UNMASKING THE POWER OF METAL OXIDE NANOPARTICLES FOR SELF-CLEANING HEAVY DENIM: INVESTIGATING AND OPTIMIZING PROCESS PARAMETERS

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The textile industry is consistently integrating cutting-edge technologies, introducing materials with multifaceted features, such as odour resistance, hydrophobicity, durability, and self-cleaning capabilities. This transformation is facilitated by the application of nanotechnology. The focal point of this experimental endeavour lies in closing the gap in employing ZnO nanoparticles on high GSM denim fabric, enhancing self-cleaning, UV protection, and antimicrobial capabilities. Initially, a solution containing nanoparticles, binder, softener, ethanol, and their auxiliaries was formulated. Zinc oxide nanoparticles, along with their auxiliaries, were applied to the denim using the pad-dry-cure and pad-dry-steam methods. Various trials were conducted to optimize the concentration of ZnO NPs, with the formulation containing 5% ZnO NPs, 5% binder, and 25% ethanol. Experimentation ensued to establish optimal time–temperature profiles for drying, curing, and steaming. Comprehensive evaluations, including drop tests, stain tests, colour strength assessments, crocking tests, SEM analysis, antimicrobial testing and UV protection factor determination were conducted on the samples. The study revealed that fixation of the self-cleaning finish by curing gives better results than by steaming. SEM examination highlighted the distribution of ZnO nanoparticles on the denim fabric. Lastly, antimicrobial properties were assessed, concluding that treated fabrics exhibited antibacterial activity compared to untreated fabrics.

Keywords: denim fabric, self-cleaning, metal oxide, nanoparticles, curing, steaming

INTRODUCTION

The textile industry is currently advancing in the development of self-cleaning materials through a variety of methods. Researchers have applied various chemical treatments and utilized nanotechnology to produce fabrics with self-cleaning properties. Multiple techniques are employed in achieving self-cleaning materials, with nanotechnology playing a crucial role in creating fabrics that not only repel external dirt, but also resist bacterial contamination, keeping the textile material clean. Continuous advancements in technologies for self-cleaning clothing and fabrics can contribute to cost reduction and enhance the longevity of the utilized nanoparticles. Self-cleaning textiles and garments can maintain their original look and feel, eliminating the need for frequent washing. This not only preserves the cleanliness of the clothes, but also results in significant utility savings by reducing the frequency of laundering.[1,2,3]

A single pair of denim jeans necessitates 7,100 glasses of water for washing, rendering them among the most water-intensive clothing items. The introduction of self-cleaning and sustainable denim could significantly reduce laundry requirements, potentially conserving up to 3,800 liters of water per wash.[4]

In recent times, nanotechnology has gained increased significance due to the unique characteristics and behavior of nanomaterials. The application of nanotechnology to textiles opens up the possibility of developing products with entirely novel attributes or a blend of multiple functionalities. Through nanotechnology, metals and metal oxides can have distinctive qualities, such as UV protection and antimicrobial properties.[5] Thus, specific finishes are produced for imparting a range of attributes to fabrics, including enhanced fabric durability, water repellency, increased tensile strength, softness, improved surface quality, fire retardancy, UV protection and antimicrobial capabilities. Through the incorporation of nanoparticles, like silver, silica, titanium dioxide, and zinc oxide into fabric treatments, it becomes possible to attain enduring water, oil, and stain repellency.[2] By employing nanotechnology and essential surface finishing, coating, or modification procedures, a fabric's surface characteristics can experience varied alterations and improvements. The consistent emphasis on incorporating nanoparticles remains pivotal in crafting fabrics resistant to water or stains.[6]

Zinc oxide nanoparticles stand out as highly versatile materials among various metallic nanoparticles, owing to their diverse capabilities, characteristics, and applications. ZnO nanoparticles can exhibit significant antibacterial capabilities at low concentrations, targeted against specific bacteria and fungi. The antibacterial activity arises from the interaction of ZnO nanoparticles with bacterial cell surfaces, inducing oxidative stress that results in cell membrane breakdown and eventual cell death. As the concentration of particles per unit area rises, the antibacterial efficacy also increases.[7] Additionally, these nanoparticles exhibit exceptional physical and optical properties.[10]

Utilizing materials possessing photocatalytic properties allows for the coating of nanoparticles. Nanoparticles, either individually or in combination, are employed to confer self-cleaning and antibacterial attributes. Subsequently, a slim layer of these nanoparticles, formulated with binders, softeners, and other additives, is applied to the fabric. When the textile material's surface is exposed to sunlight, impurities such as dirt, pollutants, and microbes undergo transformation into carbon dioxide and oxygen. This process effectively purifies the surface, eliminating all stains and contaminants.[8]

The self-cleaning properties of denim fabric were evaluated by the application of zinc oxide nanoparticles (ZnO NPs), which were synthesized naturally. XRD and SEM analyses were used to confirm green synthesis of ZnO NPs and their homogeneous deposition on the denim fabric. The study reported that 5% ZnO NPs with 7% binder concentrations resulted in an even and smooth layer on the denim fabric, providing good stain removal grading (Grade 4) against ketchup, coffee, grape and orange juice, with insignificant changes in tensile strength.[9] Also, apart from repelling water, ZnO can cause chemical decomposition of dirt when exposed to sunlight. When the surface of a photocatalyst is illuminated, an electron in the valence band becomes excited, generating a positive hole that oxidizes the dirt. Concurrently, an electron in the conduction band reduces the oxygen absorbed by the photocatalyst (ZnO) during this process. The addition of zinc oxide nanoparticles imparts UV absorption properties to the material. This enhancement significantly augments the material's natural UV-absorbing capacity, providing effective protection against solar radiation. With the ability to absorb UV radiation within the range of 300 to 400 nm, zinc oxide nanoparticles serve as excellent shields for textile materials, acting as a protective barrier for the body against harmful rays.[11] Other treatment approaches for textiles involved silica and titanium dioxide nanoparticles, providing fabrics with air permeability, strength, low water absorption rate, improved heat resistance, and self-cleaning capabilities. These essential qualities enable the fabric to be adaptable in various climatic conditions.[13]

A novel approach for discoloration of denim via H_2O_2 treatment, followed by UV irradiation, has been demonstrated by Ebrahimi and his group.[12] Indigo dyed denim was exposed to a combined procedure of H_2O_2 and UV irradiation treatment at different duration. UV–vis spectroscopy results exhibited that UV irradiation led to a decrease in the intensity of the bands of indigo dye, and the decrease was in direct relation to the duration of exposition. They have proposed a mechanism for indigo dye degradation based on the generation of •OH and •OOH radicals. Several changes in the FTIR spectra of H_2O_2/UV treated denim were observed, which confirmed the successful aged-look finishing. Furthermore, they claimed that the discoloration process has no yellowing effect on the color shade of denim.[12]

In line with the literature review, in this investigation, zinc oxide nanoparticles were used to develop a finish formulation to impart multi-functional properties to heavy denim fabric. The zinc oxide formulation was applied to the heavy denim fabric by two methods: the pad-dry-cure and pad-dry-steam procedures, under varying process conditions. The surface morphology after finishing of heavy denim fabric was evaluated using scanning electron microscopy (SEM). The treated samples were then evaluated for stain release, color strength, yellowness index, hydrophobicity, crocking fastness, antibacterial activity and ultraviolet protection by standard testing procedures and comparative analyses were conducted.

EXPERIMENTAL

Fabric

Two differently shaded heavy denim fabrics, light and dark blue, were provided by Soorty Enterprises. Samples are shown in Figure 1 (a and b, respectively). The structure of both denim fabrics was 3/1 right hand twill. The gram square meter (GSM) weight of the light blue fabric was 329, and that of the dark blue one was 298. In addition, both fabrics were dyed using indigo dye.

Chemicals

Zinc oxide nanoparticles, of 30-80 nm particle size, with purity 99%, were purchased from Sensor Lab Pakistan, and used as self-cleaning agent in the treatment of fabrics. Ethanol was used to disperse zinc oxide nanoparticles (NPs) in the solution, dispersing agent (PEG 400) – for enhancing the dissolution and dispersion of zinc oxide nanoparticles, Perapret – an acrylic binder – was used to bind the nanoparticles to the fabric and Solu-Soft softener – to maintain the required handle of the fabric. The pH of the solution was maintained alkaline using sodium hydroxide. All these auxiliaries were supplied by Archroma Pakitsan to be used in the self-cleaning formulation.

Application procedures

Denim fabrics were treated with zinc oxide nanoparticles using the pad-dry-cure and pad-dry-steam process. 100 mL of solution was prepared using 5% zinc oxide, 5% acrylic binder, 2 g/L softener, 25% ethanol and 1 mL of dispersing agent (PEG-400). The pH of the solution was maintained at 9-10 by adding NaOH. In preliminary tests, the zinc oxide nanoparticles tended to agglomerate when prepared in acidic and neutral conditions (pH 6 and 7). Meanwhile, fine solutions were obtained when the pH was increased to 9-10. This ensures uniform distribution of the nanoparticles when applied to the fabrics and thus effectiveness in stain removal.

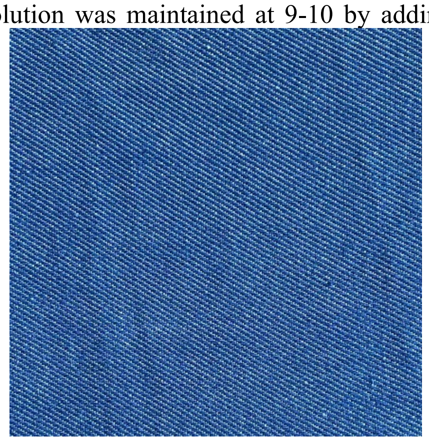
The solution was stirred using a magnetic stirrer for 40-50 minutes at medium speed, which was then shifted to high speed and additionally stirred at 1000 rpm for 10 minutes. Once the nanoparticles were dissolved, a translucent mixture was obtained, as shown in Figure 2. The denim fabric was padded with the thus-obtained formulation at 1 bar pressure. The padded fabric was then dried, followed by curing or steaming. The time and temperature for drying, curing and steaming were varied, as shown in Table 1.

Experimental runs

Various experimental runs were conducted, varying the process conditions of temperature and time, in order to establish the optimum conditions for imparting self-cleaning properties to denim. The time and temperature of the drying, curing, and steaming stages were chosen as the main variables to determine the greatest outcomes in terms of self-cleaning. The experimental runs were conducted as shown in Table 1. In the table, A, B, C, D represent the cured samples, and E, F, G, H, K – the steamed ones. In the samples codes, number "1" stands for light blue denim, and "2" stands for dark blue denim. The untreated (UT) denim fabrics were coded as UT1 and UT2.

Evaluation of self-clean finished fabric

The performance of self-clean denim fabrics was evaluated using standard test procedures. The finished fabrics were tested for color fastness to rubbing in accordance with AATCC-TM08, and yellowness index – with ASTM E313. Color strength was assessed using a Datacolour Spectroflash 650 spectrophotometer, with a 10° standard observer and D65 illuminant.


a)


b)

Figure 1: Samples of (a) light blue and (b) dark blue denim fabrics

Figure 2: Solution of ZnO NPs and auxiliaries

Table 1
Experimental runs for self-cleaning application

Run	Sample name	Drying temperature (°C)	Drying time (min)	Fixation mode	Fixation temperature (°C)	Fixation time (min)
1	A1	40	9	Curing	150	3
	A2	40	9	Curing	150	3
2	B1	50	8	Curing	140	4
	B2	50	8	Curing	140	4
3	C1	60	6	Curing	130	5
	C2	60	6	Curing	130	5
4	D1	60	5	Curing	160	3
	D2	60	5	Curing	160	3
5	E1	60	6	Steaming	102	6
	E2	60	6	Steaming	102	6
6	F1	60	6	Steaming	102	7
	F2	60	6	Steaming	102	7
7	G1	60	6	Steaming	102	8
	G2	60	6	Steaming	102	8
8	H1	60	6	Steaming	103	8
	H2	60	6	Steaming	103	8
9	K1	60	6	Steaming	103	10
	K2	60	6	Steaming	103	10

The drop test was performed according to AATCC-TM79, and the stain release test – to AATCC-TM130. Scanning electron microscopy (SEM) analysis was performed to examine the morphology of the fabrics surface and confirm the presence of the zinc oxide finish on the fabrics. Antimicrobial testing was carried out according to AATCC-TM147 and ultra-violet protection was assessed by AATCC 183. The tests were carried out in standard environment, as mentioned in the test procedures. In the stain release test, a flat unstained specimen was placed on a single thickness of AATCC white textile blotting paper, on a smooth, horizontal surface. Using a medicine dropper, 3 drops (approx. 0.2 mL) of stain were placed approximately in the center of the test specimen. Glassine paper was placed over the stained area and then 5 lbs weight was applied for 60 ± 5 seconds. After 1 minute, the glassine paper was removed, the specimen was sprayed with water and left in sunlight for 2 hours for photocatalytic degradation.

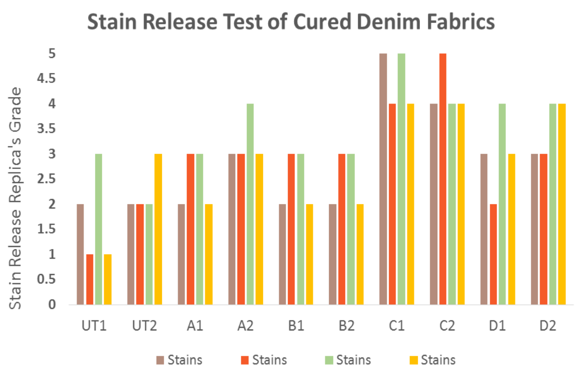
RESULTS AND DISCUSSION

In this study, denim fabrics underwent functionalization with ZnO nanostructures to induce roughness to fibers, imparting physical self-cleaning properties, akin to the lotus effect. The lotus effect, originating from the natural cleaning of lotus leaves under rolling rain droplets, served as inspiration in the development of finishes for obtaining self-cleaning fabrics. In this work, the application of the finish was carried out by two fixation methods: curing and steaming. As discussed below, the analysis of the test results, encompassing stain release, color strength, yellowness index, and hand feel, revealed that cured denim fabrics exhibited more favorable outcomes, compared to steamed fabrics, particularly in terms of hand feel.

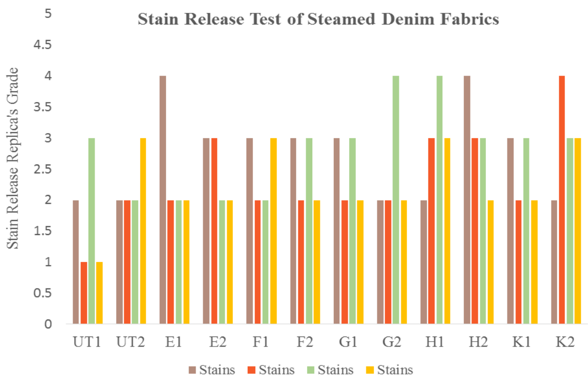
Stain release test

The stain release test assesses the ability of treated fabric to effectively eliminate stains from garments. As established earlier, the stain removal mechanism of ZnO nanoparticles involves adsorption, catalytic activity, and UV light-induced reactive oxygen species (ROS) generation.[14] The ZnO nanoparticles exhibited significant stain release property, which rises with the amount of applied ZnO.[15] In this study, coffee, mud, ketchup, and oil stains were applied to both untreated and treated denim fabrics for 60 seconds, then after spraying with water, the stained fabrics were left for photocatalytic degradation. Standard stain release replicas [AATCC 130] were employed to evaluate the stains immediately after application and again after a 2-hour interval. Typically, a stain release rating better than 3 is considered satisfactory for finished fabric. The stain test results for cured and steamed denim fabrics are presented in Figure 3 (a and b, respectively). Observing Figure 3, it is evident that untreated fabric UT1 exhibits moderate stain release for mud stains, while UT2 demonstrates moderate oil stain release ability. Further analysis of the data reveals that UT2 outperforms UT1 in stain release, possibly due to its higher depth of shade, resulting in less visible stains after a 2-hour interval.

Additionally, Figure 3 (a, b) highlights that the stain release performance of cured fabrics surpasses that of steamed fabrics. This distinction is more pronounced in denim fabrics C1 and C2, compared to G1 and G2. In C1 and C2, the stain release ratings range from 4 to 5, while in G1 and G2, the range is from 2 to 4. This difference may be attributed to the suboptimal interaction between zinc oxide nanoparticles and the fabric. The elevated temperatures and steam might have caused nanoparticle agglomeration or structural alterations, resulting in diminished stain release performance. Figure 3 (c and d) shows the staining results of C1 and C2, immediately after staining and 2 hours later.



a)



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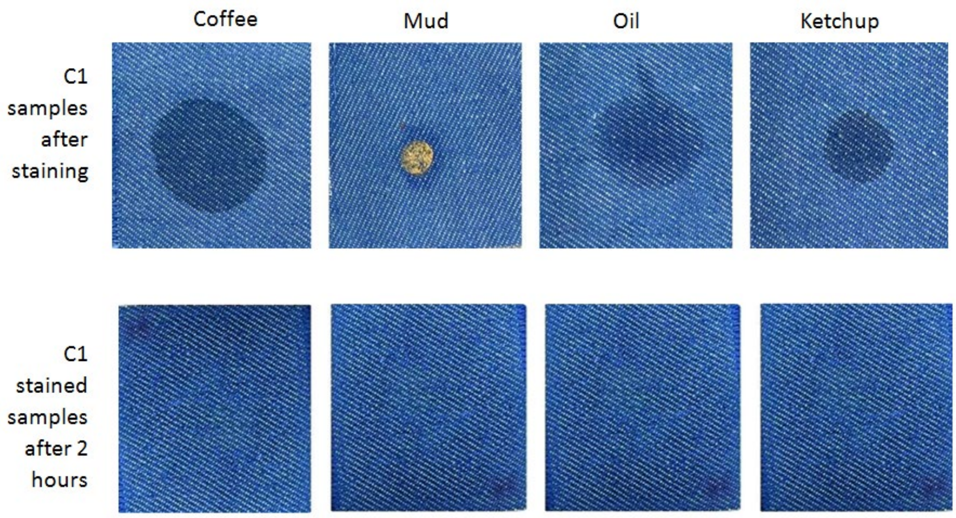
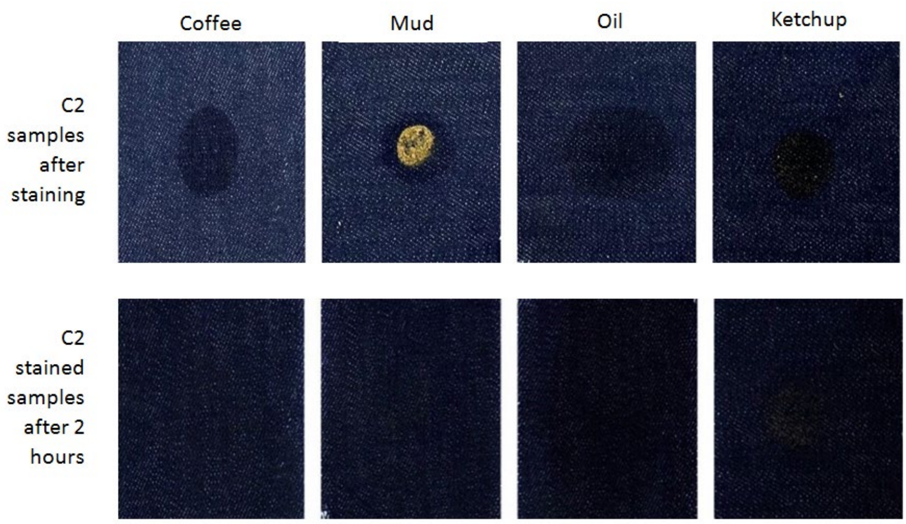


c)



d)

Figure 3: Stain test results of (a) cured denim fabrics and (b) steamed denim fabric after 2 hours; stained samples C1 (c) and C2 (d) immediately after staining and 2 h later

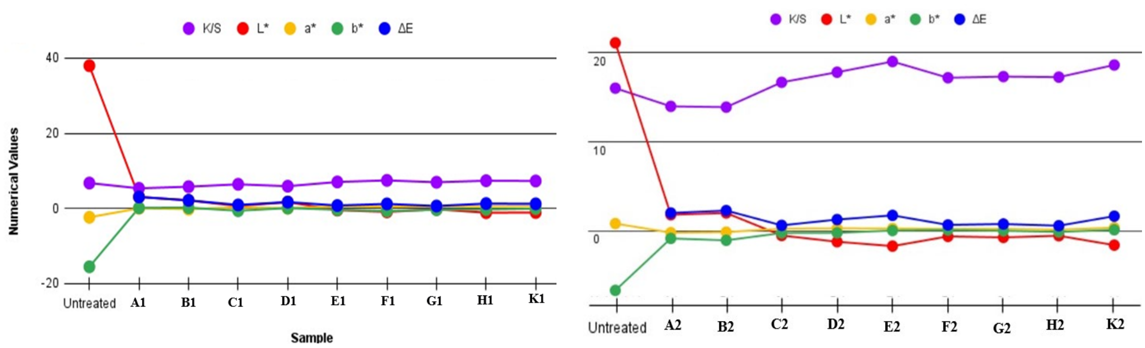


Figure 4: Color strength (k/s, L*a*b values and ΔE) of cured and steamed (a) light blue and (b) dark blue denim fabrics

Color strength test

Color strength assesses a dye's capacity to impart color to materials, and it is determined through the measurement of light absorption within the visible spectrum.[16] K/s values serve as the measurement for color strength, aiding in the assessment of how finishes impact the color strength of dyed fabric.[17] L*a*b values and ΔE serve as metrics for comparing color strength before and after the finishing of dyed fabric. In this investigation, the L*a*b values and ΔE were assessed both before and after the finishing process to examine the impact of ZnO NPs on the color strength of denim fabrics. The influence of the finish on the color strength of denim fabrics is illustrated in Figure 4 (a and b).

The k/s value, or E value, of any dyed sample is indicative of its suitability for use. In the case of the light blue denim, this experimental assessment reveals that the k/s values, representing the color strength of the dyed sample, remain relatively stable, closely align with those of the blank sample (with a difference ranging from 0.71 to 1.41). Particularly, the k/s values for sample Cl exhibit minimal variance, indicating a difference of 0.33. This consistency may be attributed to the even distribution of nanoparticles across the fabric, resulting in an appearance akin to that of the untreated sample.

Conversely, the k/s value of the dark blue denim demonstrates a significant difference (ranging from 2.13 to 2.99), with sample Cd exhibiting a difference of 0.66. The treatment involving zinc oxide nanoparticles and ethanol appears to contribute to a more uniform and even distribution of colorants on the fabric, thereby enhancing color strength. In contrast, untreated fabric may lack this uniformity, leading to diminished color intensity.

However, the treated samples of light blue denim reveal a noticeable color distinction, as evident from the E values exceeding 1. ΔE values for sample El and sample Gl stand at 0.79 and 0.66, respectively. Despite this, they fail to demonstrate satisfactory stain results. Consequently, sample Cl, with an E value of 0.95, is opted for. In contrast, the treated samples of dark blue denim exhibit E values surpassing 1, depicting a significant color contrast. The introduction of zinc oxide nanoparticles can modify the way the fabric interacts with light, potentially causing variations in light absorption and scattering compared to untreated fabric, contributing to the observed color distinction. ΔE values for sample Gd and sample Hd are 0.77 and 0.58, respectively. However, they do not exhibit acceptable stain results. Hence, sample Cd, with a ΔE value of 0.62, is chosen.

The application of zinc oxide nanoparticles to fabric surfaces can enhance light scattering, imparting a brighter and lighter appearance to the treated samples compared to the untreated ones and consequently reducing their L* values. The observed shifts in L* values may stem from the alteration of the denim fabric's surface properties due to the nanoparticle finish, influencing how it interacts with light. L* represents brightness in the CIELAB color space, where higher values indicate lighter colors, and lower values indicate darker colors. Consequently, the notably lower L* values in the treated samples suggest that the zinc oxide nanoparticle finish has induced a lighter and brighter appearance in the fabrics, compared to their untreated counterparts. Thus, it can be inferred that the active ingredients responsible for the self-cleaning effect also play a role in the color transformation of the treated samples.

Yellowness index test

Yellowing affects various textile materials, including both natural fibers like cotton and synthetic fibers. White and pastel colors tend to show more noticeable yellowing compared to dark colors, while the impact is less prominent in darker shades. Factors contributing to yellowing include a highly acidic pH, excessive thermal exposure, contamination from dyestuffs, and zinc contamination.[18] Fabric yellowness is quantified using the yellowness index obtained from spectrophotometry. Calculated according to ASTM E313, the yellowness index is a numerical representation indicating the shift in color of a fabric from white to yellow. Higher yellowness index values are undesirable. Optimal finish performance is indicated by finished fabric exhibiting zero to very low yellowness index values.

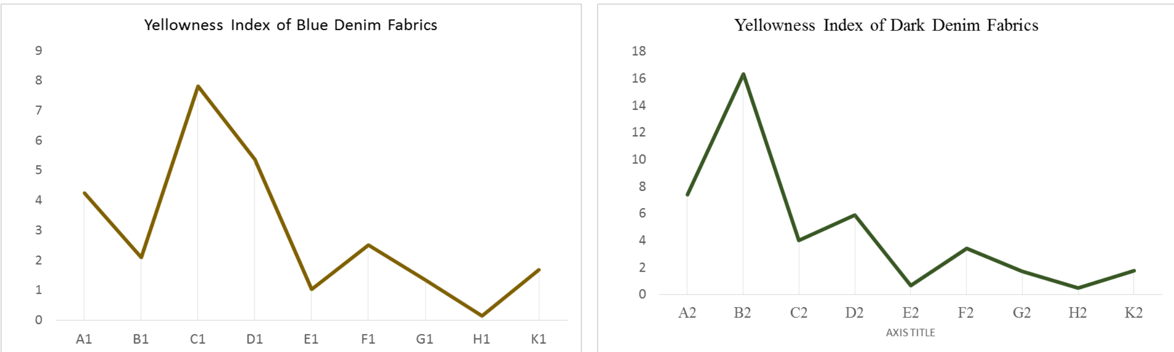


Figure 5: Yellowness index of cured and steamed (a) light blue denim fabrics and (b) dark blue denim samples

In this investigation, the test was conducted to assess the impact of ZnO NPs on the yellowness of denim fabrics. Figure 5 (a and b) illustrates the influence of ZnO NPs on the yellowness index of finished denim fabrics. It is apparent from the graphs that denim fabrics subjected to the steaming fixation process exhibit lower yellowness index values, compared to the cured samples. This difference could be attributed to the exposure of steamed samples to moisture, resulting in a hydrating effect. Moisture has the potential to modify a material's light reflection and absorption characteristics, potentially diminishing its perceived yellow tint. The higher moisture content in steamed samples may contribute to their yellowness index values aligning more closely with those of untreated fabric, which is likely closer to its inherently damp state. Furthermore, the drying and curing processes often involve permanent chemical reactions or physical changes that can alter the color of the material.

Drop test

Drop tests assess a material's capacity to absorb and retain liquid or water within its pores and crevices. In this procedure, a water droplet is allowed to fall onto the stretched surface of a fabric from a predetermined height. The wetting time, defined as the duration until the specular reflection of the water droplet disappears, is then measured and recorded according to AATCC TM79. The denim fabrics utilized in this study have a high GSM and a tightly compacted structure, impeding rapid absorption of water droplets. The water drop test was performed to examine the impact of ZnO NPs on these denim fabrics. The results of the drop test are presented in Table 2. It is evident from the table that both untreated denim fabrics (UT1 and UT2) showed no absorbency even after 60+ seconds, whereas all the treated fabrics exhibited absorbency within the range of 50 to 60+ seconds. This distinction could be attributed to the facilitation of capillary action within the fabric fibers through the deposition of a thin film of ZnO NPs. This deposition enhances the fabric's ability to absorb liquids by providing additional surface area and improving overall wettability.

Color fastness to crocking

During actual use, fabrics come into contact with many solid surfaces, such as other textile materials. When two fabric surfaces are rubbed against each other, the poor colorfast material may transfer its colorant. In color fastness to crocking, a colored test specimen is rubbed with white rubbing cloth under controlled conditions. The amount of color transferred onto the rubbing cloth is then accessed using the gray scale for staining [AATCC TM08]. Generally, denim fabrics exhibit poor to fair crocking fastness, especially in wet crocking. This is because denim fabrics are dyed using indigo dye. Indigo dyes have poor substantivity for cellulose, therefore, they mostly lie on the surface of the fabric after dyeing, and the process is usually called ring dyeing.[19] Because of the surface dyeing on denim, a dry crocking level of 3 or better and a wet crocking of 2 or better are considered as good for denim fabrics.

In this study, a color fastness to crocking test was conducted to assess the impact of the finish (ZnO NPs) on denim fabrics. The results of the color fastness to crocking test are depicted in Figure 6. It is observable in Figure 6 that both untreated denim fabrics (UT1 and UT2) exhibited fair to good color fastness to crocking, ranging from 3 to 3.5 in dry crocking and 2 to 2.5 for wet crocking, which is deemed acceptable for practical use. The figure also reveals that the crocking fastness results of all fabrics treated with ZnO NPs did not show significant changes from the untreated fabrics. This suggests that ZnO NPs did not compromise the color fastness properties of denim fabrics. However, in comparison to all treated fabrics, C1 and C2 displayed particularly good color fastness to crocking.

Table 2
Drop test results of denim fabrics

Sample code	Observation time (seconds)	Description
UT1	60+	The drop was not absorbed into the fabric
UT2	60+	The drop was slightly absorbed into the fabric
A1	60+	The drop was absorbed from its edges
A2	60+	The drop was absorbed from its edges
B1	60+	The drop was absorbed from its edges
B2	55+	The drop was absorbed from its edges
C1	60+	Kept its spherical shape
C2	55+	The drop was partially absorbed
D1	50+	A portion of the drop was absorbed
D2	50+	The drop was partially absorbed

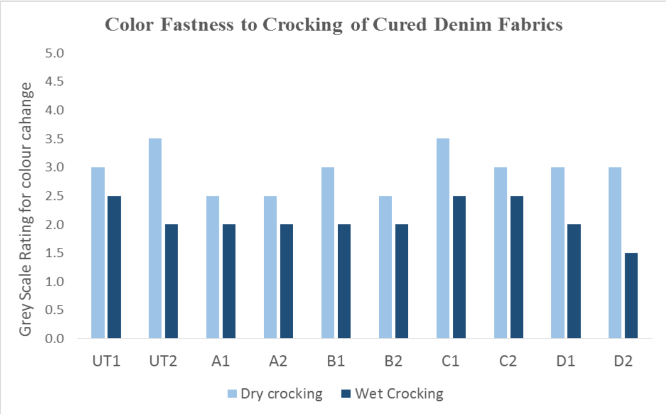


Figure 6: Color fastness to crocking of cured denim fabrics

Antibacterial test

For the antibacterial test, C1 and C2 were chosen based on their commendable performance. In various tests, ZnO nanoparticles stand out for their remarkable potential, as they may possess antimicrobial and antifungal properties against certain strains.[1,10] Hence, the effectiveness of denim fabrics treated with ZnO NPs was evaluated against Gram-positive *Bacillus subtilis* and Gram-negative *E. coli* bacteria. The well diffusion method was employed in the nutrient agar test, where swatches of the coated fabric were placed on inoculated agar plates. Following a 24-hour incubation period at 37 °C, images of the agar plates were captured and are presented in Figure 7 (a and b). In the images, (.) is for untreated, (x) is for treated, (B) – for dark blue and (D) – for light blue denim fabrics. Figure 7 (a and b) clearly shows that there is no zone of inhibition in any of the finished fabrics against *E. coli* and *Bacillus subtilis*. Still, it was ascertained that the bacteria could not grow underneath the zinc oxide finished fabric. This indicates that denim fabric treated with zinc oxide nanoparticles still had a biocidal effect.

Scanning electron microscopy (SEM) analysis

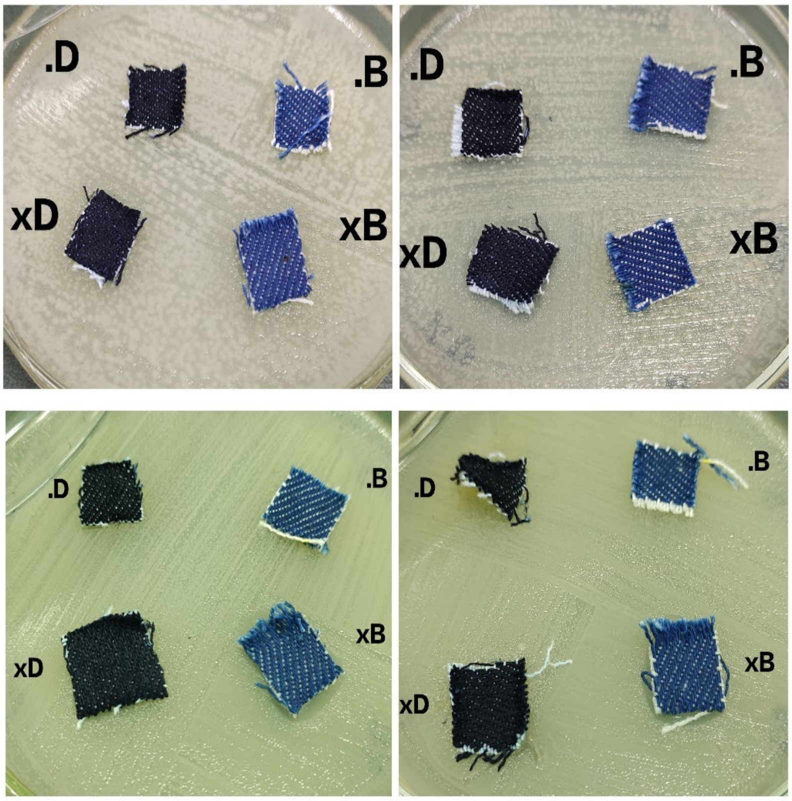
In this investigation, SEM analysis was conducted for both untreated and ZnO NPs-treated denim, and the results are depicted in Figure 8 (a and b, respectively). For the SEM analysis, C1 and C2 were chosen based on their commendable performance in various conducted tests. A magnification of 500x was employed for the SEM analysis.

Figure 8 (a) reveals that the untreated denim fabric possesses a highly textured microscale structure, with distinct parallel ridges and a very smooth surface. In contrast, Figure 8 (b) illustrates that the parallel ridges in the ZnO NPs-treated denim fabric disappeared, and the rough surface induced hydrophobicity. The fiber structure is clearly and smoothly visible in the untreated fabric (Fig. 8 a), while the treated fabric (Fig. 8 b) exhibits a considerable number of nanoparticles on the fabric surface.

The SEM images highlight that the dark blue denim fabric samples have a significantly higher deposition of ZnO NPs than the light blue ones. This difference can be attributed, in part, to the greater surface roughness of the dark blue samples, which have a higher GSM than the light blue ones. The rougher surface of the dark blue fabric provides more areas for nanoparticle attachment and deposition.

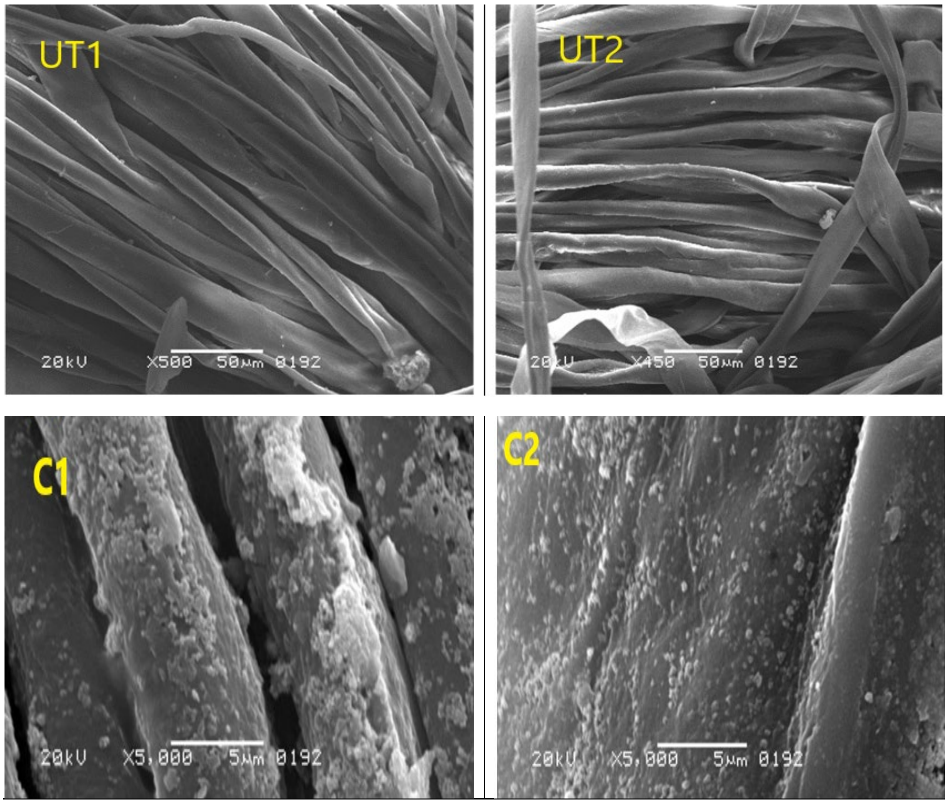
Ultraviolet protection

The ultraviolet protection factor (UPF) is a numerical value utilized to gauge the effectiveness of fabrics or skincare products in shielding the skin from the harmful effects of ultraviolet (UV) radiation from the sun. The interpretation of the UPF rating was performed according to the AATCC Technical Manual (2020). Table 3 illustrates the UV factor of untreated and ZnO NPs-treated light blue and dark blue denim fabrics. As evident in the table, UT1 exhibits a UPF factor of 10, signifying poor protection against ultraviolet radiation. However, upon treatment with ZnO NPs (C1), the UPF factor increases to 38, indicating a substantial enhancement in UV protection, categorized as “very good protection”. This improvement underscores the effective improvement of the fabric’s ability to block harmful UV rays through nanoparticle incorporation.



a)
b)

Figure 7: Antibacterial activity test of xB and xD treated fabrics and .B and .D untreated fabrics against (a) *Bacillus subtilis* and (b) *E. coli*



a)
b)

Figure 8: SEM images of (a) untreated fabrics at 500x magnification, and (b) C1 and C2 samples at 5000x magnification

Similarly, UT2 demonstrates a moderate UPF factor of 12. Following the treatment with 5% zinc oxide nanoparticles, the UPF factor increases to 40, elevating the UV protection to the category of "excellent protection". This notable UPF increase signifies that nanoparticle treatment significantly boosts the fabric's capacity to protect the skin against UV rays.

Table 3
Ultraviolet protection factor of samples

Sample code	UVF	Category
UT1	10	Poor protection
C1	38	Very good protection
UT2	12	Moderate protection
C2	40	Excellent protection

CONCLUSION

The utilization of nanoparticles for self-cleaning textiles represents an environmentally conscious approach. The increasing significance of incorporating nanoparticles into textile materials for self-cleaning purposes is evident. Consequently, this research undertook a comprehensive examination to assess the effectiveness of self-cleaning finishes on fabrics, achieved through the optimization of process parameters. Zinc nanoparticles were applied to heavyweight denim fabrics, dyed in both light and dark blue colors.

The experimental design encompassed two distinct process routes: pad-dry-cure and pad-dry-steam methods. In the experimental runs, drying, curing, and steaming time-temperature profiles were varied to identify the conditions producing the best self-cleaning outcomes. Subsequently, the treated fabrics underwent drop tests, stain tests, color strength tests, and crocking tests. Additionally, SEM analysis, antimicrobial property evaluation, UV protection assessment, and hand feel analysis were conducted on all samples. Stains produced by ketchup, coffee, mud, and oil were used in the stain test. After evaluation, the light blue sample (Cl) exhibited the best stain resistance, scoring 5.0 for coffee and mud, and 4.0 for ketchup and oil, following a drying temperature of 60 °C for 5-10 min and curing at 130 °C for 3-5 min. For dark blue denim, sample C2 demonstrated the best stain resistance, scoring 5.0 for ketchup, and 4.0 for coffee, mud, and oil under similar drying and curing conditions. Color strength and yellowness index assessments revealed that samples Cl and C2 closely matched untreated samples. SEM analysis showed the surface morphology of these samples, while UV protection factor evaluations indicated very good and excellent protection for Cl and Cd samples, respectively. It was established that *Bacillus subtilis* and *E. coli* bacteria cannot grow under the zinc oxide finished fabrics. This specifies that zinc oxide nanoparticles treated denim fabrics have a biocidal effect (Cl and C2) compared to untreated fabrics. Lastly, the hand feel assessment revealed an uncompromised feel for light blue denim fabric, whereas the dark blue denim fabric exhibited a rougher texture. Importantly, steaming had no adverse effects on the hand feel.

The findings revealed that a formulation containing 5% zinc oxide nanoparticles and its auxiliaries, prepared with a high-speed stirrer, and applied by the pad-dry-cure method, followed by drying at 60 °C, and curing at 130 °C for 5 min, demonstrated the best results in enhancing the self-cleaning properties of denim fabrics.

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