Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

Core 2.0 Nebulization Technique - A Sustainable Denim Finishing Approach

Shah Md. Maruf Hasan, Md. Nahid-Ull-Islam, Md. Kamrul Hassan Chowdhury, Mahmuda Akter, Md Shahidul Islam Sakib

How to cite: Hasan SMM, Islam MNU, Chowdhury MKH, Akter M, Sakib MSI. Core 2.0 Nebulization Technique - A Sustainable Denim Finishing Approach. Textile & Leather Review. 2024; 7:582-596. https://doi.org/10.31881/TLR.2024.053

How to link: https://doi.org/10.31881/TLR.2024.053

Published: 11 April 2024

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License

Core 2.0 Nebulization Technique - A Sustainable Denim Finishing Approach

Shah Md. Maruf HASAN, Md. Nahid-Ull-ISLAM, Md. Kamrul Hassan CHOWDHURY, Mahmuda AKTER*, Md Shahidul Islam SAKIB

Department of Apparel Engineering, Bangladesh University of Textiles, Tejgaon, Dhaka-1208, Bangladesh

*mahmuda.akter.mitu88@gmail.com

Article

https://doi.org/10.31881/TLR.2024.053

Received 5 March 2024; Accepted 08 April 2024; Published 11 April 2024

ABSTRACT

Sustainability has emerged as a key concept in the modern techniques of washing and treating denim. The clothing industry, specifically the denim washing sector, confronts substantial sustainability issues due to its impact on water pollution and the generation of large quantities of chemical waste. This research aims to investigate the long-term sustainability of the nebulization process in the context of denim finishing. The goal is to assess the dependability of the technology as a feasible option by demonstrating its effectiveness using environmental impact measuring software. The environmental impact assessment assesses the ecological consequences of clothing across four fundamental areas: water usage, chemical utilisation, energy consumption in the production process, and labour implications. The aforementioned methods proved to have low energy and water demands, resulting in less waste and pollution. This study evaluated several aspects of nebulization on denim and concluded that nebulization is a beneficial method for applying eco-friendly finishing.

KEYWORDS

denim, sustainability, nebulization, core machine, environmental impact measuring (EIM) software

INTRODUCTION

The apparel sector has a significant negative impact on the environment, consuming 93 billion cubic metres of water and emitting 3.30 million metric tonnes of CO_2 annually, contributing to 10% of global carbon emissions. In 2018, the fashion industry used 79 billion cubic metres of water and produced 1.72 million metric tonnes of CO_2. Additionally, textile dyeing and washing generate 20% of wastewater, with 87% of clothing fibres ending up burned or in landfills. Only 20% of clothes are recycled or reused [1]. Bangladesh's textile sector is a key contributor to export revenue, with the washing business generating significant industrial waste [2]. Denim's popularity has surged due to its comfort, aged look, and customisation options. Technological advancements in spinning, washing, and finishing techniques have further boosted denim's recognition in the fashion industry. Effluent from textile mills, including denim garment washing plants, contains high levels of water quality metrics like TSS, DO, BOD, COD, TDS, and pH, along with a mix of organic and inorganic substances beyond normal levels [3,4]. Mixing the effluent with freshwater can increase toxicity levels, posing a risk of skin problems like dermatitis, liver damage, and kidney cancer [5,6].

A study compared the effectiveness of Care Applications S.L.U.'s Eco finish system for denim fabrics to traditional methods. Researchers used a UV-visible spectrophotometer to analyse colour differences and examined CIELAB values to assess the quality of the final product [7]. A study used ozone treatment on denim fabric samples to enhance the effects of washing conditions on their physical and visual properties. Treated and untreated denim fabrics were tested for spectroscopic properties, shrinkage, force at break, rubbing fastness, and Fourier transform infrared analysis [8]. A study was conducted to create water-repellent cotton fabrics using a short-chain fluoropolymer and the e-flow technique, which includes nanobubbles and exhaustion technologies. The study evaluated the durability, air permeability, mechanical characteristics, and wettability of the treated fabrics. Cotton samples were analyzed using ATR-FTIR and SEM techniques to detect changes in morphology and chemical composition. The results showed that cotton treated with nanobubble technology and short-chain fluoropolymers displayed outstanding water repellency [9]. Another method involved the utilization of model microassays to evaluate the denim-washing effectiveness and indigo back staining caused by *Trichoderma reesei* and *Chrysosporium lucknowense* commercial cellulase preparations on a small scale resembling test tubes [10]. Researchers used a bio-treatment approach with enzymes like amylase, cellulase, and laccase on denim clothes to achieve bio-desizing and bio-washing in one step, making the garments look old. The method was tested and evaluated, measuring the colour changes, whiteness degree, and surface morphology of denim samples. The results showed that a combination of these enzymes effectively treated the bio-desizing and enzymatic bio-washing processes [11]. Researchers used CO2 lasers to fade denim colors, treating denim fabrics made with traditional ring-spun yarn and torque-free ring-spun yarn. The denim fabrics were created using commercially available torque-free ring-spun cotton yarn [12]. A study introduced a sustainable finishing method for stretch denim using low-pick-up foam coating technology, eliminating formaldehyde. By optimizing thickening and foaming components, the stability of the finish was enhanced. The fabric's performance was assessed through tests on crease recovery, rubbing fastness, colour retention, tear strength, stretch and elongation, stiffness, air permeability, and antimicrobial properties [13]. Researchers have developed a new method using nanobubble technology to dye cotton fabric with an exceptionally low liquid ratio of 1:1, addressing issues like uneven dyeing and poor fastness. This eco-friendly approach allows for dyeing cotton in eleven different reactive hues and has shown improved fabric dyeing performance parameters compared to conventional methods with higher liquid ratios [14]. Research focused on sustainability in denim washing processes and digitally printed denim. Various advanced techniques were used, such as enzymatic bleaching, ozone washing, and laser fading. Sustainability was assessed using Environmental Impact Measuring (EIM) and Environmental Score (eScore) software [15].

The growing concept of "sustainable apparel washing" seeks to reduce the environmental impact of the garment-washing process. Sustainable apparel washing methods include reducing waste, using ecologically friendly chemicals and detergents, and conserving electricity and water. Nebulization is a novel concept in the field of sustainable clothing washing. This procedure involves nebulizing chemical liquors to generate a mist that surrounds the garment or fabric (Figure 1). As a result, the particles gradually enter the fibres of the support fabric, adhering and depositing the required amount of chemicals in a controlled manner, depending on the structure and weft of the garment.

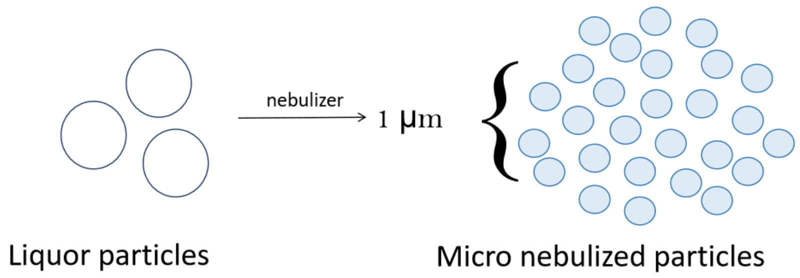

Figure 1. Schematic diagram of the nebulization process

Tonello, an Italian company, has integrated Core technology into their garment finishing process to achieve consistent or contrasting results using less water and low liquor ratios. This technology can be easily incorporated into various Tonello washing and dyeing machines without disrupting production cycles. Core 2.0 is a fully automated system controlled by the machine, capable of creating fine mist in the drum to produce consistent or contrasting effects on clothing. This process is efficient, requires no specific preparations, and allows for precise replication of effects on each garment [16]. The input describes the features and benefits of Core 2.0, a garment treatment technology that offers unique effects on garments while ensuring reproducibility through Tonello software. Core 2.0 reduces water usage, optimises the application of various goods, and decreases energy expenses. It allows for the nebulization of items on two workstations simultaneously, enhances consistency between sampling and production, and offers compatibility with a wide range of garment products. Additionally, Core 2.0 includes features like novel nozzles, software management for work cycles, and the ability to be used for both sampling and production purposes. The EIM (Environmental Impact Measuring) Software V2.0 (Figure 2) was utilised to do a systematic evaluation of several sustainable strategies. The tool evaluates garment washing operations' effects on worker health, chemicals, water and energy use, and energy consumption, aiming to improve environmental performance in jeans finishing. The EIM tenets include:

i. Universal

ii. Simple

iii. Clear

iv. Economically Viable

v. Aligned with industry evolution

vi. Aligned with industry sustainable criteria

EIM assesses environmental impacts using four criteria: labour implications, chemical consequences, water and energy demands, and additional variables. The software involves three steps: quantification for each category, establishing standards, and categorising processes with assigned scores. EIM helps apparel industry players adhere to standards, set goals, and reduce environmental consequences [17, 18].

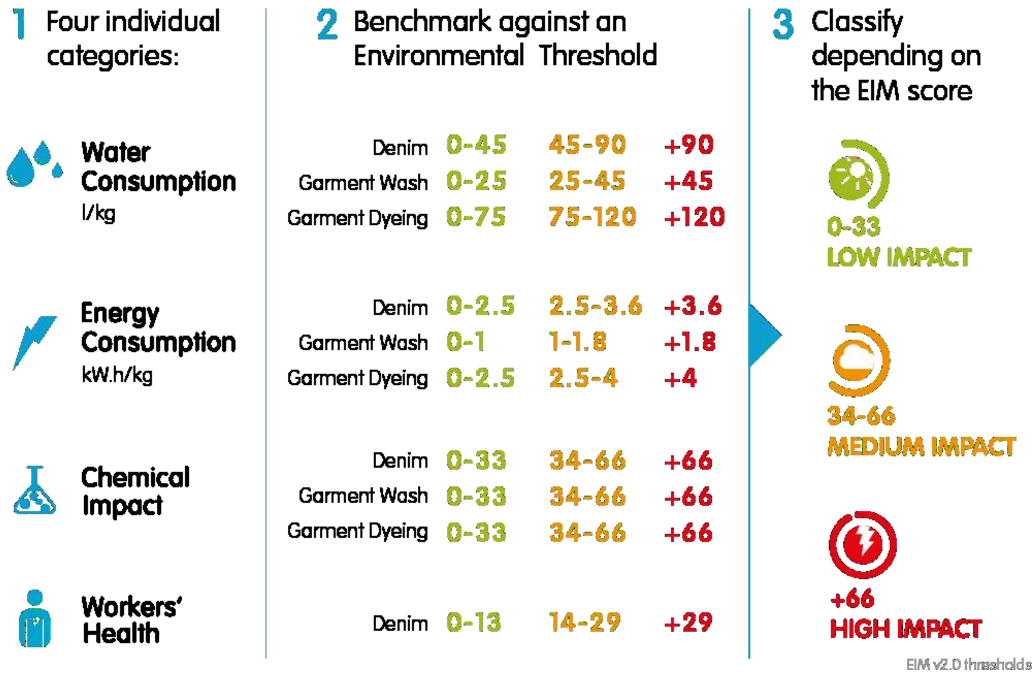

Figure 2. EIM (Environmental Impact Measuring) Software V2.0

EXPERIMENTAL

Materials and Methods

The denim fabric is collected from a renowned denim industry in Bangladesh. Table 1 demonstrates the specification of materials and methods used for our experiment.

Table 1. Materials and methods with specification

SL.	Materials and Methods	Specification
1	Fabric structure	3/1 warp-faced twill
2	Average weight	0.40 kg
3	Washing technique	Wet processes and dry processes
4	Primary operation	Nebulization

The denim wash with nebulization involves a combination of dry and wet processes, often performed manually and using front-loading washing machines, respectively. The process was conducted using an industrial washing machine paired with an additional core machine (Figure 3).

Figure 3. Industrial washing machine with an additional core machine

Process of denim finish

The nebulized system, developed by CORE 2.0 technology, is a novel and sustainable approach for denim. It utilizes eco-efficient technology to achieve its objectives. Figure 4 indicates the operations flow chart of denim considering nebulization. Before nebulization, many operations are commenced such as bleaching, whiskering, scrapping, stone-enzyme etc. After nebulization, potassium permanganate (PP) and chlorine neutralization are carried out with additional operations consisting of grinding, tinting, and softening.

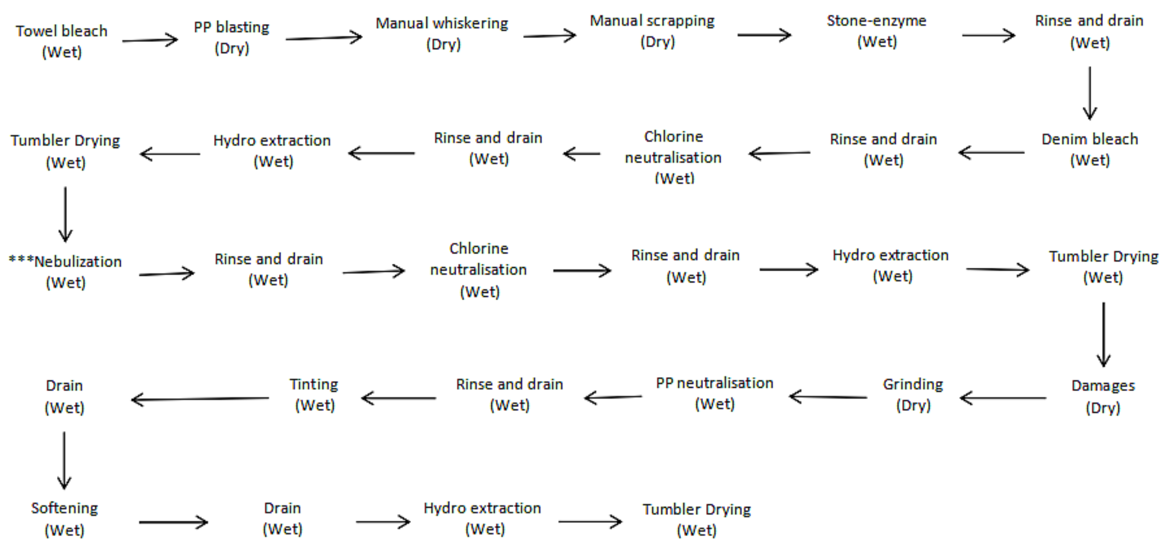

Figure 4. Operations flow chart of denim considering nebulization

To begin, towel bleach was applied in the washing machine with a towel to achieve cloudy or random effects on denim clothing using sodium hypochlorite (2 g/L) in LR 1:5 for 15 minutes at 25 °C. Then PP blasting was done in the spray cabin for 45 seconds with acetic acid (2 g/L) and potassium permanganate (5 g/L). Subsequently, manual whiskering, and scraping were performed on the scraping table, with each process requiring 2 minutes. Following the manual process, the stone-enzyme process was carried out in the washing machine in the presence of a dispersion agent, cellulase enzyme (3% owg), and pumice stones (0.8 kg/kg) with LR 1:5, temperature 60 °C, and time 30 minutes. Then rinsing and draining followed. Later, denim bleaching was carried out with sodium hypochlorite (3 g/L) with LR 1:5 for 3 minutes at 50 °C. Again, followed by rinsing and draining. Following that, neutralization was done with sodium metabisulfite (2 g/L) for 5 minutes at 50 °C with LR 1:5. After rinsing and draining, hydro-extraction was done for 2 minutes. Then drying of the samples was carried out in a tumble dryer machine for 30 minutes at 80 °C. Then, the nebulization process was carried out with potassium permanganate ($KMNO_4$) (5 g/L) for 25 minutes at 25 °C in LR 1:2, followed by rinsing and draining for 2 minutes. Neutralization was carried out with sodium thiosulfate (2 g/L) at a temperature of 50 °C for 5 minutes. Then rinsing and draining were done. The hydro-extraction and tumble-drying processes were then carried out using the same settings as before. Afterwards, two additional procedures were conducted using the grinding apparatus: one involved subjecting the material to a damaging action for 80 seconds, while the other entailed grinding for 1 minute. After the dry processes, the PP neutralisation was carried out using sodium metabisulfite (2 g/L) for 5 minutes at a temperature of 50 °C. Next, rinsing and draining were performed. Then tinting was accomplished in the washing machine with direct dyes (0.3% owg) at 60 °C for 2 minutes in LR 1:5, followed by draining. Following the aforementioned procedures, the softening process was carried out using a cationic softener (3 g/L) for an average of 3 minutes at a temperature of 25 °C, after which the liquid was drained. Ultimately, the process of hydro-extraction was completed within 4 minutes. The samples were dried in a tumble dryer at 80 °C for 30 minutes.

EIM (Environmental Impact Measuring) Software

The EIM V2.0 software was used to conduct a comparison analysis of nebulization procedures to determine their sustainability. Table 2 depicts the EIM software results presentation. The name of the process, the time, and the EIM score are all displayed here. Low impact, medium impact, and high impact are the three levels that make up the EIM score, which can take on values between 0 and 33, 33 and 66, and +66, respectively. The EIM score breaks down the effects on water, energy, chemicals, and workers into their distinct categories. The results of each category are compared to an environmental criterion that has been pre-set by the software. It sorts the procedure's total impact from low to high after classifying each category independently. The results are presented in an easy-to-understand format utilizing colour coding.

Table 2. EIM (Environmental Impact Measuring) software result display

EIM (Environmental Impact Measuring)					
Process name: Conventional denim wash				Threshold: EIM V2.0 – ABC	
EIM Score		Water	Energy	Chemical Impact	Worker Impact
74		84.00	2.54	100	100
Low impact	0-33	0-45	0-2.5	0-33	0-13
Medium impact	33-66	45-90	2.5-3.6	33-66	13-29
High impact	+66	+90	+3.6	+66	+29

Test Methods

Testing is carried out to guarantee that the items fulfil the desired quality standards. It helps companies detect and resolve any problems or concerns in the manufacturing process, ensuring that they are addressed before the product is delivered to the market. Table 3 displays the various tests and the corresponding standard methodology employed in this research study to quantify those qualities. All of these tests were conducted at the in-house laboratory of the renowned denim industry in Bangladesh. The pH was determined via the standardised ISO 3071:2020 protocol. The colour fastness against rubbing, washing, and water was assessed using ISO 105-X12:2016, ISO 105-C06:2010, and ISO 105-E01:2013. The tear force measurements were conducted according to the IS0 13937-1:2000 standard. The study experiments were carried out entirely on the machines specified in the table.

Table 3. Test Methods

Test Name	Standard
pH	ISO 3071:2020
GSM	ISO 105-X12:2016
Colour fastness to rubbing	ISO 105-C06:2010
Colour fastness to washing	ISO 105-E01:2013
Colour fastness to water	ISO 13937-1:2000
Tear force	ISO 105-X12:2016

RESULTS AND DISCUSSION

Core 2.0 greatly reduces water consumption and enables the optimal application of diverse items, optimising their consumption and making a significant contribution to reducing energy costs [19]. Table 4 summarises the insight of nebulization technology in terms of water and energy consumption with the Core machine. According to the table, the nebulization process uses 30.19 litres less water, and each garment needs 2.01 litres of water for renewal. It can be observed that in terms of water saving, nebulization is very effective (90.01%). It also signifies that each garment preserves 0.12 kilowatt-hours (kWh) of energy and that 0.175 kWh of energy may be renewed for each garment.

Table 4. Insight of nebulization technology in terms of water and energy consumption

Parameters	Conventional (without nebulization)	With nebulization	Renewability in nebulization
Water (litre/garment)	33.54	3.35	2.01
Energy (kwh/garment)	1.29	1.17	0.175

Figure 5 illustrates the successive renewability of nebulization on denim. Each garment requires 3.35 litres of water for nebulization on denim. Out of this, 2.01 litres (60% of the total water required) are renewable, whereas 1.34 litres (40% of the total water used) are non-renewable. These parameters determine the sustainability of nebulization in denim finishing. On the other hand, the nebulization process requires 1.17 kilowatt-hours (kWh) of energy per garment. Out of this, 0.175 kWh (15%) is renewable energy, while 0.995 kWh (85%) is non-renewable energy.

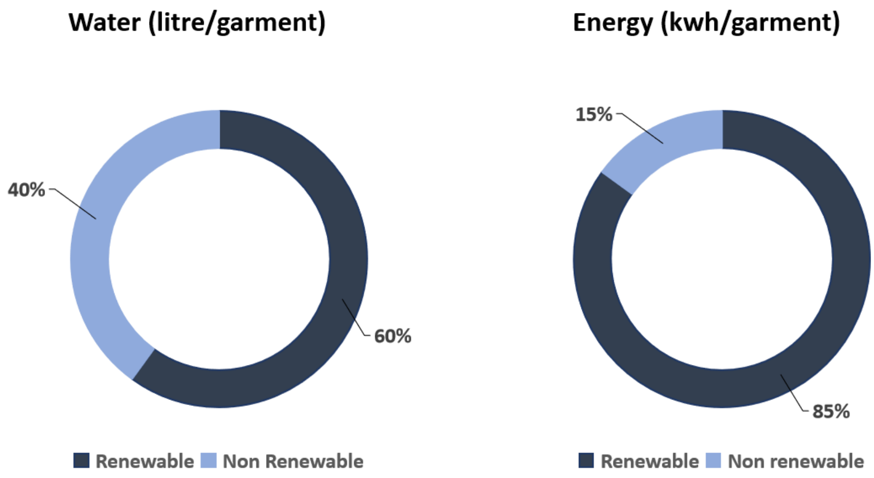

Figure 5. Renewability of Nebulization

Table 5 shows the EIM score for water, energy, and chemical nebulization technology. It is feasible to make sustainability measurable throughout the production process by using the EIM score. It can be seen that nebulization technology has a minimal environmental effect in terms of water and energy use. The impact factor of water is 33, which aligns with the low-impact EIM score range of 0-45. The EIM score for energy is 2.12, which falls within the lower range of 0-2.5. Both of these EIM grades signify the long-term viability of nebulization. Nevertheless, the significant chemical effect score of 85 gives rise to concern.

Table 5. EIM score for water, energy and chemical used and standard parameter

Category	EIM Score	Standard	Parameter (EIM Score)		
			Water	Energy	Chemical
Water	33	Low impact	0-45	0-2.5	0-33
Energy	2.12	Medium impact	45-90	2.5-3.5	34-66
Chemical	85	High impact	+90	+3.6	+66

Comparison of Product Quality

Product quality refers to how well a product aligns with consumer expectations, fulfils its intended function, and complies with industry standards. This study examines how different washing methods affect product quality, including consumer preferences. Figure 6 shows samples before and after nebulization, together with the statistical significance of the changes in perspective and appearance. Figure 6(a) depicts the denim sample before nebulization, while Figure 6(b) illustrates the nebulized denim sample, showing a notable modification in the sample's perspective. Generating a fine mist in the drum consistently has either similar or different effects on the denim fabric.

(a)

(b)

Figure 6. Before the nebulized sample and after the nebulized sample: (a) Before the nebulized sample, (b) After the nebulized sample

Table 6 shows the dimensional stability of the nebulized material over numerous care cycles. Following each care cycle, the product experiences considerable dimensional reduction, which has no impact on the product's lifespan. The test for dimensional stability is conducted by following the ISO 6330:2021 standard. Before nebulization, the original dimension of the front length of the right leg was 91 cm, and after 1, 3, and 5 cycles, it decreased to 89.4 cm, 89 cm, and 88.7 cm. For the front length of the left leg, it decreases from 90.3 cm to 88.7 cm, 88.5 cm, and 88.3 cm after the subsequent 1, 3, and 5 care cycles. In the case of the back length of the right leg, it decreases from 96 cm to 94.7 cm, 94.3 cm, and 94 cm with the same care cycle. The same issues occurred for the front ½ waist, front ½ hip, and front ½ leg. For example, the front hip drops from 49.5 cm to 48.5 cm, 48.3 cm, and 48.1 cm following the same 1, 3, and 5 care cycles, a very modest change that does not affect the dimension.

Table 6. Dimensional stability of nebulized denim after 1, 3 and 5 care cycle

SL No	Original (cm)	After 1 wash, Dry & Iron (cm)	After 3 washes, Dry & Iron (cm)	After 5 wash, Dry & Iron (cm)
L1- Front length of the right leg	91.0	89.4	89.0	88.7
L2- Front length of the left leg	90.3	88.7	88.5	88.3
L3- Back length of the right leg	96.0	94.7	94.3	94.0
W1- On front ½ waist	40.0	39.5	39.3	39.0
W2- On front ½ hip	49.5	48.5	48.3	48.1
W3- On front ½ leg	25.5	25.0	24.9	24.8

Figure 7 illustrates the dimensional change of nebulized denim after multiple care cycles. The required limit of dimensional change (decrease) is 3%. It can be seen that the percentage of dimensional decrease does not exceed the limit, so the test is passed.

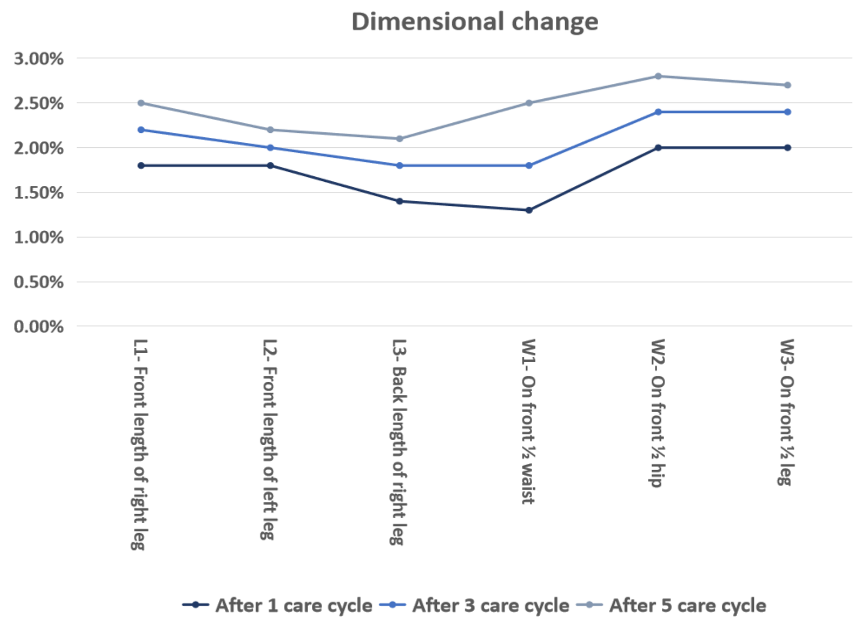

Figure 7. Dimensional change of nebulized denim aftercare cycle

Table 7 shows the product quality parameters of denim after nebulization through various tests. The results demonstrate that the goods exhibited favourable durability characteristics after nebulization, with all test parameters falling within the acceptable ranges. Although a variety of chemicals and neutralising agents were employed in this wash, the pH level was determined to be 5.8, which falls within the permissible range. The results suggest that the nebulized items had a decreased GSM of 390 compared to the standard value, mostly due to fading. However, there is no notable alteration in their overall properties. The denim fabric's grade 4 rating signifies its higher resistance to colour fading when subjected to rubbing, washing, and water. This implies a stronger ability to retain its colour. The value in the table falls within the expected range, indicating improved performance.

Table 7. Product quality parameters of denim after nebulization

Tests	Standard	After nebulization
pH	4.0-7.5	5.8
GSM	415 gsm	390 gsm
Colour fastness to rubbing	3-4	4
Colour fastness to washing	3-4	4
Colour fastness to water	3-4	4

Table 8 illustrates the tear force performance of denim after nebulization. Six nebulized, same denim samples are taken to test the tear force. The table presents the results, revealing that the nebulized denim exhibits warp and weft-way tear force values [20] that stay above the minimum standard values of 43 N and 32 N, respectively, demonstrating superior performance. For example, in the case of sample 4, the value of the tear force of nebulized denim in both the warp and weft directions is 32.0 N and 25.7 N, within the minimum standard for the ability to resist failure perpendicular to the stress being applied. For samples 1, 2, 3, 5, and 6, the same things happened, and the value of tear force for both warp and weft way is within the minimal standard and shows better performance.

Table 8. Tear force performance of denim after nebulization

	Standard	Tear force(N)					
		Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
Warp way	Min. 30 N	33.4 N	43.0 N	31.1 N	32.0 N	37.1 N	34.4 N
Weft way	Min. 24 N	26.1 N	32.0 N	24.1 N	25.7 N	26.8 N	26.4 N

CONCLUSION

The study found that nebulization technology-based denim finishing is an eco-friendly and sustainable technique due to its high energy and water efficiency. The testing parameters showed that nebulization is sustainable in terms of water and energy consumption, with 90.01% and 9.30% efficiency with renewable usage of water and energy (60% and 15%, respectively). This technology has no environmental impact on water and energy use, making it a cost-effective and efficient option for denim finishing. Dimensional stability following nebulization is considered acceptable if there is an acceptable reduction in both length and width, as long as the decline does not go beyond the specified limit. The desired outcome is achieved in terms of appearance after undergoing five care cycles, which include changes in colour, colour staining, pilling, wash creases, fraying of fabrics and trimmings, etc. The product has completed all assessments. The testing parameters, including pH, GSM, and colour fastness against rubbing, washing, water, and tear force after nebulization, demonstrate superior performance. The impact factor of water is 33, which aligns with the low-impact EIM score range of 0-45. The EIM score for energy is 2.12, which falls within the lower range of 0-2.5. The EIM score of the chemical is high (85) due to the utilisation of potassium permanganate, a hazardous substance, regardless of its limited usage. This study did not undertake a thorough investigation into the chemical impacts on nebulized finishing. Further research is required in the selected field of study.

Author Contributions

Conceptualization – Hasan SMM, Islam MNU and Akter M; methodology – Hasan SMM and Islam MNU; formal analysis – Chowdhury MKH and SAKIB MSI; investigation – Hasan SMM; resources – Sakib MSI; writing-original draft preparation – Hasan SMM, Islam MNU and Chowdhury MKH; writing-review and editing – Chowdhury MKH and Akter M; visualization – Hasan SMM; supervision – Akter M. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Funding

The authors did not receive any funding for this study.

Human research subjects

The research was conducted in accordance with relevant guidelines and regulations for experiments involving humans or affirmation that informed consent was obtained from all human research subjects.

REFERENCES

[1] Niinimäki K, Peters G, Dahlbo H, Perry P, Rissanen T, Gwilt A. The environmental price of fast fashion. Nature Reviews Earth & Environment. 2020; 1(4):189-200. https://doi.org/10.1038/s43017-020-0039-9

[2] Muthukumarana TT, Karunathilake HP, Punchihewa HKG, Manthilake MMID, Hewage KN. Life cycle environmental impacts of the apparel industry in Sri Lanka: Analysis of the energy sources. Journal of Cleaner Production. 2018; 172:1346-1357. https://doi.org/10.1016/j.jclepro.2017.10.261

[3] Kabir SMF, Chakraborty S, Hoque SMA, Mathur K. Sustainability assessment of cotton-based textile wet processing. Clean Technologies. 2019; 1(1):232-246. https://doi.org/10.3390/cleantechnol1010016

[4] Haque N. Mapping prospects and challenges of managing sludge from effluent treatment in Bangladesh. Journal of Cleaner Production. 2020; 259:120898. https://doi.org/10.1016/j.jclepro.2020.120898

[5] Dadi D, Stellmacher T, Senbeta F, Van Passel S, Azadi H. Environmental and health impacts of effluents from textile industries in Ethiopia: the case of Gelan and Dukem, Oromia Regional State. Environmental Monitoring Assessment. 2016; 189:11. https://doi.org/10.1007/s10661-016-5694-4

[6] Kumar PS, Gunasundari E. Sustainable Wet Processing—An Alternative Source for Detoxifying Supply Chain in Textiles. In: Muthu SS, editor. Detox Fashion. Singapore: Springer; 2018. https://doi.org/10.1007/978-981-10-4876-0_2

[7] Bou-Belda E, Montava I, Díaz-García P, Hinojosa B, Bonet-Aracil MÁ. Study of the "Ecofinish" finishing system to obtain a worn-effect denim. Revista Cintex. 2017; 22(2):11-22. https://doi.org/10.33131/24222208.293

[8] Ben Fraj A, Jaouachi B. Effects of ozone treatment on denim garment properties. Coloration Technology. 2021; 137(6):678-688. https://doi.org/10.1111/cote.12568

[9] Zouari A, Manich A, Marti M, Gargoubi S, Boudokhane C. Nanobubble Technology for A Water-Repellent Treatment on Cotton Fabrics: A Comparative Study. ChemEngineering. 2023; 7(3):47. https://doi.org/10.3390/chemengineering7030047

[10] Sinitsyn AP, Gusakov AV, Grishutin SG, Sinitsyna OA, Ankudimova NV. Application of microassays for investigation of cellulase abrasive activity and backstaining. Journal of Biotechnology. 2001; 89(2-3):233-238. https://doi.org/10.1016/S0168-1656(01)00306-6

[11] Maryan AS, Montazer M. A cleaner production of denim garment using one step treatment with amylase/cellulase/laccase. Journal of Cleaner Production. 2013; 57:320-326. https://doi.org/10.1016/j.jclepro.2013.05.041

[12] Kan C. CO2 laser treatment as a clean process for treating denim fabric. Journal of Cleaner Production. 2014; 66:624-631. https://doi.org/10.1016/j.jclepro.2013.11.054

[13] Sarwar N, Mohsin M, Bhatti AA, Ahmmad SW, Husaain A. Development of water and energy efficient environment friendly easy care finishing by foam coating on stretch denim fabric. Journal of Cleaner Production. 2017; 154:159-166. http://dx.doi.org/10.1016/j.jclepro.2017.03.171

[14] Mohsin M, Sardar S, Hassan M, Akhtar N, Hassan A, Sufyan M. Novel, sustainable and water efficient nano bubble dyeing of cotton fabric. Cellulose. 2020; 27:6055-6064. https://doi.org/10.1007/s10570-020-03187-6

[15] Khan MKR, Jintun S. Sustainability Issues of Various Denim Washing Methods. Textile & Leather Review. 2021; 4(2):96-110. https://doi.org/10.31881/TLR.2021.01

[16] Tonello. CORE 2.0 Garment Finishing with Special Effects 2024. Available from: https://tonello.com/en/component/core/

[17] Jeanologia. Water is over: Air is the future: Jeanologia; 2023. Available from: https://www.jeanologia.com/eflow-k-lab/

[18] Jeanologia. Improve Your Ecological Footprint: Jeanologia; 2023. Available from: https://www.jeanologia.com/eim/

[19] Textile Technology. New generation of washing and dyeing machines; 2022. Available from: https://www.textiletechnology.net/technology/news/tonello-new-generation-of-washing-and-dyeing-machines-32660

[20] Telli A, Babaarslan O. The effect of recycled fibers on the washing performance of denim fabrics. The Journal of The Textile Institute. 2017; 108(5):812-820. https://doi.org/10.1080/00405000.2016.1192236