitched clothing while also making it more appealing, fashionable, soft, and comfortable [5]. The finishing of denim jeans is one of the most significant value-adding procedures in washing facilities. To get the desired appearance, methods including acid cleaning, bleach, and enzymes are frequently employed. Customers frequently ask for particular garment washing procedures based on their tastes and current fashion trends [6]. The purpose of this study is to examine how the physical and visual characteristics of denim fabric are affected by three typical industrial washing methods: acid wash, stone enzyme wash, and bleach wash. The research aims to establish appropriate strategies that guarantee both fabric quality and customer happiness by analyzing changes in strength, color fastness, and visual qualities using standardized ISO testing methodologies [7].

## 1.2 Aim & Objective:

This study's main goal is to investigate how certain industrial washing methods such as bleach, acid, and stone enzyme washing affect the physical and visual characteristics of raw denim fabric. In order to find appropriate techniques that strike a compromise between performance and fashion-driven expectations, the research aims to assess how these processes affect fabric strength, durability, and look.

To achieve this aim, the specific objectives of the study are:

- To subject raw denim fabric to three industrial washing processes: bleach wash, stone enzyme wash, and acid wash.
- To assess the physical properties of washed denim fabric by testing: o Maximum force and elongation at maximum force (using EN ISO 13934-1 method). o Tear strength (using EN ISO 13937-1:2000 method).
- To evaluate the color fastness of washed denim using ISO standard methods for: o Color fastness to washing (using ISO 105-C03 method) o Color fastness to rubbing (using ISO 105-X12 method)
- To investigate the variation in areal density (GSM) among different washed denim fabrics using a GSM cutter.
- To recommend suitable washing processes that ensure an optimum balance between fabric durability and visual appeal in line with fashion industry requirements.

# 2. LITERATURE REVIEW

## 2.1 Historical Background of Denim Washing and Their Properties:

Denim originated as a durable work-wear fabric in the mid-19th century, particularly associated with miners, laborers, and industrial workers due to its remarkable strength and long-lasting wearability [1]. The fabric, woven in a twill structure with indigo-dyed warp yarns and white weft yarns, became popular for its distinctive appearance and resilience [2]. Over time, denim transcended its utilitarian origins to become a central element of global fashion. By the late 20th century, denim jeans were no longer perceived merely as work clothing but as a symbol of youth culture, individuality, and casual lifestyle [8].

To meet the growing aesthetic expectations of consumers, the textile industry introduced industrial garment washing processes in the 1970s and 1980s [1]. Initially aimed at softening stiff denim and improving comfort, these processes quickly evolved into techniques for imparting fashionable appearances such as faded, vintage, and distressed looks. Washing methods such as stone washing, enzyme washing, bleaching, and acid washing have since become integral to denim finishing, significantly contributing to its commercial and cultural success [5]. Alongside the development of these finishing methods, the textile industry also advanced in testing procedures to assess denim quality after washing. Since washing treatments often compromise fabric durability, physical property testing gained importance. Tensile strength, tear resistance, and elongation tests became routine to evaluate whether fabrics maintained structural integrity after undergoing harsh treatments [9]. Such evaluations ensured that denim garments not only met aesthetic expectations but also retained the durability that originally defined the fabric.

Similarly, as washes introduced faded looks and lighter shades, the issue of color durability emerged. Color fastness testing, including fastness to washing, rubbing, and light was established to measure resistance to fading and dye transfer. These tests, standardized under ISO and AATCC methods, became critical for verifying product quality and consumer satisfaction. They allowed manufacturers to quantify the trade-offs between fashion-driven effects and long-term garment performance.

In contemporary practice, denim washing is considered one of the most significant value adding processes in the textile industry. Its historical development reflects both technological innovation and the evolving need to balance durability with aesthetic appeal. Equally, the inclusion of systematic physical and color fastness testing in production highlights the fabric's dual identity: a material rooted in strength but adapted to meet fashion's demand for comfort and style.

## 2.2 Literature Review

A considerable body of research has examined the influence of industrial washing processes on the structural and visual qualities of denim. Early investigations showed that traditional stone washing imparted a desirable worn appearance but caused significant reductions in tensile strength and fabric weight due to mechanical abrasion [10]. To overcome these drawbacks, enzyme washing was introduced, which relies on cellulase enzymes to selectively degrade surface fibers. This process has been shown to achieve smoother finishes with less fiber loss compared to pumice stones, making it a more sustainable and fabric-friendly method [5].

Bleach washing has been widely studied for its effectiveness in producing lighter shades and vintage looks. However, research consistently highlights its adverse effects on fiber structure, leading to reduced tensile strength, lowered tear resistance, and poor color fastness due to oxidative damage [11]. Similarly, acid washing, popular during the late 1980s fashion boom, produces striking contrast effects but has been reported to result in uneven shade distribution and substantial weakening of fabric integrity [10].

Several studies have focused on color fastness properties following different washing methods. Enzyme-treated fabrics generally show better retention of dye compared to bleached or acid-washed denim, where fading and poor rubbing fastness are more pronounced. This indicates a direct correlation between the intensity of chemical/mechanical treatments and the loss of color durability [12].

Recent research has also explored innovative and eco-friendly alternatives to traditional washing methods. Techniques such as ozone treatment, laser fading, and waterless enzyme applications are gaining attention for their reduced environmental footprint while maintaining consumer-preferred aesthetics. Studies in this area emphasize the textile industry's ongoing challenge of achieving sustainable production without compromising fabric quality [13].

Despite these advancements, gaps remain in the literature regarding comprehensive comparative analyses of multiple washing methods under standardized conditions. Most prior studies have focused on isolated treatments or limited property evaluations, leaving insufficient evidence about the combined effects on both physical durability (tensile, tear, elongation) and aesthetic performance (color fastness, visual appeal, softness). This research seeks to address this gap by systematically evaluating bleach wash, stone enzyme wash, and acid wash using standardized ISO testing methods, thereby providing practical insights for balancing fashion requirements with fabric longevity.

# 3. MATERIALS AND METHODS

### 3.1 Materials

The following materials were used in this study to investigate the effects of industrial washing techniques on the physical and aesthetic properties of denim fabrics:

#### 3.1.1 Fabrics

- Raw denim fabric
- Bleach-washed denim fabric
- Stone enzyme-washed denim fabric
- Acid-washed denim fabric
- Multi-fiber lining fabrics
- Rubbing cloths

#### 3.1.2 Chemicals

- Detergents
- Sodium carbonate
- Water

#### 3.1.3 Equipment

- Sewing machine
- Scissors
- Digital balance
- Pipette
- Measuring cylinder
- Stainless steel balls
- Stirring rod
- Grey scale for color change
- Grey scale for color staining
- Color matching cabinet

### 3.2 Machines

The following testing machines were employed to evaluate the physical and colorfastness properties of the denim samples:

#### 3.2.1 James Heal Titan (Tensile Strength Tester)

The Universal Strength Tester (UST) is an advanced testing machine used to measure the mechanical properties of textile materials. In this project, the James Heal 1710 Titan 5, manufactured in England, was used. It has a maximum capacity of 5000 N with a high resolution of 0.01 N, ensuring accurate and reliable results. This tester is capable of performing multiple tests such as tensile strength, tear strength, seam strength, elongation, and seam slippage, which are essential for assessing fabric performance and durability.

#### 3.2.2 Elma Tear (Tear Strength Tester, James Heal 1555)

The Elma Tear Strength Tester is a specialized instrument designed to measure the tear strength of textile fabrics. The model used in this project is the James Heal 1555, manufactured in England. It has a maximum capacity of 128 N and dimensions of approximately 63.4 cm (H) × 36.5 cm (W) × 61.7 cm (D), making it compact and efficient for laboratory use. This machine works on the principle of the pendulum method, where a pre-cut sample is torn under a controlled force, and the energy required to propagate the tear is recorded. The test results provide critical information on the resistance of fabrics to tearing, which is essential for evaluating durability and performance in end-use conditions.

#### 3.2.3 Crock Meter

The Crock Meter is a laboratory instrument used to assess the color fastness of textiles to rubbing (dry and wet). It measures the amount of color transferred from a dyed or printed fabric when rubbed under controlled conditions, helping determine the durability of the fabric's coloration. In this study, a Mesdan Crock Meter (Model 2540) with a capacity of 128 N (origin: Italy) was used. The machine operates by moving a weighted rubbing finger covered with a standard white test cloth back and forth over the specimen for a fixed number of strokes. After the test, the cloth is examined to evaluate the extent of color transfer according to standard scales.

#### 3.2.4 SDL Atlas Rotawash Color Fastness Tester

The SDL Atlas Rotawash Color Fastness Tester is a laboratory instrument used to evaluate the color fastness of textiles to washing and laundering. It simulates domestic or commercial washing conditions under controlled temperature, time, and agitation to determine how well a fabric retains its color or resists staining adjacent fabrics during washing.

#### 3.2.5 Schroder GSM Cutter

The Schroder GSM Cutter is a precision instrument used in textile laboratories to accurately measure the Grams per Square Meter (GSM) of fabrics. GSM is a key parameter in assessing fabric weight and quality, which is essential for ensuring consistency in production and meeting customer specifications. This device allows users to cut a circular specimen of a fixed area (usually 100 $cm^2$) from the fabric quickly and uniformly. The cut sample is then weighed using a digital balance, and the weight is multiplied by a conversion factor to determine the fabric's GSM.

### 3.3 Methods

#### 3.3.1 Tensile Strength Test Method

The tensile strength of denim fabrics was evaluated according to EN ISO 13934-1:2013, Determination of Maximum Force and Elongation at Maximum Force using the Strip Method.

**Specimen Preparation:** Fabric specimens measuring 200 mm × 100 mm were prepared from four different denim fabrics. Samples were cut in both warp and weft directions. For each direction, a minimum of five specimens was taken to ensure accuracy and reproducibility.

**Testing Machine:** A Universal Tensile Strength Tester (James Heal Titan) equipped with two jaws and a load cell capacity of 5000 N was used to conduct the test. The initial jaw separation (gauge length) was maintained at 200 mm before each test.

### Test Conditions:

- Gauge length (jaw separation): 200 mm
- Pretension applied: 2.00 N
- Break detection sensitivity: 10%
- Crosshead speed: 100 mm/min
- Load cell capacity: 5000 N

### Test Procedure:

- Each specimen was mounted centrally between the two jaws of the tester, ensuring that 25 mm of each end was clamped securely.
- A tensile force was applied at a constant rate by the movable jaw until rupture occurred.
- The machine automatically recorded the maximum breaking force and the corresponding elongation at break.
- The tests were repeated for at least five specimens in both warp and weft directions for each fabric sample. The mean tensile strength and mean elongation values were then calculated separately for warp and weft directions.

### 3.3.2 Tear Strength Test Method

The tear strength of the denim fabrics was measured according to EN ISO 13937-1:2000, Textiles Tear properties of fabrics Part 1: Determination of tear force using the ballistic pendulum method (Elmendorf method). This test evaluates the resistance of denim fabrics to tearing under applied force.

**Specimen:** Preparation Specimens of standard size were prepared from four different denim fabrics in both warp and weft directions. Multiple specimens were taken for each direction to ensure reproducibility of the results.

**Testing Machine:** The test was performed using an ElmaTear (Tear Strength Tester, James Heal 1555). This machine operates on the principle of a pendulum equipped with a knife, which propagates a pre-cut slit in the fabric to measure the tearing force.

**Test Conditions:**

- Testing method: Elmendorf ballistic pendulum
- Initial slit length: 20 mm (pre-cut using the integrated knife)
- Pendulum capacity: 1600 cN (standard range, extended with weights if required)
- Specimens tested in both warp and weft directions.

### Test Procedure:

- Each specimen was mounted in the jaws of the tester and a 20 mm pre-cut slit was made using the integrated cutting knife.
- The pendulum was released, and the tearing force required to propagate the slit across the fabric was measured.
- The machine digitally displayed the tear force values in Newtons (N).
- For each denim fabric, a minimum of five specimens were tested in both warp and weft directions. The average tear strength values were then calculated separately for warp and weft directions.

### 3.3.3 Color Fastness to Wash Test Method

The color fastness of denim fabrics to washing was evaluated according to ISO 105-C03: Textiles, Tests for Color Fastness Part C03: Color fastness to washing. This method evaluates the resistance of fabrics to color change and staining under specified washing conditions.

**Specimen Preparation:** Denim specimens of size 10 cm × 4 cm were prepared. Each specimen was sewn with a multi-fiber adjacent fabric of the same size at one corner. Multiple specimens were prepared from four different denim fabrics to ensure reproducibility of results.

**Testing Machine** The test was performed using a Rotawash machine equipped with stainless steel balls. A grey scale was used for assessing shade change and staining, while a color matching cabinet (light box) was employed for evaluation under standard light conditions.

**Test Conditions:**

- Washing solution: 5 g/L detergent (ECE type B) + 2 g/L sodium carbonate in distilled water with a ratio of 1:50 for material and liquor.

- Liquor volume: 150 mL per pot
- Temperature: 40°C
- Washing time: 30 minutes
- Number of stainless-steel balls: 10 per pot
- Drying: Air drying or oven drying at a temperature not exceeding 100°C

**Test Procedure:**

- Each specimen with multi-fiber fabric was placed into a pot containing 150 ml washing solution and stainless-steel balls.
- The pot was mounted in the Rotawash machine and rotated at 40°C for 30 minutes.
- After washing, specimens were rinsed thoroughly with hot water followed by cold water, then squeezed to remove excess solution.
- Samples were dried either in air or in an oven (≤100°C).
- The multi-fiber fabric was separated from the denim specimen, leaving one end attached for identification.
- The degree of color change in denim and staining on the multi-fiber fabric was evaluated using the grey scale and examined under a color matching cabinet.
- The tests were carried out from each denim fabric sample. The mean grey scale ratings were then calculated separately for color change and staining to obtain reliable results.

### 3.3.4 Color Fastness to Rubbing Test Method

The color fastness to rubbing (crocking) of denim fabrics was evaluated according to ISO 105-X12 and AATCC 8 test standards. This test determines the resistance of dyed or printed fabrics to color transfer when subjected to rubbing in both dry and wet conditions.

**Specimen Preparation:** Four denim fabric types were tested in this study: Raw Denim, Bleach Washed Denim, Stone Enzyme Washed Denim, and Acid Washed Denim. Test specimens were cut into square pieces as specified in the standards. For each fabric sample, both dry and wet rubbing tests were conducted.

**Testing Machine:** The test was performed using a Crockmeter (Rubbing Fastness Tester). The apparatus consists of a reciprocating arm equipped with a finger on which a standard white cotton rubbing cloth is mounted. The denim specimen was fixed securely on the testing surface during the test.

**Test Conditions:**

- Number of rubbing cycles: 10 cycles
- Pressure: Standard pressure as per ISO 105-X12
- Rubbing cloth: White cotton cloth
- Wet rubbing condition: Rubbing cloth wetted with distilled water to a standard pick-up level

**Test Procedure:**

- Dry Rubbing: A dry cotton rubbing cloth was mounted on the finger of the crockmeter and rubbed against the denim specimen for 10 cycles under standard pressure.
- Wet Rubbing: The cotton rubbing cloth was wetted with distilled water to a specified level and then rubbed against the denim specimen for 10 cycles under identical conditions.
- After rubbing, the cotton rubbing cloths were evaluated against the Grey Scale for Staining to determine the degree of color transfer.
- The tests were repeated for the specimens in both warp and weft directions for each denim fabric sample, following the standard requirements.

### 3.3.5 Areal Density Measurement Method:

The areal density (GSM) of denim fabrics was measured both before and after different industrial washing processes, including bleach wash, stone enzyme wash, and acid wash. For this purpose, a Schroder GSM Cutter was used to obtain fabric specimens of standard size.

**Sample Preparation:** Fabric samples of denim (raw and washed) were conditioned under standard atmospheric conditions for textiles (temperature: 20 ± 2°C, relative humidity: 65 ± 2%) before testing.

**Testing Machine:** The test was conducted using a Schroder GSM Cutter, which provides circular specimens of fixed area (100 $cm^2$). An electronic balance with a sensitivity of 0.001 g was employed for accurate weight measurement.

**Test Procedure:**

- Using the Schroder GSM Cutter, circular specimens of 100 $cm^2$ were cut from both raw and washed denim fabrics.
- Each specimen was weighed precisely on the electronic balance.
- The areal density of the fabric was calculated using the formula:

**GSM = Weight of the samples in gram × 100**

# 4. RESULTAND DISCUSSION

## 4.1 Tensile Strength:

Test ResultsThe tensile strength of the four denim fabric types was evaluated in both warp and weft directions. Tables 1-4 present the average maximum force (N) and the corresponding elongation at maximum force (%).

**Raw Denim Fabric:** In the warp direction, the average maximum force was 1784.72 N with an elongation of 27.37%. In the weft direction, the average maximum force was 1626.30 N with an elongation of 25.09%. These results indicate that raw denim exhibits comparatively high tensile strength in both directions, with slightly greater resistance to breakage along the warp due to the higher density and twist of warp yarns.

**Bleach Washed Denim Fabric:** After bleach washing, the average maximum force in the warp direction decreased to 1114.73 N (elongation 27.28%) and in the weft direction to 1076.42 N (elongation 25.19%). This substantial reduction in strength compared to raw denim may be attributed to the chemical action of bleaching agents, which can degrade cellulose and weaken yarn structure, although the elongation percentages remained similar.

**Stone Enzyme Washed Denim Fabric:** Stone enzyme washed denim showed an average maximum force of 1130.68 N (elongation 28.08%) in the warp direction and 1090.11 N (elongation 26.17%) in the weft direction. These results suggest that although enzymatic washing also lowers tensile strength compared to raw denim, the effect is slightly less severe than that of bleach washing. Moreover,elongation values remained comparable or slightly improved, indicating some softening  and flexibility induced by the enzymatic treatment.elongation values remained comparable or slightly improved, indicating some softening and flexibility induced by the enzymatic treatment.

**Acid Enzyme Washed Denim Fabric:** The tensile strength of the acid washed denim fabric was evaluated in both warp and weft directions. In the warp direction, the fabric exhibited an average maximum force of 1099.35 N with an elongation of 27.4%, while in the weft direction the average maximum force was 1049.62 N with an elongation of 25.55%. These findings indicate that acid washing substantially reduc-

**Table1:** Average maximum force and the corresponding elongation at maximum force (%) of raw denim

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Maximum Force (N) | Elongation at Max Force (%) | Specimen No. | Maximum Force (N) | Elongation at Max Force (%) |
| 1 | 1797.72 | 27.88 | 1 | 1638.71 | 25.4 |
| 2 | 1757.10 | 26.43 | 2 | 1689.11 | 26.10 |
| 3 | 1744.67 | 25.59 | 3 | 1602.88 | 24.94 |
| 4 | 1789.32 | 27.56 | 4 | 1677.42 | 25.23 |
| 5 | 1834.80 | 29.40 | 5 | 1523.50 | 23.78 |
| **Average** | **1784.72N** | **27.37%** | **Average** | **1626.30 N** | **25.09%** |

**Table 2:** Average maximum force and the corresponding elongation at maximum force (%) of bleached wash denim

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Maximum Force (N) | Elongation at Max Force (%) | Specimen No. | Maximum Force (N) | Elongation at Max Force (%) |
| 1 | 1107.24 | 27.85 | **1** | 1070.80 | 25.65 |
| 2 | 1154.41 | 28.79 | **2** | 1110.56 | 26.87 |
| 3 | 1090.34 | 25.67 | **3** | 1050.34 | 23.56 |
| 4 | 1170.67 | 30.23 | **4** | 1139.54 | 28.34 |
| 5 | 1050.67 | 23.87 | **5** | 1010.87 | 21.54 |
| **Average** | **1114.73 N** | **27.28%** | **Average** | **1076.42 N** | **25.19%** |

**Table 3:** Average maximum force and the corresponding elongation at maximum force (%) of stone enzyme washed denim

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Maximum Force (N) | Elongation at Max Force (%) | Specimen No. | Maximum Force (N) | Elongation at Max Force (%) |
| 1 | 1168.65 | 28.90 | 1 | 1120.34 | 26.87 |
| 2 | 1102.23 | 27.66 | 2 | 1070.45 | 25.45 |
| 3 | 1140.67 | 28.11 | 3 | 1100.78 | 26.11 |
| 4 | 1090.87 | 25.87 | 4 | 1048.34 | 23.87 |
| 5 | 1150.98 | 29.87 | 5 | 1110.67 | 28.56 |
| **Average** | **1130.68 N** | **28.08%** | **Average** | **1090.11 N** | **26.17%** |

**Table 4:** Tensile test result of acid washed denim fabric

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) | Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) |
| 1 | 67.28 | 51 | 1 | 65.56 | 50 |
| 2 | 68.44 | 52 | 2 | 66.13 | 51 |
| 3 | 65.23 | 49 | 3 | 63.89 | 48 |
| 4 | 69.10 | 53 | 4 | 67.34 | 52 |
| 5 | 70.45 | 54 | 5 | 68.45 | 55 |
| **Average** | **68.10N** | **51.80%** | **Average** | **66.27N** | **51.20%** |

es the tensile strength of denim compared with the raw fabric, although the warp direction still maintains higher strength than the weft direction due to the inherently stronger and more tightly twisted warp yarns. The elongation values remain within a similar range to other washed fabrics, suggesting that while fiber damage lowers strength, the fabric's ability to stretch under load is only moderately affected.

### 4.1.1 Comparative Analysis of Tensile Strengths


**Figure 1:** Comparative analysis of tensile strength

Figure 1 shows the average tensile strength and elongation of the four denim fabrics in both warp and weft directions. Raw denim exhibited the highest strength in warp (1784.72 N) and weft (1626.30 N) directions, as its yarns and structure were unaffected by finishing. After washing, tensile strength decreased notably. Among the washed fabrics, stone enzyme washed denim retained slightly higher strength (1130.68 N warp, 1090.11 N weft) compared to bleach washed (1114.73 N warp, 1076.42 N weft) and acid washed (1099.35 N warp, 1049.62 N weft), indicating that enzyme treatment causes less damage than harsh chemical washes. In all samples, warp strength was consistently higher than weft due to greater yarn density and twist. Elongation at maximum force remained fairly stable (25–28%), showing that washing mainly reduced strength but had little effect on extensibility. Overall, raw denim was the strongest, while stone enzyme washed fabric preserved better strength than bleach or acid washed denim.

## 4.2 Tear Strength Test Results

The tear strength of the four denim fabric types was evaluated in both warp and weft directions.

### Raw Denim Fabric

The tear strength of raw denim was evaluated in both warp and weft directions. The fabric showed an average tear force of 87.89 N in warp (66.2% pendulum capacity) and 87.12 N in weft (66.6% pendulum capacity). These values indicate nearly equal tear resistance in both directions, reflecting the balanced construction and strong interlacement of yarns in raw denim. The slightly higher warp strength is linked to greater yarn density and twist, while the weft shows comparable performance due to its inherent robustness.

### Bleach Washed Denim Fabric

The tear strength of bleach washed denim fabric was evaluated in both warp and weft directions. In the warp direction, the tear force values varied between 63.34 N and 72.23 N, with an average of 67.94 N and a pendulum capacity utilization of 52.6%. In the weft direction, the tear force ranged from 61.45 N to 70.12 N, with an average of 66.20 N and a pendulum capacity utilization of 50%. The overall results indicate that the warp direction exhibited slightly higher tear strength than the weft direction, which can be attributed to the greater yarn density and structural support provided by warp yarns in denim construction. Although bleach washing generally leads to fiber damage and a reduction in fabric strength due to the chemical degradation of cellulose, the fabric retained a relatively balanced performance between warp and weft directions, suggesting that durability is still maintained to a reasonable extent after the bleaching process.

### Stone Enzyme Washed Denim Fabric

The tear strength of stone enzyme washed denim fabric was analyzed in both warp and weft directions. In the warp direction, the tear force values ranged between 59.23 N and 63.29 N, with an average of 61.27 N and a pendulum capacity utilization of 46%. In the weft direction, the tear force varied from 57.09 N to 61.31 N, with an average of 59.28 N and a pendulum capacity utilization of 48.2%. The results show that the tear strength in the warp direction was slightly higher than in the weft direction, which is consistent with the structural dominance of warp yarns in denim. However, compared to bleach washed fabric, the overall tear strength was lower, indicating that the combined action of pumice stone abrasion and enzymatic treatment contributed to fiber weakening and yarn surface damage. Despite this reduction, the difference between warp and weft values remained relatively small, suggesting that stone enzyme washing uniformly affects fabric strength in both directions.

### Acid Washed Denim Fabric

The tear strength of acid washed denim fabric was assessed in both warp and weft directions. In the warp direction, the tear force ranged from 65.23 N to 70.45 N, with an average value of 68.10 N and a pendulum capacity utilization of 51.80%. In the weft direction, the tear force values varied between 63.89 N and 68.45 N, with an average of 66.27 N and a pendulum capacity utilization of 51.20%. The results indicate that the warp direction exhibited slightly higher tear

**Table 5:** Tear streanth result of raw denim fabric

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) | Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) |
| 1 | 85.93 | 65 | 1 | 81.78 | 64 |
| 2 | 87.89 | 66 | 2 | 85.42 | 66 |
| 3 | 83.87 | 64 | 3 | 83.78 | 65 |
| 4 | 89.33 | 67 | 4 | 91.45 | 68 |
| 5 | 92.48 | 69 | 5 | 93.23 | 70 |
| **Average** | **87.89 N** | **66.2%** | **Average** | **87.12 N** | **66.6%** |

**Table 6:** Tear streanth result of bleached washed denim fabric

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) | Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) |
| 1 | 69.81 | 53 | 1 | 66.23 | 51 |
| 2 | 66.12 | 50 | 2 | 65.87 | 49 |
| 3 | 72.23 | 60 | 3 | 70.12 | 53 |
| 4 | 63.34 | 48 | 4 | 61.45 | 47 |
| 54 | 68.23 | 52 | 5 | 67.34 | 50 |
| **Average** | **67.94 N** | **52.6%** | **Average** | **66.20 N** | **50%** |

**Table 7:** Tear streanth result of stone enzyme washed denim fabric

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) | Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) |
| 1 | 62.08 | 47 | 1 | 60.23 | 50 |
| 2 | 63.29 | 48 | 2 | 61.31 | 51 |
| 3 | 61.12 | 46 | 3 | 59.07 | 48 |
| 4 | 60.67 | 45 | 4 | 58.70 | 47 |
| 5 | 59.23 | 44 | 5 | 57.09 | 45 |
| **Average** | **61.27N** | **46%** | **Average** | **59.28N** | **48.2%** |

**Table 8:** Tear streanth result of acid washed denim fabric

| Warp Direction | | | Weft Direction | | |
|---|---|---|---|---|---|
| Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) | Specimen No. | Tear Force (N) | Pendulum Capacity Used (%) |
| 1 | 67.28 | 51 | 1 | 65.56 | 50 |
| 2 | 68.44 | 52 | 2 | 66.13 | 51 |
| 3 | 65.23 | 49 | 3 | 63.89 | 48 |
| 4 | 69.10 | 53 | 4 | 67.34 | 52 |
| 5 | 70.45 | 54 | 5 | 68.45 | 55 |
| **Average** | **68.10N** | **51.80%** | **Average** | **66.27N** | **51.20%** |

strength than the weft direction, reflecting the typical dominance of warp yarns in denim construction. Compared to stone enzyme washed fabric, the acid washed fabric retained higher tear strength, which suggests that although the acid wash treatment leads to surface abrasion and partial weakening of fibers, it causes less extensive structural damage than the combined effect of stones and enzymes.

### 4.2.1 Comparative Analysis of Tear Strengths Tests:

The comparative analysis of tear strength for raw and washed denim fabrics in both warp and weft directions is presented in Figures 2 and 3. For the warp direction, the raw denim exhibited the highest tear strength at 87.89 N, followed by acid washed denim (68.10 N), bleach washed denim (67.49 N), and stone enzyme washed denim (61.27 N). A similar trend was observed in the weft direction, where raw denim recorded 87.12 N, while acid washed, bleach washed, and stone enzyme washed fabrics showed 66.27 N, 66.20 N, and 59.28 N, respectively. The pendulum capacity utilization followed the same trend, being highest in raw denim and lowest in stone enzyme washed denim.

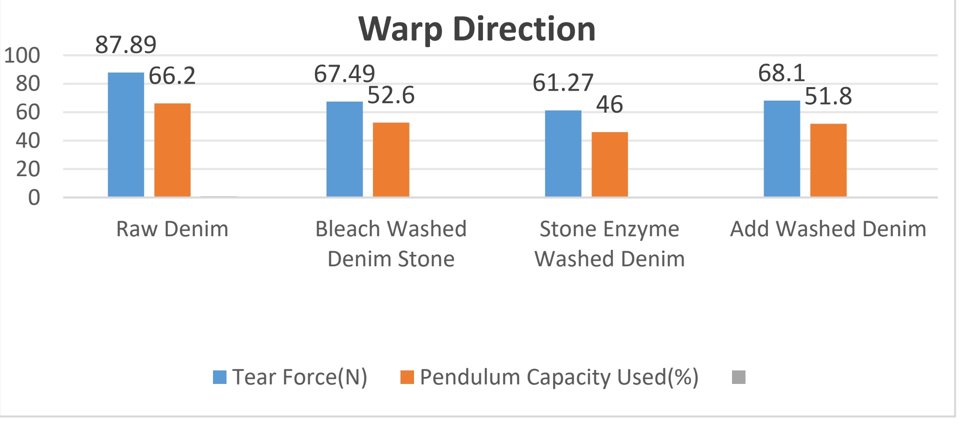


**Figure 2:** Tear strength test result warp direction

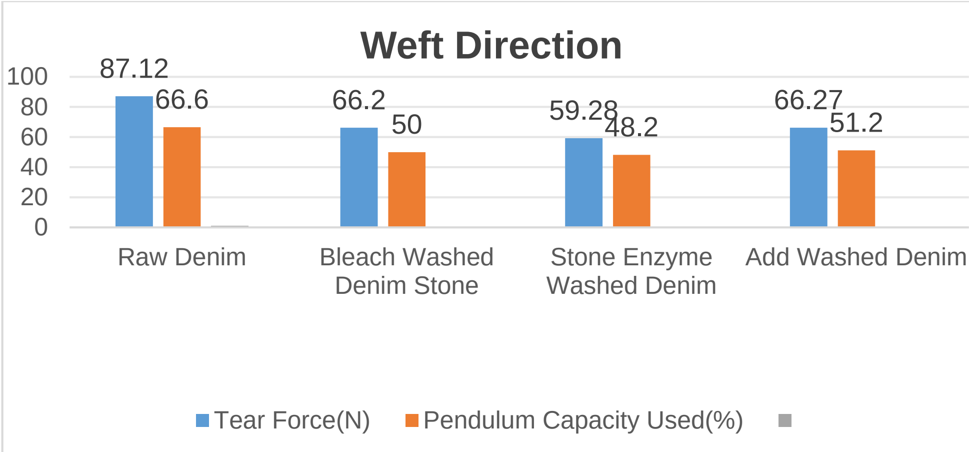


**Figure 3:** Tear strength test result weft direction

## 4.3 Color Fastness to Wash Test Results

Color fastness to wash is evaluated by observing two aspects: change in color and staining. Change in color indicates how much the tested fabric itself has faded, dulled, or altered in shade after washing, while staining refers to the extent of dye transfer from the tested fabric onto adjacent fabrics, such as cotton or polyester.

### 4.3.1 Staining

**Table 9:** Color fastness to wash

| Raw Denim Fabrics | Staining to adjacent multifiber fabric | |
|---|---|---|
|  | Acetate | 4/5 |
| | Cotton | 2/3 |
| | Nylon | 4/5 |
| | Polyester | 4 |
| | Acrylic | 4/5 |
| | Wool | 3 |

| Bleach Washed Denim Fabrics | Staining to adjacent multifiber fabric | |
|---|---|---|
|  | Acetate | 5 |
| | Cotton | 4/5 |
| | Nylon | 4/5 |
| | Polyester | 5 |
| | Acrylic | 5 |
| | Wool | 4 |

| Stone Enzyme Washed Denim Fabrics | Staining to adjacent multifiber fabric | |
|---|---|---|
|  | Acetate | 4/5 |
| | Cotton | 4 |
| | Nylon | 3/4 |
| | Polyester | 4 |
| | Acrylic | 4/5 |
| | Wool | 4/5 |

| Acid Washed Denim Fabrics | Staining to adjacent multifiber fabric | |
|---|---|---|
|  | Acetate | 5 |
| | Cotton | 4/5 |
| | Nylon | 4 |
| | Polyester | 4 |
| | Acrylic | 5 |
| | Wool | 4/5 |

### 4.3.2 Change in Color

Sample: Raw Denim
Fastness Rating: **3/4**
Meaning: Slight to moderate change

Sample: Bleach Washed Denim
Fastness Rating: **4**
Meaning: Slight Change

Sample: Stone Enzyme Washed Denim
Fastness Rating**: 3**
Meaning: Moderate Change

Sample: Acid Washed Denim
Fastness Rating: **4**
Meaning: Slight Change

**Figure 4:** Change in color of denim fabric
(Raw, bleached wash, stone enzyme wash, acid wash)

### 4.3.3 Comparative Analysis of Color Fastness to Wash

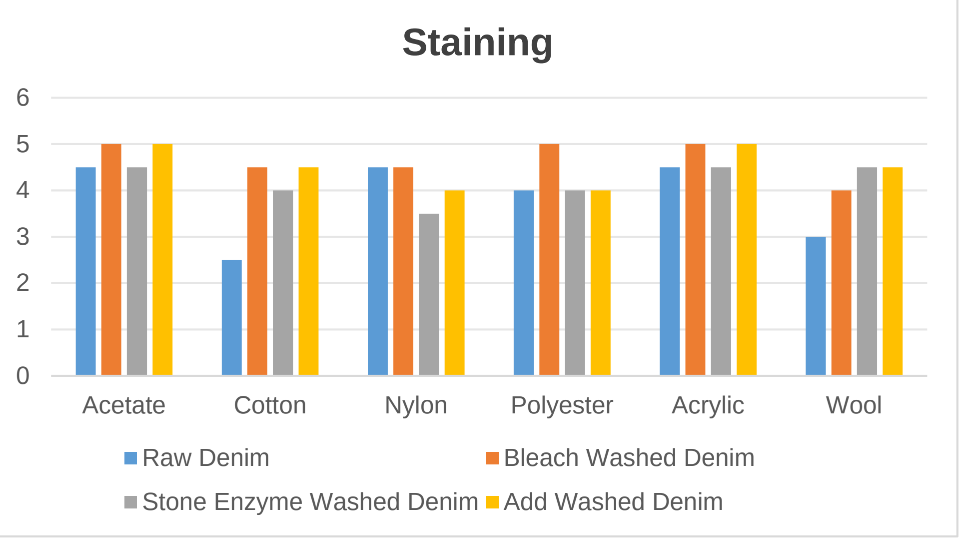


**Figure 5:** Staining rating report

The graph shows the color fastness to washing in terms of staining for different fiber types across four denim finishes. Bleach washed denim generally exhibits high staining resistance, achieving top scores of 5 for acetate, polyester, and acrylic. Acid washed denim also performs well, matching bleach washed denim in acetate and acrylic. Raw denim has comparatively lower resistance to staining on cotton (2.5) and wool (3), while stone enzyme washed denim shows moderate performance overall. These results indicate that bleaching and acid washing processes tend to enhance denim's resistance to staining on various fibers during washing.

The graph illustrates the color fastness to washing (measured as change in color) for different types of denim fabrics. Bleach washed denim and acid washed denim both show the highest color fastness rating of 4, indicating better resistance to color change during washing. Raw denim follows with a rating of 3.5, while stone enzyme washed denim has the lowest rating of 3, suggesting it is more prone to noticeable color change after washing. This comparison highlights how different finishing processes influence the wash durability of denim color.

## 4.4 Color Fastness to Rubbing Test Results

To evaluate the effect of different washing techniques on this property, tests were carried out on raw denim and washed denim fabrics, including bleach washed, stone enzyme washed, and acid washed samples. The results obtained for both dry and wet rubbing are summarized in Table 10.

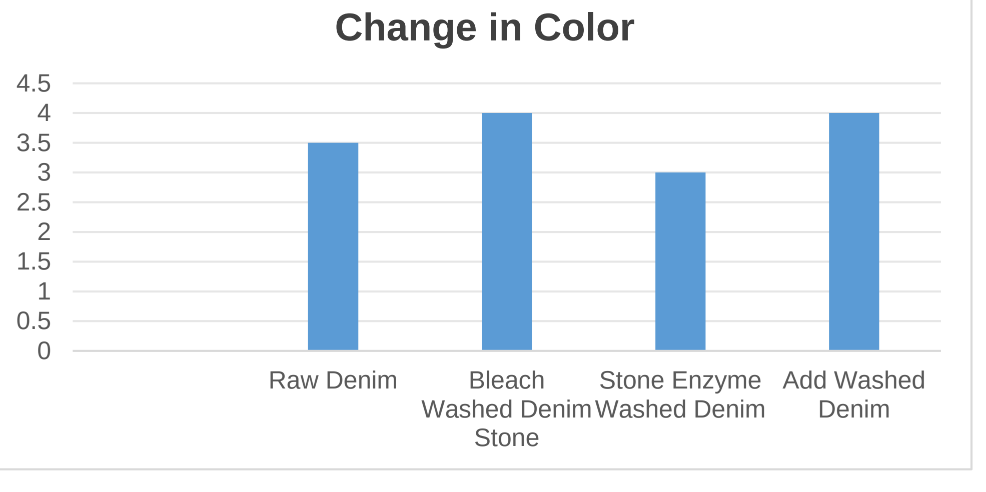


**Figure 6:** Staining rating of the washed samples on grey scale

**Table 10:** Color fastness to rubbing

| Type of Samples | Dry Rubbing Grade | Wet Rubbing Grade |
|---|---|---|
| Raw Denim Fabric | 4 | 1-2 |
| Bleach Washed Denim Fabric | 4-5 | 2-3 |
| Stone Enzyme Washed Denim Fabric | 4 | 1-2 |
| Acid Washed Denim Fabric | 4-5 | 3 |

The results of the color fastness to rubbing test show that all denim samples exhibited better grades in dry rubbing compared to wet rubbing. In dry conditions, the ratings ranged between 4 and 4-5, indicating good resistance to color transfer and suggesting that the dyes are fairly stable under friction without moisture. However, under wet conditions, the grades were lower, falling between 1 and 3. This reduction highlights the greater tendency of dyes to loosen and transfer when moisture is present, which is a common characteristic of denim fabrics due to their deep indigo coloration and surface dye particles. Overall, the findings emphasize that while denim fabrics maintain satisfactory dry rubbing fastness, wet rubbing remains a more critical issue requiring attention in processing and finishing.

#### 4.4.1 Comparative Analysis of Color Fastness to Rubbing

The graph shows the performance of different denim washing techniques in terms of color fastness to rubbing under both dry and wet conditions. In dry rubbing, all denim samples achieved high grades, with bleach washed and acid washed denim reaching 4.5, while raw denim and stone enzyme washed denim followed closely at 4.0. These values indicate that denim fabrics generally have strong resistance to color transfer when rubbed in dry conditions, regardless of the washing treatment.

In contrast, the wet rubbing results were considerably lower, reflecting the effect of moisture on indigo dye stability. Acid washed denim performed the best with a grade of 3.0, while bleach washed denim recorded 2.5. Raw denim and stone enzyme washed denim showed the lowest grades at 1.5, indicating higher staining in wet contact. Overall, the findings highlight that while dry rubbing fastness is strong across all finishes, wet rubbing significantly reduces performance, making it an important factor for practical use and quality evaluation.

### 4.5 Areal Density Test Results

The areal density (GSM) of the four denim fabric samples was measured using the standard test method. The results are presented in Table 11.

**Table 11:** Areal density test results

| Type of the samples | GSM |
|---|---|
| Raw Denim Fabric | 440 |
| Bleach Washed Denim Fabric | 415 |
| Stone Enzyme Washed Fabric | 420 |
| Acid Washed Fabric | 410 |

The areal density of the denim samples was determined and the results are presented in Table 11. The table lists the measured GSM values of the raw denim fabric along with  the three washed denim fabrics used in the study, namely bleach washed, stone enzyme  washed, and acid washed fabrics. These values represent the mass per unit area of each sample as obtained from the standard testing procedure.

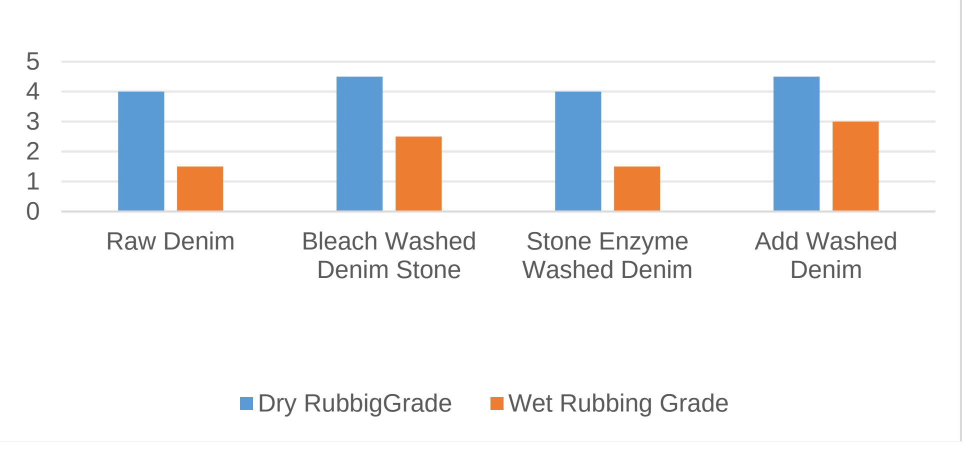


**Figure 7:** Rating of the washed samples for color fastness to rubbing

### 4.5.1 Comparative Analysis of Areal Density

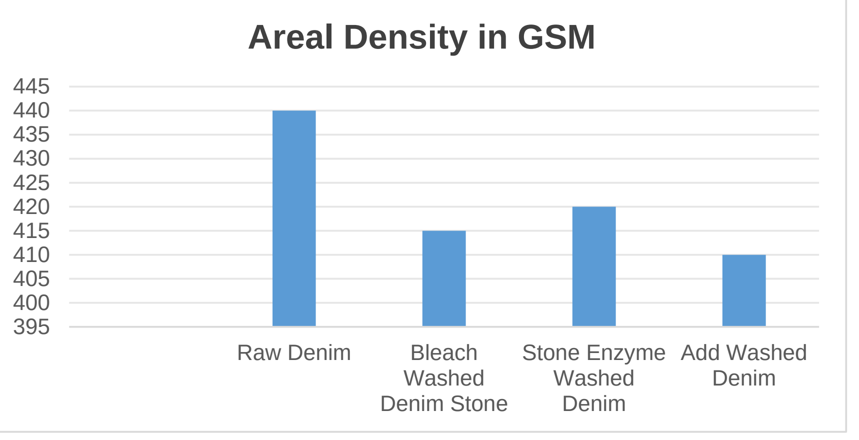


**Figure 8:** Chart of changes in areal density in GSM

The comparative analysis of the areal density (GSM) of the four denim fabric samples is shown in Figure 8. The bar chart illustrates the measured GSM values for raw denim, bleach washed denim, stone enzyme washed denim, and acid washed denim fabrics obtained through the standard testing procedure. Presenting the results in graphical form provides a clearer understanding of the mass per unit area of each fabric sample. It highlights the variation in GSM among the untreated and treated fabrics and visually supports the data listed in table 11. This representation also helps to easily observe the differences in areal density resulting from the different processing methods applied to the denim fabrics.

## 4.6 Recommendations for Suitable Washing Processes

A comparative evaluation of physical and aesthetic properties highlights the trade-offs among the three washing methods. Bleach wash, although effective in achieving maximum color fading, caused the most reduction in fabric strength and slightly compromised tactile feel. Acid wash provided strong fashion appeal through high contrast effects but resulted in rough surface texture and reduced durability. Stone enzyme wash, however, delivered moderate fading, enhanced softness, and preserved fabric strength better than the other two methods.

From both performance and aesthetic perspectives, stone enzyme wash emerged as the most balanced technique. It provided a desirable worn-out look while maintaining acceptable physical integrity, making it highly suitable for mainstream denim fashion. Bleach wash may still be employed for lightweight or less strength-demanding products where bright fading is the priority, while acid wash can be used selectively for niche markets aiming at bold, vintage-inspired styles despite the trade-offs in durability.

Overall, the study recommends stone enzyme wash as the most appropriate industrial washing technique for ensuring a balance between durability and visual appeal. This process aligns well with the fashion industry's need for garments that not only look attractive but also withstand repeated wear and washing.

## 5. CONCLUSION AND FURTHER WORK

## 5.1 Conclusion

This project examined the effects of three common industrial washing techniques, bleach wash, stone enzyme wash and acid wash on denim fabrics in comparison with raw (unwashed) denim. The work involved systematic sampling, preparation and testing according to standard textile testing procedures. Physical property assessment focused on the areal density (GSM) of each fabric sample, while visual documentation captured the surface appearance changes produced by each treatment.

The results confirmed that industrial washing processes produce measurable differences in the mass per unit area of denim fabrics and create distinct aesthetic effects. Each washing technique caused a reduction in GSM compared to raw denim, indicating a loss of material from the fabric surface, while also imparting characteristic color fading and texture. By combining numerical test data with photographic evidence, the study gives a clear picture of how industrial washing modifies both the physical integrity and the visual character of denim.

Overall, the findings demonstrate that the choice of washing technique directly influences the performance and look of denim fabrics, which is critical for manufacturers and designers aiming to balance strength, comfort and desired fashion appearance. The study therefore provides a useful reference for selecting and optimizing washing processes in the denim industry.

## 5.2 Further Work

While the present research focused on the areal density and visual changes of denim fabrics after industrial washing, there are additional aspects that could be investigated to broaden the findings. Future work may include:

- Evaluating other mechanical and comfort-related properties such as tensile strength, tear strength, air permeability, and dimensional stability of the washed fabrics.
- Conducting color fastness and abrasion resistance tests to assess long-term wear performance of washed denim.
- Studying the environmental impact of each washing technique by measuring water consumption, chemical use, and effluent quality.
- Applying advanced analytical tools (e.g., scanning electron microscopy or digital image analysis) to examine microstructural changes in the fabric after washing.
- Expanding the study to include different fabric weights, yarn types, and blends to understand how raw material composition interacts with industrial washing processes.

Such extended research would provide a more holistic understanding of how industrial washing influences both the performance and sustainability of denim fabrics.

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