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Sustainable Denim Finishing through Commercial Acid and Neutral Cellulase Enzyme Treatments under Application-Oriented Processing Conditions: A Comparative Study

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Abstract

Denim finishing is a crucial process that transforms raw denim into a wearable fabric. Different washing treatments, such as stone washing, enzyme washing, bleach washing, and acid washing, enhance the appearance, comfort, and utility of denim apparel by causing fading, softening, or damaged patterning. Among these, enzyme-based treatment is widely used for controlled fading, as well as from an environmental perspective. This research work proposes an application-oriented comparative assessment of commercial acid cellulase and neutral cellulase enzyme washes on indigo-dyed denim fabric under industrially relevant particular processing conditions. Thus, the differences observed should not be interpreted as a general performance difference between acid and neutral cellulase categories. The treated samples were evaluated in terms of GSM, shrinkage, EPI (Ends per Inch), PPI (Picks per Inch), bending rigidity, breaking strength, and color depth evaluation to discern the distinctions between the two processes. Findings indicated that under the specific conditions, commercial neutral enzyme washes resulted in slightly greater GSM reduction, softer fabric in warp direction, and enhanced fading effects measured with a lower grey scale compared to commercial acid enzyme washes. Furthermore, due to the absence of acids in commercial neutral enzyme wash, it offers a potentially more sustainable solution for the denim industry, reducing costs in the context of less consumption of chemicals, and minimizing overall environmental impact.

Keywords

Denim Finishing, Commercial Cellulase Comparison, Fabric Performance, Color Fading, Process Economics, Environmental Impact

1. Introduction

Apparel washing is a contemporary technique designed to provide a trendy aspect to fabrics or garments. It is a finishing technique that uses multiple chemicals to generate a range of appearances. Currently, "Denim wash" mostly produces attractive items that swiftly satisfy consumer desires and significantly alter their look. The denim washing process may modify several properties, including removing excess material, dirt, dust, and other contaminants, imparting softness, and controlling shrinkage, ensuring that items do not shrink further after purchase [1] [2]. The washing procedure may be categorized into two types: dry wash and wet wash. Wet washing encompasses several techniques, including acid wash, enzyme wash, bleach wash, pigment wash, and silicon wash, among others. As the current world increasingly prioritizes sustainability, enzyme wash can meet this expectation. Enzymes are proteins present in all living organisms. An enzyme functions as a catalyst in a chemical process, increasing the reaction rate. The primary advantage of enzymatic treatment or washing is its biodegradability, allowing it to decompose in the environment without introducing dangerous chemicals that might compromise water quality. Environmental sustainability pertains to the well-being of the environment, and enzyme wash possesses the potential to uphold this standard. It is an environmentally friendly wash that is advantageous for both manufacturers and consumers, as some washing techniques, such as acid stone wash, which utilize stones to produce a faded appearance, can now be accomplished using enzymes. Enzymes will supplant the usage of stones, which can cause harm to washing machines (thereby diminishing their lifetime) and textiles. Additionally, the acid wash process involves chemicals such as potassium permanganate ($KMnO_4$), which is a heavy metal and non-biodegradable, ultimately resulting in environmental damage. An enzyme wash can be regarded as preferable to conventional fading processes [3] [4]. Primarily, cellulase enzymes are utilized in the washing process. Denim fabric primarily consists of two types of yarn: warp and weft. The warp threads are colored with indigo, while the weft yarns remain undyed. Hence, it is referred to as the surface dyeing method. The cellulase enzyme primarily targets the indigo-dyed areas, producing a faded appearance. In addition, the protruding fibrous structures on the surface are hydrolyzed by enzymes [2] [5] [6]. The progression of denim and garment washing methods illustrates the textile industry's continuous balance among aesthetic requirements, mechanical efficiency, and environmental accountability. Recent studies indicate a transition from conventional stone-washing and chemical-heavy techniques to enzymatic treatments, owing to their enhanced controllability and less environmental impact. A novel study showed the effects of acid and neutral enzyme washes on 100% cotton denim using varying liquor ratios (1:10, 1:15, 1:20). The denim was desized with an anti-backstaining agent (1:10 MLR), where acid enzyme required pH adjustment (4.5 - 5.5) with acetic acid, while neutral enzyme did not. Post-wash, fabrics were hydro-extracted (70% wet pick-up, 200 rpm) and dried (75˚C). Testing revealed no significant differences in fastness (rubbing, washing, light) between acid and neutral enzymes, but neutral enzymes showed higher weight loss at lower liquor ratios due to increased friction. PPI changes occurred without notable EPI differences. Neutral enzyme proved more cost-effective and efficient than acid enzyme [7].

Recent research has thoroughly investigated diverse denim washing methods, emphasizing their impact on fabric characteristics and ecological sustainability. Biodegradable washing methods enhance fabric smoothness and air permeability while diminishing environmental effects [8]. Comparative studies have shown that neutral cellulase enzymes provide enhanced fading effects with less back staining relative to acid enzymes; however, stone-enzyme combinations provide improved abrasion at the expense of tensile strength [9] [10]. Studies consistently demonstrate that enzymatic treatments improve fabric softness, water absorption, and color fading, while diminishing stiffness [11] [12]. Acidic enzymes such as BPA provide superior reflectivity, but neutral enzymes like N9 reduce weight loss [13]. Optimal washing conditions were determined to be 50˚C, pH 8 for a duration of 30 minutes [14]. Environmental issues have spurred innovation in sustainable practices, with research promoting enzyme washes as preferable to detrimental bleach treatments [15] [16]. Nonetheless, obstacles persist regarding expenses, equipment damage from stone washing [17], and the equilibrium between aesthetic appeal and fabric resilience. Recent research validates that ecological treatments enhance fabric tactile quality while mitigating pollution issues, underscoring the industry's transition towards sustainable procedures that satisfy both quality and environmental criteria [18].

This research work evaluates the impact of selected commercial acid and neutral enzyme washes on fabric qualities (GSM, tensile strength, stiffness, EPI/PPI, count, color fading) as well as economic and environmental considerations, maintaining a constant liquor ratio under application-oriented conditions between two commercial cellulase formulations: the acid cellulase Cellzyme 2000L Super and the neutral cellulase Biowash SL-D Ultra. While previous studies have compared acid and neutral cellulase treatments, there has been little focus on comparing full commercial cellulase wash formulations, improved color fading with lower auxiliary chemical consumption, and reduced chemical cost due to less process under industrially relevant processing conditions. The present study, therefore, focuses on an application-oriented assessment of two commercially available cellulase washing systems to provide information relevant to industrial decision-making.

Activities conducted in university (Bangladesh University of Textiles, BUTEX) textile laboratories assess performance variations in fading quality, fabric durability, chemical expenses, and environmental effect. The results have compared the performance characteristics of the two enzyme washing systems and provided the best outcomes, balancing quality, cost-effectiveness, and sustainability to inform industry implementation.

2. Methodology

2.1. Materials

100% indigo-dyed 3/1 twill denim apparel was selected for the experiment. It was collected from the Bangladesh University of Textiles (BUTEX). The GSM of the denim was 300.

All information related to chemicals was obtained from the TDS sheet provided by the chemical company.

2.2. Chemicals Used

There are various types of chemicals used in both washing processes represented in Table 1.

Table 1. Overview of chemicals utilized in washing and their properties.

Chemical	Key Properties	Appearance	pH	Other Features
Detergent	- Anionic - Water-soluble in any proportion	Slightly yellow liquid	7 ± 1 (10%)	
Desizing Agent (L-40)	- Thermostable bacterial α-amylase - Removes starch-based sizes	Brown liquid	-	Specific gravity 1.1
Acid Cellulase Enzyme	- Activity: 9000 IU/mL (min) - Works at 40˚C - 50˚C	Brown liquid	4.0 - 5.0	Specific gravity 1.1 - 1.2
Neutral Cellulase (Biowash SL-D Ultra)	- Higher contrast on denim - Low back staining - Works at 50˚C - 68˚C - Reduces pumice need	-	-	User-friendly, broad temperature range
Silicone Softener	- Premium softness - Improves wash durability & crease recovery	Clear/hazy liquid	6.0 ± 1 (10%)	Pourable, elastic handle

2.3. Machines Used

Machines used in conducting both washing processes are represented in Table 2.

Table 2. Equipment details for washing operations.

Equipment Type	Brand	Origin	Model	Capacity
Sample Washing Machine	NGAI SHING	China	NS 2205	Water capacity: 350 L
Hydro-Extracting Machine	MESDAN s.p.a	Italy	C-240	Drum volume: 38 L
Tumble Dryer Machine	CREDA	England	37761	Load capacity: 5 kg

3. Methods

3.1. Washing Processes

3.1.1. Desizing Treatment

Remove sized materials from yarn-dyed denim fabric.

Parameters:

- **Total Load:** 2 kg (248 g sample + 175 g dummy fabric + additional dummy to reach 2 kg)
- **Liquor Ratio:** 1:10 (20 L water for 2 kg fabric)
- **Chemicals:**
  - Desizing agent: 2 g/L → 40 g total
  - Detergent: 1.5 g/L → 30 g total
- **Process Conditions:**
  - Temperature: 60˚C
  - Duration: 20 minutes

3.1.2. Commercial Cellulase Washing Treatment

a. Commercial Acid Cellulase (Cellzyme 2000L) Enzyme:

The treatment with acid cellulase enzyme involved the addition of 4 g/l of the enzyme to the desized denim clothing.

Figure 1 illustrates the addition of acid cellulase enzyme. During that period, the bath pH level was assessed using litmus paper, revealing a value of approximately 9.2.

Figure 2 illustrates the measurement of the solution's pH. To sustain the pH, acetic acid was added at a concentration of 2.5 g/L.

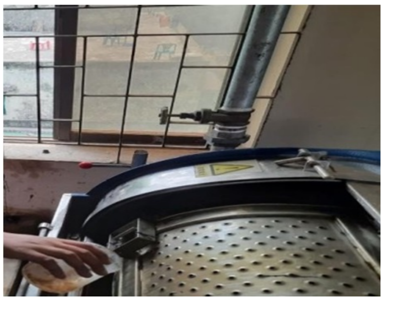

Figure 1. Addition of commercial acid cellulose enzyme.

Figure 2. Acid Bath PH measurement.

The pH level was subsequently determined to be around 8.5. These values correspond to the real bath conditions during the applied application-oriented washing procedure. The pH determinations were made with litmus paper and are therefore only approximate. The present study is limited in that no independent verification of enzyme activity or continuous pH monitoring was performed, which is acknowledged as a limitation.

Acidic cellulose enzyme concentration: 4 g/L = 80 g total, Acetic Acid = 2.5 g/L = 50 g, Temperature: 45˚C, Duration: 30 minutes as per the standard industry benchmark to activate the acid cellulase enzyme.

The treatments were carried out under application-oriented processing conditions based on laboratory and industrial practice. Although the treatment with acid cellulase was outside the range recommended by the manufacturer, it was carried out for 30 minutes as the experimental design was application-oriented, aiming at evaluating two complete commercial cellulase washing formulations under their respective practical processing procedures. Therefore, each formulation was evaluated as a complete washing system, including the corresponding processing conditions and post-treatment operations rather than simply as a comparison between acid and neutral cellulase enzyme categories.

b. Commercial Neutral Cellulose (Biowash SL-D Ultra) Enzyme:

A neutral cellulase enzyme was applied at a concentration of 4 g/l to the desized denim garments. Figure 3 illustrates the addition of neutral cellulase enzyme. The temperature was maintained at 60˚C for a duration of 40 minutes to activate its operation as per the industrial range and technical data sheet provided by the manufacturer. The pH level was assessed using litmus paper and determined to be around 6.5. Figure 4 illustrates the pH measurement of the solution, which was determined to be 6.5.

Figure 3. Addition of commercial neutral cellulose enzyme.

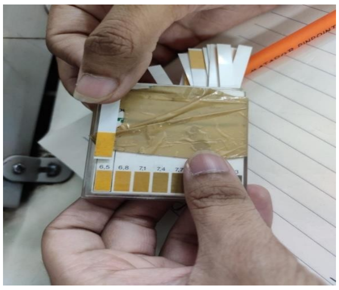

Figure 4. Neutral bath PH measurement.

3.1.3. Neutralization

The neutralisation procedure is conducted to regulate pH levels. The neutralisation procedure during acid cellulase enzyme treatment was accomplished by the addition of sodium metabisulfite ($Na_2S_2O_5$). It's a strong reducing and neutralizing agent to adjust the bath PH into the neutral range (shown in **Figure 4**) for wearable purposes in later stages. The temperature was established at 40˚C for a duration of 10 minutes. The pH level was assessed using litmus paper and determined to be 6.5.

A hot wash was conducted at 80˚C for 2 minutes following the neutralisation process.

No neutralisation step was required for the neutral cellulase enzyme treatment, as the pH was automatically maintained near 6.5 after the addition of commercial neutral cellulase. As a result, it eventually became suitable for the wearer's skin without the addition of any neutralising agent.

3.1.4. Softening

Following the neutralization procedure, a softening treatment was conducted. Softening is performed to enhance the tactile quality of denim garments. Softening was achieved with the use of a silicone softener. The temperature was maintained at room temperature for ten minutes.

Silicone softener: 2.5 g/L = 50 g

Temperature: Ambient temperature

Duration: 10 minutes

3.1.5. Hydro-Extraction

Hydro-extraction is used to eliminate surplus water from the garments. The denim garments were subjected to a hydro-extractor machine for a duration of 7 minutes.

3.1.6. Tumble Dryer

Upon completion of the hydro-extraction drying process, drying was accomplished using a tumble dryer. The temperature was at ambient conditions.

The final output was found and is shown in **Figure 5**, showing neutral cellulose and acid cellulose-treated samples.

Figure 5. Commercial neutral cellulase and acid cellulase-treated sample.

3.2. Assessment Techniques of Various Tests

The treated apparel was conditioned to moisture equilibrium as directed in ASTM D 1776. We conducted all the washing processes and testing procedures mentioned in Table 3 in the BUTEX Apparel Washing lab, Physical Testing lab, Accreditation lab, and Wet Process lab.

Table 3. Fabric testing methods with standards and equipment.

Test Name	Standard Used	Key Equipment
Stiffness Test	BS 3356	Shirley Stiffness Tester
GSM Test	ASTM D 3776	GSM Cutter
Breaking Strength	ASTM D 5034 (Grab Test)	Tensile Testing Machine
Color Change (Grey Scale)	ISO 105-A02:1993	Grey Scale
Shrinkage Test	N/A	Ruler/Marking Tool
EPI & PPI Measurement	N/A	Counting Glass
Yarn Count Measurement	N/A	Digital Balance

After assessment of various tests through the above-stated machines, values are recorded and illustrated through Excel.

4. Results & Discussion

4.1. GSM Test

The GSM prior to washing was 300 (Figure 6). Following the Acid Enzyme Wash, the GSM was 275; after the Neutral Enzyme Wash, the GSM was 273, as illustrated in Figure 6. The neutral enzyme has superior fading efficacy due to its structural attributes, resulting in enhanced contrast compared to the acid enzyme, which therefore leads to having slightly greater GSM reduction than the acid variant.

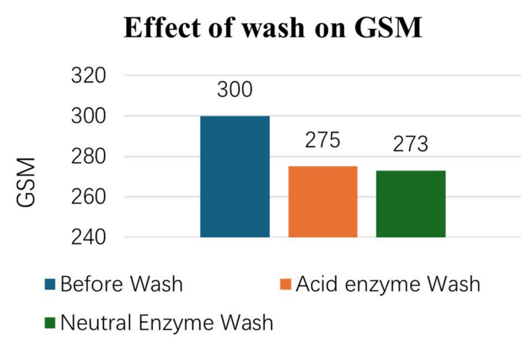

Figure 6. Effect of washing treatment on GSM (Acid vs. Neutral Enzyme).

4.2. Shrinkage Test

Prior to washing, both the length and width were 10 cm (Figure 7). Post Acid Enzyme Wash, dimensions are 10.1 cm in length and 9.9 cm in breadth (Figure 7). Dimensions of the Neutral Enzyme Wash: length 10.3 cm, breadth 9.7 cm (Figure

7). In the longitudinal direction, warp yarn may experience stretching; hence, growth occurs instead of shrinkage. Tension applied during the processing step is removed in the widthwise direction, resulting in shrinkage.

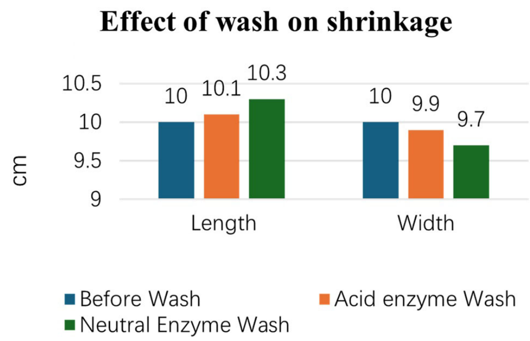

Figure 7. Effect of washing treatment on shrinkage—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

4.3. Thread Density

Prior to washing, EPI was 60, and PPI was 55 (Figure 8). Post acid enzyme washing, EPI was 61, and PPI was 54 (Figure 8). Following neutral enzyme washing, EPI is 63, and PPI is 53 (Figure 8). In a neutral enzyme wash, PPI is reduced compared to acid due to more lengthwise development.

Regarding EPI, widthwise shrinking is more pronounced since the EPI of neutral is greater than that of the acid wash.

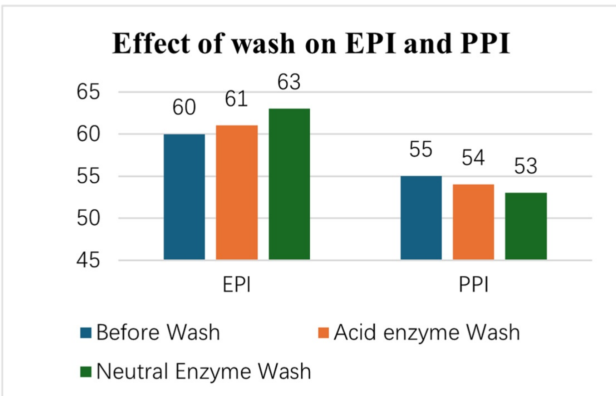

Figure 8. Effect of washing treatment on EPI and PPI—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

4.4. Yarn Count

Prior to washing, the warp count is 10.68 Ne, and the weft count is 14.80 Ne (Figure 9). Following the acid enzyme wash, the warp count is 11 Ne, and the weft count is 16 Ne (Figure 9). Following the Neutral Enzyme Wash, the warp count is 12 Ne, and the weft count is 15 Ne (Figure 9). A marginal rise in yarn count is seen in both washes. This is attributable to the finishing technique, which renders the yarn somewhat softer.

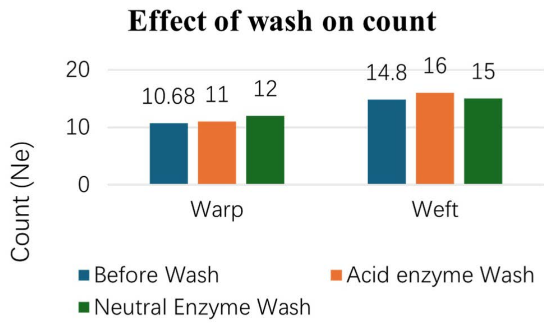

Figure 9. Effect of washing treatment on yarn count—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

4.5. Breaking Strength

Prior to washing, the breaking strength of the warp is 515.45 N, and the weft is 263.76 N (Figure 10). Following the Acid Enzyme Wash, the breaking strength of the warp is 455.74 N and the weft is 208.94 N (Figure 10). Following the Neutral Enzyme Wash, the breaking strength of the warp is 448.76 N and the weft is 248.17 N (Figure 10). Finer yarn requires less breaking power, requiring more force for acid warp than neutral warp, and acid weft yarn has inferior breaking strength compared to neutral weft.

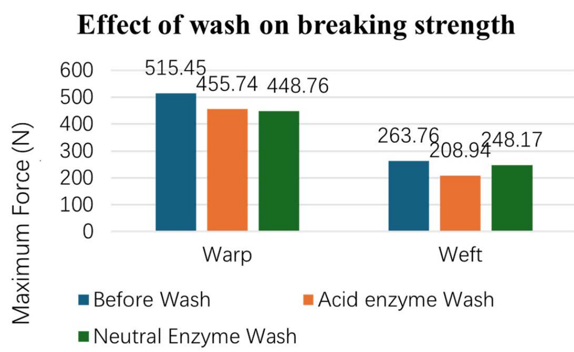

Figure 10. Effect of washing treatment on breaking strength—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

4.6. Bending Stiffness

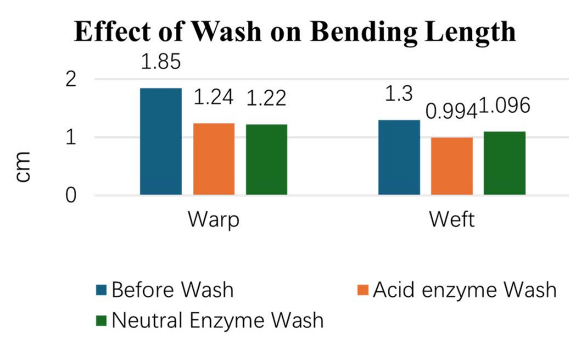

Figure 11. Effect of washing treatment on bending length—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

Prior to washing, the bending lengths of the warp and weft are 1.85 cm and 1.3 cm, respectively (**Figure 11**). Following the Acid Enzyme Wash, the bending length of the warp is 1.24 cm, and the weft is 0.994 cm (**Figure 11**). Following the Neutral Enzyme Wash, the bending length of the warp is 1.22 cm, and the weft is 1.096 cm (**Figure 11**). Acid warp yarn is coarser than neutral warp yarn, making it difficult to bend. As the bending length increases, the bending stiffness will also increase. The contrary scenario is found in the weft direction.

4.7. Color Change Assessment

Prior to the wash, no color change was seen (5); subsequent to the Acid Enzyme Wash, the color change was recorded as 4 (**Figure 12**). The color shift following the Neutral Enzyme Wash was ¾ (**Figure 12**). Earlier studies have often reported more fading with acid cellulase, but in the present study, enhanced fading was observed with the commercial neutral cellulase (Biowash SL-D Ultra). This observation is consistent with the technical information of the manufacturer, which states that the product provides higher contrast denim than conventional commercial acid-stable cellulases.

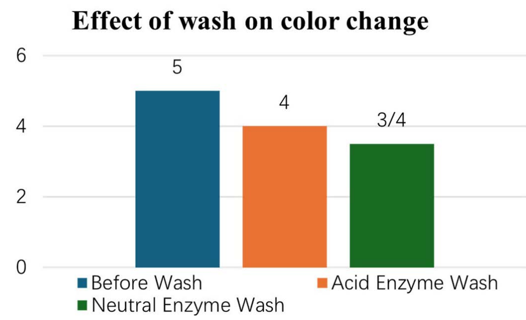

Figure 12. Effect of washing treatment on grey scale rating—pre-wash vs. post-wash (Acid vs. Neutral Enzyme).

4.8. Environmental Impact

Both acid and neutral cellulase washing are potentially more sustainable than conventional stone washing because of the reduced fabric damage and no consumption of pumice stone. The use of commercial neutral cellulase (Biowash SL-D Ultra), however, provides further environmental benefits by avoiding neutralization, thus reducing the use of auxiliary chemicals and simplifying the washing process. The acid cellulase process involves pH adjustment and subsequent neutralization, resulting in increased chemical consumption and wastewater treatment requirements. Therefore, under the processing conditions investigated, the commercial neutral cellulase process presents a higher potential for sustainable denim finishing, although further environmental assessments, such as life cycle analysis, are recommended.

5. Conclusion

The present study is an application-oriented comparative study on selective acid and neutral cellulase enzyme wash of indigo-dyed denim adjusted with practical operational conditions. The work is focused on the practical performance of two commercial cellulase washing formulations in their respective industrial processing procedures. Therefore, the results have been interpreted as a case-specific comparison of the overall commercial washing systems under certain conditions rather than the intrinsic performance of acid and neutral cellulase enzyme categories. It must be pointed out that the acid cellulase treatment was not run at its recommended acidic pH. Hence, the observed differences between the commercial acid and neutral cellulase treatments should not be generalized to universal differences between acid and neutral cellulase types. The results are only valid for the commercial formulations and processing conditions studied in this application-oriented study. The outcome significantly impacts indigo-dyed denim fabric characteristics and offers significant financial and environmental benefits. Previous studies have frequently reported greater fading with acid cellulase than with neutral cellulase. However, under the selected processing conditions, the commercial neutral cellulase process produced slightly greater fading with the help of a lower grey scale, together with reduced fabric weight and improved softness in the warp direction, compared with the acid cellulase process, where the acid enzyme was not operated at its optimal pH, and also under non-identical conditions for both washes. Furthermore, the commercial neutral enzyme wash (Biowash SL-D Ultra) offers potentially lower processing costs due to lower costs incurred as a result of less chemical consumption and promotes environmental sustainability. It provided better weft-strength retention and fabric softness in the warp direction, and regulates indigo extraction at neutral pH, avoiding dye redeposition and inconsistent hues. The selective neutral enzyme washing system approach enhances sustainable denim production by minimizing water and energy use, reducing wastewater treatment needs, and lowering the environmental footprint compared to conventional chemical cleansers. Overall, enzymatic washing offers practical advantages for denim finishing, as it enables controlled modification of the fabric and reduces the need for harsh chemical treatments. The results support the selection of appropriate enzyme systems depending on the quality of the desired product and the process conditions. Further studies under identical processing conditions are recommended to isolate the influence of enzyme type from other process variables.

Author Contributions

Conceptualization: Shourin Alam Mou; **Methodology:** Shourin Alam Mou; **Validation:** Shourin Alam Mou, Jaglul Haque Mridha, and Md. Sakib-Uz-Zaman; **Formal analysis**: Shourin Alam Mou; **Investigation**: Shourin Alam Mou, Ferdous Nahiyan, and Md. Shariful Islam; **Resources:** Shourin Alam Mou, Md. Shariful Islam, and Golam Muktadir Joy; **Data curation**: Shourin Alam Mou and Md. Sakib-Uz-Zaman; **Writing—original draft preparation:** Shourin Alam Mou; **Writing—review and editing:** Shourin Alam Mou, Jaglul Haque Mridha, and Md. Sakib-Uz-Zaman; **Visualization:** Shourin Alam Mou, Jaglul Haque Mridha, Md. Sakib-Uz-Zaman, Ferdous Nahiyan, and Golam Muktadir Joy; **Supervision:** Shourin Alam Mou and Jaglul Haque Mridha; **Project administration:** Jaglul Haque Mridha and Md. Sakib-Uz-Zaman; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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