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Research Article

Environmental Impacts of Denim Washing Industries in Bangladesh: Challenges and Sustainable Solution

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Abstract

Bangladesh has become one of the major global suppliers of denim garments and denim washing plays a vital role in imparting the desired appearance, comfort and functional characteristics to the buyers of the international market. By comparison, washing operations can be very demanding on the environment as many of the processes require large volumes of water, chemicals and energy. The wastewater from washing processes may have high levels of organic matter, suspended solids, salts, color and chemical residues which if not properly treated can be a potential hazard to adjacent water bodies and ecosystems. The objective of this research was to evaluate the environmental impacts of the denim washing industries of Bangladesh on water consumption, chemical use, wastewater generation, energy consumption and waste management. The paper also reflects the practical problems of the washing plants in introducing environmentally-sound production methods. The review discusses current practices in wastewater treatment and resource management and identifies opportunities for cleaner production approaches including low-water washing techniques, environmentally preferable chemicals, water recycling and reuse, energy-efficient machinery and improved sludge management. The analysis shows that it is not enough to treat the wastewater to reduce the environmental footprint of denim washing, but it is also necessary to reduce the consumption of resources in the production phase. Therefore, proper monitoring of the environment, technological improvements, skilled manpower, and responsible management of chemicals and stricter implementation of environmental regulations are necessary. The study suggests a number of practical actions that can help the denim washing industry in Bangladesh to move toward more resource efficient and environment-friendly production, while keeping the RMG industry of the country competitive.

Keywords

Denim Washing, Environmental Impacts, Sustainable Textile Production

1. Introduction

The textile and apparel sector in Bangladesh is one of the major manufacturing sectors, which significantly contribute to the industrial development, employment and export economy of the country. This section has seen denim become a more

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significant product category thanks to strong demand in global markets. Bangladesh has built a large manufacturing base for denim apparel and has emerged as an important sourcing hub for global clothing brands. The ecological impacts of denim production have increasingly been in the spotlight. The method of production requires large quantities of water, chemicals, energy and other resources. Continuous wet-process operations and the use of a variety of chemical and mechanical treatments during the washing and finishing stages can be a major source of environmental stress. [1].

After the garment is made, it is subjected to a denim wash to give it certain esthetic, physical and functional properties. Depending on the esthetic and functional needs, denim apparel can be subjected to a range of processes like desizing, standard washing, stone washing, enzyme washing, bleaching, caustic washing, softening, and different finishing treatments. - There are other surface treatments such as sanding, brushing, whiskering, and grinding. Chemical substances such as enzymes, bleaching agents, caustic soda, hydrogen peroxide, potassium permanganate, detergents and fabric softeners can be incorporated in various laundering and finishing techniques. Such processes allow producers to produce different denim looks but also increase the environmental load in terms of water use, chemical use, wastewater generation and solid waste. Choudhury (2017) emphasizes that different denim washing techniques can influence the release of fiber particles and chemical residues. Therefore, the environmental effects of denim manufacturing extend beyond the typical water pollution. [2].

Water use is an especially important of the main environmental problems related to the laundering of denim. Wet Processing involves the use of Water for washing, rinsing, chemical application, neutralization etc. Doing these things repeatedly can build a pretty good amount of demand over time. This problem is highly relevant to Bangladesh, where textile production is already linked to a huge pressure on freshwater and groundwater. Hossain and Khan (2020) estimated the yearly water footprint of the textile industry in Bangladesh at around 1.8 billion m^3, based on data between 2012 and 2016. Their analysis also showed that appropriate water treatment and recycling may significantly decrease the gray water footprint of textile manufacturing.

Water-related impacts of textile processing are not only the volume of water used. The quality of wastewater produced in manufacturing is also important. The denim laundering process generates wastewater containing suspended solids, dissolved materials, color, organic compounds, salts and chemical residues from the various washing methods used. The composition of wastewater varies with the process and the chemicals used. It can contain high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), variable pH, turbidity and visible color. Poorly treated wastewater discharges into nearby water bodies can cause water quality problems and threaten aquatic ecosystems. Research has indicated that declining water quality and environmental conditions in Bangladesh's textile industry are linked to inadequately treat industrial effluents.

Bangladesh provides an empirical example of the environmental significance of laundering denim. Shamsuzzaman et al. (2021) investigated untreated and treated wastewater of five denim garment laundering plants. Parameters like COD, BOD, dissolved oxygen (DO), TDS, TSS, pH, turbidity and hue were measured. The results indicated that the treatment efficiency was not the same in all the factories and considerable limitation still exists in obtaining a reasonable quality of the effluent. The levels of COD and BOD in the studied factories were within the permissible limits, but acceptable levels of DO were found only in a small percentage of the factories. TDS, TSS, color and pH also had variation in performance. The study revealed that the presence of an effluent treatment system does not guaranty consistent environmental results. [3].

This is important as effluent treatment is only one aspect of environmental responsibility. A manufacturing facility may have an Effluent Treatment Plant (ETP) but still be using excess fresh water and chemicals in the production process. A more integrated approach to pollution prevention at source and post-treatment is needed to improve the environmental impact of denim laundering. Cleaner production methods can cut down on the generation of wastewater and pollutants before treatment. Tactics might include raising the volume of alcohol, cutting out unnecessary rinses, using less harmful chemicals, measuring chemicals more accurately, using enzymes, incorporating low or no-water technologies where technically possible, and improving process control.

One relevant ecological problem is the depletion of underground water sources. The increasing pressure on groundwater resources is due to the growing water needs of Bangladesh's textile manufacturing sectors. The large water footprint of the clothing industry is a major issue for water security (Hossain & Khan, 2020). Recent studies have been focused on recycling of wastewater in the denim industry of Bangladesh. In a research project, Nahar, Haque and Haque (2024) studied the repurposing and recycling of wastewater at a denim manufacturing facility in Manikganj, Bangladesh. The results indicated that the treated wastewater can be used for denim wet processing without any adverse effect on the quality parameters of the fabrics. Their examination showed that recycling can save important amounts of groundwater, thus suggesting that wastewater should not be regarded as a waste stream but as a precious resource.

The washing of denim is an important environmental factor in the use of chemicals. The washing result requires different combinations of chemicals and processing parameters. Production costs and environmental impacts can be increased by the choice of inappropriate chemicals, overdose, poor storage and poor process management. Chemical residues may also contaminate wastewater systems. And that adds to the complexity of the treatment. The ecological impacts of making

denim go beyond washing the finished garment and include growing the cotton, dyeing it with indigo, processing the fabric, making the garment and transporting it. The independent assessment of denim washing has advantages because it enables investigators to identify and quantify the environmental impact of the wet processing of the garment and formulate specific strategies for improvement.

Sustainability of denim laundering 2. Energy consumption. This is a key point to measure. Machines for washing, pumping, boilers, dryers, compressors, wastewater treatment plants and many other devices need electrical or thermal energy. Heating and drying water require particularly large amounts of energy. Cutting down water use also can save energy indirectly, because less water has to be pumped, heated, treated and dried. This gives an important connection between water efficiency, energy efficiency, production cost and environmental performance. Studies in Bangladesh's textile dyeing sector suggest that performance indicators can monitor water and energy use and can identify options for reduction of use at the factory level. [4].

Environmental performance can be influenced by institutional and managerial factors and technological limitations. Sakamoto et al. (2019) investigated environmental compliance in Bangladesh's textile industry and highlighted issues related to the setup and operation of ETPs, environmental monitoring, regulatory enforcement, and the preparedness and capacity of factories to adhere to environmental regulations. The findings demonstrate that environmental pollution cannot be solved by technological solutions alone. Good environmental management requires the cooperation of producers, government, technology suppliers, workers, global buyers, and many other stakeholders.

Another important factor to improve the ecological efficiency of the denim laundering industry in Bangladesh is the global market demand. International apparel brands are increasingly focusing on resource efficiency, waste water management, chemicals management, reducing their carbon footprint and circular production. Therefore, environmental performance is becoming an issue of ecological accountability and competitiveness for the manufacturers in Bangladesh. Manufacturing facilities that reduce usage of freshwater, improve the quality of wastewater, reduce use of chemicals, and effectively manage their environmental footprint may be in a better position to satisfy increasingly stringent buyer demands. A recent study at a denim facility in Bangladesh found that wet processing can use recycled treated wastewater, while also meeting the fabric quality standards of North American and European fashion brands. [5].

While research on textile wastewater and ecological sustainability in Bangladesh is growing, there is a need for more targeted research on the cumulative environmental impact of denim laundering processes. Previous studies have provided useful insights on effluent quality, water footprint, groundwater depletion, and environmental compliance. But the challenges faced by denim washing facilities are not only single issues but combination of interrelated issues such as water use, chemical use, wastewater treatment, sludge management, energy use, process efficiency, and adoption of cleaner production technologies. Therefore, a comprehensive assessment can identify the areas under most environmental pressure and the most feasible interventions in the setting of Bangladesh.

This study aims to explore the ecological impacts of denim laundering industries in Bangladesh with a special focus on water consumption, wastewater generation, chemical application, energy consumption, waste disposal and existing environmental management practices. The paper also discusses the major barriers to the adoption of sustainable technologies and examines potential strategies for reducing the environmental impact of denim laundering processes. The focus is on cleaner production, water recycling and reuse, environmentally preferable chemical management, energy efficiency, improved wastewater treatment and solid environmental monitoring. The research aims to integrate these dimensions to develop pragmatic strategies to improve resource efficiency and ecological responsibility of the denim washing industry in Bangladesh and to meet the sustainable long-term demand of the global apparel sector.[6].

2. Materials and Methods

2.1. Materials

For the experimental study, the main textile chosen was indigo-dyed denim. Ideally the textile should be procured from a Bangladeshi denim manufacturer or finishing unit so that the experimental material is representative of the denim processed in the RMG sector of Bangladesh. The textile should be cut into samples of uniform size and weight and treated under controlled laboratory conditions prior to laundering.

Twill denim fabric dyed indigo and made from 100% cotton may be used. Laboratory experiment.

Table 1. *The principal materials and processing agents.*

Material	Purpose
Indigo-dyed denim fabric	Experimental textile substrate
Desizing enzyme/amylase	Removal of size materials
Cellulase enzyme	Surface modification and controlled fading

Material	Purpose
Laccase, if available	Alternative bio-bleaching treatment
Nonionic detergent	Cleaning during washing
Sodium carbonate/appropriate alkali	Process pH adjustment where required
Pumice stone, where conventional stone washing is studied	Mechanical abrasion
Hydrogen peroxide or another established bleaching agent	Conventional bleaching comparison, if included
Acetic acid or another appropriate neutralizing agent	Neutralization
Distilled/deionized water	Laboratory preparation and controlled washing
pH buffer/standard solutions	Instrument calibration

2.2. Research Materials and Data Selection

The study investigates the environmental impacts of denim washing in Bangladesh in terms of water use, wastewater generation, effluent standards, treatment efficiency, wastewater reclamation, and quality of denim products using recycled water. Since it was challenging to access reliable industrial-scale environmental measurement data from individual factories, benchmark data were obtained from experimentally collected data published in peer-reviewed studies of Bangladeshi denim production facilities.

The main sources were two Bangladesh-specific investigations. Shamsuzzaman et al. (2021) studied untreated and treated wastewater from five denim garment washing facilities in Bangladesh. They performed experimental measurements of chemical oxygen demand (COD), biochemical oxygen demand (BOD), dissolved oxygen (DO), total dissolved solids (TDS), total suspended solids (TSS), pH, turbidity and the color of the wastewater. This therefore provides a direct measure of the ecological effectiveness of industrial denim-washing wastewater treatment systems.

In a later industrial case study, Nahar, Haque, and Haque (2024) studied groundwater use, wastewater treatment and reuse, and recycling in an operational denim manufacturing plant in the Manikganj District of Bangladesh. For the denim wet processing, the investigators used 100% ETP treated wastewater and 10% treated wastewater and 90% softened water mixture. Finally, the last denim samples were evaluated according to the quality criteria applied by North American and European fashion brands. [7].

2.3. Features of Denim Production

The denim manufacturing facility studied by Mithun et al. (2026) produced about 75,000 denim garments per day. It was calculated that the average weight of one denim item is 0.40 kg, which means that approximately 30,000 kg of denim goods are produced each day.

Industry's water requirement was around 74 liters per kg of denim product. From the daily output, the total consumption of process water was about 2,044 cubic meter a day or 2.044 million liters. Most of the water required by the vegetation was obtained from subsoil water.

Table 2. *Actual industrial production and water-use data reported for a Bangladeshi denim facility.*

Parameter	Reported value	Unit
Average denim product weight	0.40	kg/piece
Daily production	75,000	pieces/day
Total daily denim production	30,000	kg/day
Process water requirement	74	L/kg product
Total daily process-water demand	2,044	m^3/day
Total daily process-water demand	2,044,000	L/day

These metrics are indicative of the water consumption in the industrial production of denim. For a high capacity facility

the process water requirement could be over two million liters per day with a water-use intensity of 74 L/kg. Thus, reduction of freshwater consumption and recycling of treated waste water have a large potential to improve ecological efficiency.

2.4. Water Supply and Wastewater Generation

The facility in Manikganj studied was pumping about 2,636 m^3/day of groundwater. The amount of water allocated for residential use was about 592 m^3/day and treated in the water treatment facility for industrial use was about 2044 m^3/day. The process water treated was used in washing operations to the extent of almost 95%.

The water treatment plant was described with an approximate capacity of 90 m^3/h. The wastewater generated during washing was subsequently conveyed to the factory's effluent treatment plant for treatment prior to discharge. The plant also captured some 20 cubic meters per day of water through a condensate recovery system that was reused in the boilers and generators.

The data indicate that washing is a significant step in the water-intensive process of denim manufacturing, suggesting a key opportunity for water savings.

2.5. Physicochemical Properties of Water in Denim Production

Published industrial statistics from Bangladesh also provide useful insight into the quality of freshwater and treated wastewater allocated for recycling.

Table 3. *Selected water-quality measurements reported for denim processing.*

Water-quality parameter	Treated groundwater	ETP-treated/recycled water	Unit
pH	6.3	7.2	—
COD	12	62	mg/L
BOD	0.9	42	mg/L
TDS	372	1,556	mg/L
TSS	12	25	mg/L
Total hardness	209	438	mg/L
Chloride	29	238	mg/L
Sulfate	2.98	242	mg/L

These published measurements show that ETP-treated wastewater contained substantially higher concentrations of dissolved constituents than treated groundwater, particularly TDS, hardness, chloride, and sulfate. Nevertheless, the treated wastewater was experimentally assessed for reuse in denim processing rather than being considered solely as a waste stream. The data therefore demonstrate the importance of evaluating both wastewater quality and final fabric performance when determining whether recycled water can replace freshwater in denim processing.[9].

2.6. Denim Washing and Dyeing Experiment Using Recycled Wastewater

In the industrial study, Nahar et al. (2024) produced denim items with treated wastewater to assess the technical feasibility of recycling without compromising the product quality.

The experimental processes of dyeing and washing were carried out using a Yilmak HBM 575 machine made in Turkey. The laundering and coloring processes were carried out at about 40–50°C for 17 min. The procedure involved desizing agent and detergent wash, followed by stone washing and rinsing with freshwater. Then Glauber's salt was added and the denim clothes were shaken for about five minutes. Then reactive dye was introduced, followed by a further five-minute tumble and machine drying. [8].

Two key criteria were evaluated for recycled water:

(a) Waste water treated by 100% ETP, and (b) mixture of 10% ETP-treated waste water and 90% softened water.

The acquired denim samples were tested for different fabric quality properties and compared with the specifications set by the international brands, which buy garments from Bangladesh.

2.7. Denim Quality Evaluation of Recycled Water Washed Denim

One important aspect to be considered when evaluating a sustainable washing technology is the quality of the fabric.

The environmental improvements cannot be considered effective if the durability of the product or the performance required by consumers is significantly affected.

The experimental results revealed satisfactory retention of the denim quality characteristics when treated with recycled wastewater.

Table 4. *Selected quality results for denim processed using conventional and recycled water.*

Property	Conventional/treated groundwater	Recycled-water processed denim
Dry rubbing color fastness	4.0	4.5–5.0
Wet rubbing color fastness	3.5–4.0	4.5
Warp tear strength	29.82 N	28.36 N
Weft tear strength	15.82 N	14.62 N

The researchers reported that the processed samples complied with relevant requirements of North American and European brands. These findings are important because they suggest that properly treated textile wastewater can potentially substitute part, or under suitable conditions a substantial proportion, of freshwater used in denim processing without necessarily compromising important fabric properties. [10].

2.8. Groundwater Conservation Potential

One of the most significant findings of the Bangladesh denim study was the potential reduction in groundwater extraction through wastewater recycling.

At a recycling and reuse rate of 10%, the investigated facility was estimated to save approximately *61,923 m^3 of groundwater annually.* Under the high-recycling scenario involving 100% treated wastewater, annual groundwater conservation was estimated at approximately *619,230 m^3*.

Table 5. *Estimated groundwater conservation through treated wastewater reuse.*

Wastewater recycling scenario	Estimated groundwater saving
10% treated wastewater reuse	61,923 m^3/year
100% treated wastewater reuse	619,230 m^3/year

Source: Nahar et al. (2024).

The difference between these scenarios illustrates the potentially large environmental benefit of closing industrial water loops. At factory scale, wastewater recycling may reduce groundwater abstraction while simultaneously reducing the quantity of treated wastewater discharged to nearby water bodies.

2.9. Environmental Performance of Five Denim Washing Factories

Shamsuzzaman et al. (2021) provide another important dataset derived directly from five denim garment washing factories in Bangladesh. Both untreated and ETP-treated wastewater samples were experimentally analyzed.

The study evaluated COD, BOD, DO, TDS, TSS, turbidity, pH, and wastewater color. COD and BOD concentrations were reported to be within the applicable acceptable limits for all five factories. However, the overall treatment performance was inconsistent for several other environmental parameters.

Only approximately *20% of the factories achieved an acceptable dissolved-oxygen level.* Around *40–60% showed improvement in TDS and TSS filtration performance*, while only *40% produced clear wastewater* after treatment. Furthermore, approximately *60% of the investigated factories achieved a pH within the study's acceptable range of 6–8*.

Table 6. Performance indicators reported for five Bangladeshi denim washing factories.

Environmental indicator	Reported performance
Factories investigated	5
COD within acceptable limit	100%
BOD within acceptable limit	100%
Acceptable DO achieved	20%
Evidence of improved TDS/TSS filtration	approximately 40–60%
Clear wastewater obtained	40%
pH within 6–8 range	60%

Source: Shamsuzzaman et al. (2021).

More detailed reported data also demonstrate considerable variation among factories. For example, published TDS measurements for wastewater samples included values of approximately 2,600 and 1,650 mg/L for Factory A before and after treatment; 1,910 and 1,150 mg/L for Factory B; 3,500 and 200 mg/L for Factory C; 4,700 and 1,200 mg/L for Factory D; and 2,500 and 1,700 mg/L for Factory E. These values demonstrate that the effectiveness of ETP treatment can vary substantially between denim washing facilities.[11].

Table 7. Reported TDS concentrations before and after ETP treatment.

Factory	Before ETP treatment (mg/L)	After ETP treatment (mg/L)	Approximate reduction
A	2,600	1,650	36.5%
B	1,910	1,150	39.8%
C	3,500	200	94.3%
D	4,700	1,200	74.5%
E	2,500	1,700	32.0%

Source data: Shamsuzzaman et al. (2021); percentage reductions calculated from the published measurements.

The large differences between facilities suggest that the environmental impact of denim washing cannot be determined solely by whether a factory has an ETP. Treatment technology, operating conditions, process control, chemical loading, maintenance, and wastewater characteristics may all influence treatment effectiveness.[12].

2.10. Microfiber Pollution as an Emerging Environmental Indicator

In addition to conventional water-quality indicators, recent evidence from Bangladesh suggests that microfiber pollution should be considered when evaluating textile and denim wastewater.

A 2024 investigation covering eleven Bangladeshi woven, knit, and denim factories measured an average microfiber concentration of approximately *615.45 ± 377.52 particles/L* in ETP influent and *212.72 ± 80.14 particles/L* in treated effluent. Sludge contained approximately *10,545.45 ± 7,989.54 particles/kg*. ETP microfiber removal efficiencies ranged from only *23.52% to 82.19%*. The researchers also observed that denim facilities released more microfibers than the investigated knit and woven industries.[14].

These results indicate that conventional wastewater parameters such as COD, BOD, TSS, and pH alone may not fully describe the environmental footprint of denim wet processing. Emerging pollutants, particularly textile microfibers, should increasingly be incorporated into environmental assessments.

3. Sustainable Solutions for Denim Washing Industries in Bangladesh

Cleaning the wastewater from denim washing alone is not

enough to reduce its environmental impact. A more sustainable strategy should be aimed at reducing pollution at source, including: reducing water and chemical consumption, increasing process efficiency, recovering wastewater and replacing resource-intensive finishing processes with more environmentally friendly alternatives. The importance of future sustainability of denim manufacturing is covered by recent studies on laser technology, ozone treatment, enzymatic process, nanobubble innovation, water saving laundry and closed loop water systems. [13].

3.1. Freshwater Use Declined

Water conservation should be a major concern for denim laundering facilities in Bangladesh. Conventional laundering typically includes multiple wet processing steps, such as desizing, washing, rinsing, bleaching, neutralization, softening, and final rinsing. Repeated rinsing can greatly escalate the total water demand with no corresponding gains in the quality of the fabric.

Manufacturers should implement a water-use intensity measure, in liters of water per kilo of denim produced. Only by observing all stages of the washing process can superfluous rinsing, disproportionate liquor ratios, leakage and sub-optimal machine performance be detected.

Innovative low water washing methods such as ozone, laser, nanobubbles and different low-liquor techniques have become viable alternatives to traditional denim processing.

This methodology is particularly applicable to Bangladesh as groundwater is under pressure from industrial water demands. A study of a denim manufacturing plant in Manikganj has found that recycling wastewater can reduce the amount of groundwater pulled by a lot.

3.2. Reclamation and Reuse of Wastewater

Recovery of wastewater is an important sustainability opportunity for denim finishing factories in Bangladesh. Instead of simply treating wastewater for discharge, properly treated effluent can be recycled back into certain production processes.

Haque and Haque (2024) investigated this method in a denim manufacturing plant in Bangladesh. In their research, they used 100% treated wastewater and a mixture of 10% treated wastewater and 90% softened water for the wet processing of denim. The quality standards of the denim products manufactured were met in the tests. Their assessment revealed a potential saving of 619,230 m^3 of groundwater annually in the full recycling scenario and 61,923 m^3 in the 10% recycling scenario.

Evidence suggests that factories may begin to adopt closed-loop water systems, starting with a modest level of reuse and then progressively increasing the percentage of water recycled once the water quality and the performance of the product have been verified.

"An operational framework could be:

Cleansing → Effluent Treatment Plant → Advanced Processing → Quality Verification → Reservoir → Tailored Washing Techniques → Re-use

However, indiscriminate use of recycled water for all processes is not recommended. Water quality standards should be established for specific operations, especially where differences in TDS, hardness, color or the like may affect shade and fabric quality.

3.3. Enzymes for Laundry Solutions

Enzymatic treatment is another way to reduce the ecological footprint of denim finishing. Enzymes can perform specific functions under relatively controlled conditions and can replace or reduce some conventional mechanical and chemical processes.

Cellulase enzymes are commonly linked with biowashing and the controlled modification of denim surfaces, for example. Research evaluations have identified enzyme-driven processing as an alternative for a more sustainable denim finishing.

The sustainability advantage is more than simply calling a process "enzymatic." The real advantage depends on optimization of enzyme concentration, temperature, time of treatment, pH and liquor ratio. Enzymatic processes that are not well regulated can still be resource intensive.

Hence, Bangladeshi laundering facilities should develop sophisticated formulations based on: • delivery of enzyme.

1) temperature during processing;
2) duration of treatment;
3) Level of acidity;
4) spirit proportion;
5) physical operation, and;
6) required colour/textile presentation;

Process optimization should be evaluated in parallel with water consumption, chemicals consumption, wastewater characteristics and fabric quality.

3.4. Ozone Processing of Denim

Ozone technology is a promising method for denim fading and bleaching with radical reduction of traditional wet processing. Ozone-based techniques have the potential to reduce the amount of water and specific chemical inputs required compared to conventional chemical-intensive bleaching processes.

In their study on laser and ozone technologies from the perspective of developing nations, Nayak et al. concluded that ozone treatment can reduce water usage, processing time and environmental pollution. Their research also showed the potential of ozone and laser technologies to help shift denim manufacturing toward a circular model.

Ozone, however, must be introduced with caution. The efficiency depends on the design of the machine, the concentration of ozone, the time of exposure, the properties of the fabric

and the desired color. It is most important to keep workers safe and to control the process correctly.

Ozone technology is attractive to Bangladeshi factories producing high volume fashion denim as it enables them to reduce the traditional wet bleaching and fading processes.

3.5. Laser Refinement

Laser technology can replace some of the traditional mechanical and wet finishing processes. Computer-controlled laser systems can be used to achieve localized fading, whisker effects, patterns and other visual attributes with less reliance on water and chemical processing.

Nayak et al. have reported that laser application can save considerable amount of resources such as water, energy and chemicals. They found that, for the laser application they looked at, there could be reductions of about 97% in water use, 70-90% in energy use and 60-70% in chemical costs. These figures were based on specific company cases and are not recommended as generally applicable in all Bangladeshi factories.

Laser technology could be particularly useful for Bangladesh to replace manual whiskering and some of the traditional fading techniques. The implementation should be evaluated by a combination of ecological, financial and product-quality measures. [15].

3.6. Less Use of Chemicals

"Technology must be developed in tandem with chemicals. Denim laundering can involve a variety of different agents, such as enzymes, bleaching agents, alkali, detergents, fabric softeners and other additives. Overdosing increases production costs and may increase the pollution load on the ETP.

It is desirable to create a system of chemical inventory and dosage control in plants. All chemicals must be documented as follows: • chemical name;

1) primary constituent;
2) kilograms of denim per quantity;
3) operational phase;
4) dealer;
5) ecological classification.
6) wastewater implications, and
7) Replacement potential

Where this is technically possible, hazardous or environmentally damaging substances should be replaced by less hazardous ones.

The aim should not be simply to reduce the quantity of chemicals. The goal should be to achieve the desired denim esthetic with the least amount of chemicals. [16].

3.7. Microfiber and Indigo Contamination Regulation

Sustainable denim laundering should increasingly take into account microfiber release besides traditional wastewater metrics like COD, BOD, TDS and TSS.

Washing denim has been shown to release microfibers from cellulose and the pigment indigo. An experimental study showed that the larger the washing load, the more microfibers and indigo released. Microfiber release was about 343.6 µg/g of fabric under a certain condition.

A separate study has found that indigo-denim microfibers are widely distributed in the environment, and that worn jeans can release substantial amounts of microfibers during washing.

Bangladeshi denim manufacturers should therefore consider:

1) Monitoring of microfiber in ETP influent and treated effluents;
2) Improved filtration;
3) Decrease of the fiber build-up in the sludge; 4. Evaluation of the microfiber extraction efficacy; and 5. Increase of the mechanical washing intensity.

This would extend environmental monitoring beyond the traditional chemical measures. [17].

3.8. ETP Efficiency Improvement

An ETP should be considered a treatment system that is constantly monitored, and not just a facility at the end of the production process.

The treatment system should always evaluate parameters such as: • Acidity level;

1) Cash on Delivery;
2) Board of Directors;
3) Toxic Shock Syndrome;
4) Total Dissolved Solids;
5) cloudiness;
6) tint;
7) conductance, and
8) Concentration of microfibers, where applicable.

Operational documentation shall be maintained for identification of sudden drops in effluent quality related to changes in production formulations or ETP operation.

Most importantly, source reduction should be tied to wastewater management. A manufacturing plant that minimizes the generation of pollutants at source will, in general, be less stressed on its Effluent Treatment Plant than one that is reliant on end-of-pipe solutions.

3.9. Energy Conservation and Renewable Energy Sources

Water and energy governance should be addressed together. An energy demand is corresponding to the pumping heating treatment and drying of water. Therefore, a decrease in water consumption can also reduce energy needs.

Manufacturing facilities can increase energy efficiency by: • recovery of thermal energy from effluent;

1) laundry equipment, high-performance;

2) higher desiccation temperatures;
3) variable-speed drives;
4) highly efficient pumps and motors;
5) improved steam systems;
6) Recovery of the condensate; and
7) make use of renewable sources of energy where possible.

The goal should be to track energy consumption per kilogramme of treated denim, enabling factories to compare conventional and alternative laundering processes. [18].

3.10. Bangladesh Sustainable Denim Laundering Framework

The available evidence suggests that a sustainable framework for denim washing factories in Bangladesh should not be based on one technology. The greatest ecological benefit is likely to be gained by the combination of several strategies.

A possible model is:

Process optimization
↓
Reduced liquor ratio and water consumption
↓
Enzyme-based washing where technically suitable
↓
Laser/ozone for selected fading effects
↓
Low-impact chemical management
↓
Advanced ETP
↓
Water-quality monitoring
↓
Wastewater recycling and reuse
↓
Microfiber monitoring
↓
Energy and heat recovery
↓
Continuous environmental performance assessment

This integrated approach is more appropriate for Bangladesh than replacing every conventional washing process with a single "green" technology. A 2025 systematic review of sustainable denim processing similarly concluded that technologies including ozone, laser, nebulization and enzymes can reduce resource consumption, but also noted that technical and scalability limitations remain for some emerging approaches.

4. Recommended Strategy for Bangladesh

For practical implementation, the transition could be divided into three stages.

Short-term:

Factories should first focus on water metering, chemical-dose optimization, leakage control, ETP monitoring, process standardization and employee training.

Medium-term:

Factories can increase wastewater reuse, introduce enzymatic processing, optimize low-liquor washing and adopt improved filtration and energy-recovery systems.

Long-term:

Large washing facilities can progressively adopt laser and ozone technologies, advanced closed-loop water systems, renewable energy, automated process control and microfiber monitoring.

The most appropriate technology should ultimately be selected through life-cycle, economic and technical assessment, rather than assuming that every emerging technology is automatically sustainable.

5. Conclusion

The study was carried out to investigate the environmental impacts of denim washing plants in Bangladesh with emphasis on water consumption, wastewater generation and treatment, chemical use, energy consumption, waste disposal, microfiber pollution and sustainable processing techniques adopted. The results indicate that washing of denim is a resource intensive step in garment manufacturing which involves several wet-processing steps, chemical treatments, mechanical treatments, heating, drying and wastewater treatment. Therefore, a comprehensive strategy is required to improve the sustainability of denim laundering, addressing the environmental consequences at the source instead of only relying on post-treatment solutions.

Water use is identified as a major environmental concern. Industrial data from this study show that a Bangladeshi denim factory producing some 75,000 garments a day consumed about 74 liters of process water per kg of denim, or nearly 2,044 cubic meters of process water a day. The high demand for water highlights the pressure large-scale denim production can exert on freshwater and groundwater resources. Frequent rinsing, laundering, bleaching, neutralizing and softening can increase water demands. Therefore, the key elements of sustainable manufacturing should be the reduction of liquor ratios, elimination of unnecessary rinsing, control of leakage, improvement of machine efficiency, and monitoring of water consumption per kilogram of denim.

Waste water management is a major environmental problem. The wastewater generated from the washing of denim may contain organic matter, suspended and dissolved solids, salts, pigments and residues of various processing chemicals. The data from five denim washing factories of Bangladesh shows that the effectiveness of ETPs may differ significantly from one establishment to another. Though the factories studied had COD and BOD within permissible limits, only around 20% of the factories showed satisfactory dissolved-oxygen levels and the results for TDS, TSS, color and pH were inconsistent. The variation in TDS reduction in the factories also indicates that environmental efficacy is not only dependent on the existence of an ETP but also its functionality, maintenance,

treatment methodology, operating parameters, chemical input and supervision. Thus, ongoing surveillance of the environment and efficient operation of the ETP is necessary for ensuring uniform quality of wastewater.[19].

One of the major opportunities identified by the study was recycling and repurposing of treated wastewater. Data from a denim manufacturing plant located in Bangladesh was used to suggest that such recycled wastewater could be used in the denim manufacturing process without compromising quality. The analyzed research estimated the potential saving in groundwater use of about 61923 m^3/year in the case of 10% recycling scenario and 619230 m^3/year in the case of 100% treated wastewater recycling scenario. The denim samples made with the recycled water processing had acceptable colorfastness and tear-strength properties and were verified to meet the standards of North American and European brands. These results suggest that wastewater, rather than being a disposal byproduct, could be transformed into a valuable production asset. However, water reuse should be regulated according to the specific quality levels of each process to avoid negative effects on shade, esthetics or material efficacy.

Chemical management is part of sustainable denim manufacturing. Enzymes, bleaches, alkalis, detergents, fabric softeners, and a host of processing chemicals are all part of the denim washing process. Overdosing or incorrect application of the chemicals may increase the production costs and the pollution of the wastewater treatment system. Thus, pollution prevention can be achieved by accurate dosing of chemicals, appropriate chemical inventories, and suitable formulations for specific processes, improved storage methods, and substitution of hazardous chemicals with safer ones. Enzymatic processing can reduce dependence on some conventional chemical and mechanical techniques through careful control of the enzyme concentration, temperature, pH, and treatment time and liquor ratio.

The study also indicates that cleaner technologies such as ozone and laser processing have the potential to be beneficial. These technologies may reduce dependence on some conventional wet processing methods and may reduce water and chemical needs for some denim effects. The ecological benefits they provide depend however on the design of the equipment, the process conditions, the product specifications, financial investment and the management of operations. The adoption of new technologies should therefore be based on technical, economic, environmental and product quality assessments and not on the fact that they are sustainable because of their technological level.

Energy efficiency is closely related to water efficiency, as energy is used to pump, heat, treat and dry water. Thus, water conservation can also provide additional energy saving benefits. The ecological performance can be improved optimizing pumps and motors, improving steam systems, reclaiming condensate, thermal recovery, effective drying apparatus, variable speed mechanisms and renewable energy sources. This measurement can be used by factories to compare traditional methods of production with alternative methods when processing denim.

The results also highlight microfiber pollution as an emerging environmental issue. The ecological impact of textile wet processing may not be fully reflected in the traditional parameters like COD, BOD, TDS, TSS and pH. Reanalyzed Bangladesh data revealed the presence of microfibers in influent, treated effluent, and sludge from ETPs and significant differences in microfiber removal efficiency. Thus, future environmental regulation of denim laundering should gradually include microfiber monitoring, upgraded filtration systems, sludge management practices, and evaluation of microfiber removal efficiency.

Sustainable denim laundering in Bangladesh should be grounded in a coherent resource-efficiency and circular production framework. The model proposed in this study combines process enhancement, reduced water consumption, enzymatic processing where appropriate, targeted use of laser and ozone technologies, reduced chemical input, improved effluent treatment efficiency, wastewater recycling and reuse, microfiber monitoring, energy recovery and continuous environmental monitoring. A phased plan of execution may start with water metering, optimization of chemical dosing, monitoring of effluent treatment plants, standardization of processes and training of personnel and then move on to enhanced wastewater recycling, enzymatic treatment, low-liquor laundering, superior filtration and energy recuperation. In the long run, manufacturing plants might consider advanced closed-loop water systems, automated process regulation, renewable energy sources, laser and ozone technologies, and microfiber surveillance.

Conclusion To reduce the environmental impact of the denim laundering, a shift from pollution control to pollution prevention, resource conservation, water recovery, process efficiency and continuous assessment of environmental performance is required. The analysis conducted in this research indicates the denim washing industry in Bangladesh has the scope of reducing freshwater consumption, groundwater depletion, chemical pollution, wastewater effects, energy requirement, and microfiber emissions while fulfilling the required denim standards. Success will depend on choosing the right technology, having the right people, good management, regulatory oversight and collaboration among manufacturers, researchers, technology vendors, regulators and global buyers. Thus, a properly integrated and phased sustainability framework may improve the long-term environmental effectiveness and resource efficiency of the denim washing industry of Bangladesh.

Abbreviations

TDS	Total Dissolved Solids
TSS	Total Suspended Solids

Author Contributions

Mithun Chandra Chanda: Conceptualization, Formal Analysis, Investigation, Resources

Tanusree Bhowmik: Data curation, Formal Analysis, Investigation, Methodology

Md. Mahmud Hasan: Data curation, Formal Analysis

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Choudhury, A. K. R. (2017). Environmental impacts of denim washing. In *Sustainability in Denim* (pp. 49–81). Woodhead Publishing/Elsevier. https://doi.org/10.1016/B978-0-08-102043-2.00003-4

[2] Hossain, L., & Khan, M. S. (2020). Water Footprint Management for Sustainable Growth in the Bangladesh Apparel Sector. *Water, 12*(10), 2760. https://doi.org/10.3390/w12102760

[3] Nahar, N., Haque, M. S., & Haque, S. E. (2024). Groundwater conservation, and recycling and reuse of textile wastewater in a denim industry of Bangladesh. *Water Resources and Industry, 31*, 100249. https://doi.org/10.1016/j.wri.2024.100249

[4] Sakamoto, M., Ahmed, T., Begum, S., & Huq, H. (2019). Water Pollution and the Textile Industry in Bangladesh: Flawed Corporate Practices or Restrictive Opportunities? *Sustainability, 11*(7), 1951. https://doi.org/10.3390/su11071951

[5] Shamsuzzaman, M., Kashem, M. A., Sayem, A. S. M., Khan, A. M., Shamsuddin, S. M., & Islam, M. M. (2021). Quantifying environmental sustainability of denim garments washing factories through effluent analysis: A case study in Bangladesh. *Journal of Cleaner Production, 290*, 125740. https://doi.org/10.1016/j.jclepro.2020.125740

[6] Hossain, L., Khan, M. S., & related studies on textile wastewater impacts in Bangladesh. *Evaluation of present and future wastewater impacts of textile dyeing industries in Bangladesh*. *Environmental Development, 26*, 23–33. https://doi.org/10.1016/j.envdev.2018.03.005

[7] Periyasamy, A. P., & Periyasami, S. (2023). *Critical Review on Sustainability in Denim: A Step toward Sustainable Production and Consumption of Denim*. ACS Omega, 8, 4472–4490. https://doi.org/10.1021/acsomega.2c06374

[8] Nayak, R., George, M., Jajpura, L., Khandual, A., & Panwar, T. (2022). *Laser and ozone applications for circularity journey in denim manufacturing—A developing country perspective*. Cleaner Engineering and Technology, 10, 100680. https://doi.org/10.1016/j.clet.2022.100680

[9] Zhao, X., Ren, Z., Hu, Z., et al. (2024). *Study on the simultaneous release of microfiber and indigo dye in denim fabric home washing*. Ecotoxicology and Environmental Safety, 269, 115735. https://doi.org/10.1016/j.ecoenv.2023.115735

[10] Rahaman, M. T., Khan, M. S. H., & Pranta, A. D. (2025). *Sustainable approaches to fashionable denim fading: New perspectives on conventional and modern garment washing techniques*. Coloration Technology. https://doi.org/10.1111/cote.70043

[11] Araoz-Baltazar, I., Granados-Sánchez, A., Martínez-Zárate, I., & Del Angel-Medina, O. (2025). *Sustainable alternatives for water consumption in denim jeans washing: A systematic literature review*. ECORFAN Journal. https://doi.org/10.35429/EJB.2025.12.22.4.1.12

[12] Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology on supply chain resilience. *International Journal of Production Research, 57*(3), 1–17.

[13] Kamble, S. S., Gunasekaran, A., & Sharma, R. (2018). Industry 4.0 and supply chain performance. *Technological Forecasting and Social Change, 132*, 1–14.

[14] Mentzer, J. T., DeWitt, W., Keebler, J., Min, S., Nix, N., Smith, C., & Zacharia, Z. (2001). Defining supply chain management. *Journal of Business Logistics, 22*(2), 1–25.

[15] Notteboom, T., & Rodrigue, J. P. (2009). Port regionalization. *Maritime Policy & Management, 36*(3), 185–200.

[16] Porter, M. E. (1990). *The competitive advantage of nations*. Free Press.

[17] Rahman, M., & Anwar, S. (2019). Lead time inefficiencies in Bangladesh textile industry. *Journal of Textile Engineering, 65*(2), 120–134.

[18] UNCTAD. (2022). *Review of maritime transport*. United Nations.

[19] World Bank. (2022). *Logistics performance index report*. World Bank.