Sustainable Photocatalytic Desizing Process for the Starch-Based Size

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ABSTRACT: Textile wet processing highly impacts the environment due to its massive water and energy consumption. High consumption of water also results in the generation of a considerable volume of effluents. In this regard, an ultraviolet C (UVC)-assisted desizing method of starch-sized cotton fabric has been developed to lower the utility consumption in textile pretreatment. A UVC cabinet is designed to control exposing temperature and energy of exposure on the starch-sized cotton fabric. The UVC exposure time is optimized concerning the desizing efficiency. The UVC-exposed-sized fabric is washed with different washing times and washing temperatures to optimize the process. The alkali consumption in washing is reduced by 75% and desizing efficiency is improved to 95%. The application of oxidizing agents like $NaNO_2$, $K_2S_2O_8$, and $NaBO_3 \cdot 4H_2O$ during sizing further reduced the washing temperature and washing time for desizing to obtain 100% desizing efficiency. The UVC-assisted desized fabric is characterized by the whiteness index, water absorbency, tensile strength, Fourier transform infrared (FTIR), and wide-angle X-ray diffraction and compared with the control. The UVC-assisted desizing process has the potential to save approximately 60% water, 90% energy, and more than 70% of the time. Life cycle analysis has also been done. The photocatalytic desizing process can reduce the impact on human health by more than 85% and save approximately 69% of mineral resources than the conventional technique. The textile industry can quickly adopt a novel approach for sustainable desizing.
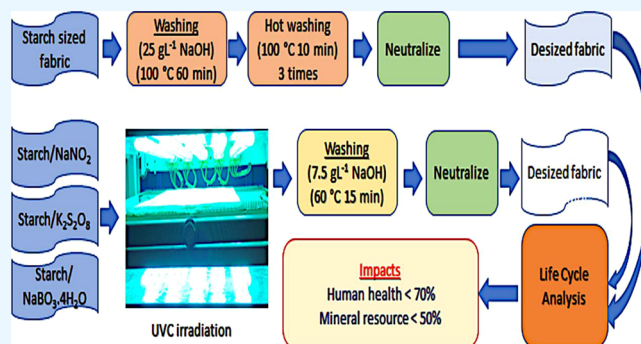
INTRODUCTION

The textile industry's contribution to employment, with a significant share, has been observed in many countries. On the contrary, it is also well known as one of the polluting industries. A considerable volume of water and energy is consumed for processing cotton textiles and generates a large amount of effluent. Lean manufacturing, a crucial idea that attempts to remove waste via continuous improvement, is not widely used in the textile sectors.[1] Industry needs to have a track of how the consumption of water, energy, and raw materials impact the environment during the manufacturing process.[2] Researchers are focusing on the substitution of water in the process.[3] Reuse and recycling of materials are quite essential for the control of resources.[4]

Desizing, scouring, mercerizing, and bleaching are the main processes for fabric preparations. Sizing is necessary to prevent warp breakages during weaving. Sizing agents based on starch have been used for years.[5] Starch may be obtained from corn, sorghum, wheat, potato, rice, cassava, or tapioca. Most of these starches also constitute a significant resource for food products, so their application in textiles depends on availability.[6]

The presence of starch in the fabric restricts the penetration of the required dyes and chemicals into it. Therefore, removing

the starch, also known as desizing, is necessary.[7] Textile wet processing requires 95−400 L of water for 1 kg of fabric, and most of the volume is consumed in the desizing process, depending on the sizing ingredient.[8] The common desizing processes used in the industry are acid desizing, alkali desizing, and desizing with hot water. These processes cannot completely remove the starch from the fabric.[9] Enzymatic desizing is also practiced.[10] α-Amylase was used for the degradation of starch in cotton fabric desizing.[11] The requirement of optimized conditions like temperature, pH, and stabilizers to control the enzymatic process is challenging and expensive.[12] Atmospheric pressure plasma was used as a waterless technology for degrading starch on cotton fabric.[13] However, designing plasma electrodes for bulk application is difficult and expensive.
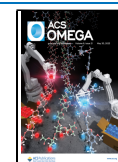
The application of UV to enhance textile printing has been studied.[14] UV light-assisted wastewater treatment has also been experimented with magnesium zinc ferrite nanoparticles.[15] The effect of ultraviolet light in textile pretreatment like desizing has been investigated for PVA-sized fabric.[16,17] Although UVC is having potential for degrading starch and assisting in desizing with the conservation of water and energy, its application in the desizing of starch-sized fabric is not studied yet. In this study, UVC-assisted photocatalytic desizing of starch-sized cotton fabric has been studied in detail. Desized fabric is also characterized using Fourier transform infrared (FTIR) and X-ray diffraction (XRD) analysis.

■ MATERIALS AND METHODS

Materials. Table 1 shows the specifications of the fabric used for the experiment. Starch (Industrial-grade, viscosity

Table 1. Specifications of the Fabric

sr. no.	specifications	value
1	construction (weave)	plain
2	warp yarn count (Ne)	40s
3	weft yarn count (Ne)	40s
4	picks per inch (PPI)	70
5	ends per inch (EPI)	130
6	grams per square meter (GSM)	120

measured at 20 °C of 10% solution = 1400 cP), laboratory-grade potassium persulfate, sodium perborate tetrahydrate, sodium nitrite, caustic soda, and acetic acid were also used in this experiment.

Experimental Method. The experiment was carried out in triplicates, and results were given with error bars. The experimental method is depicted in a flowchart (Figure 1). The process and characterization details are described in the subsequent sections.
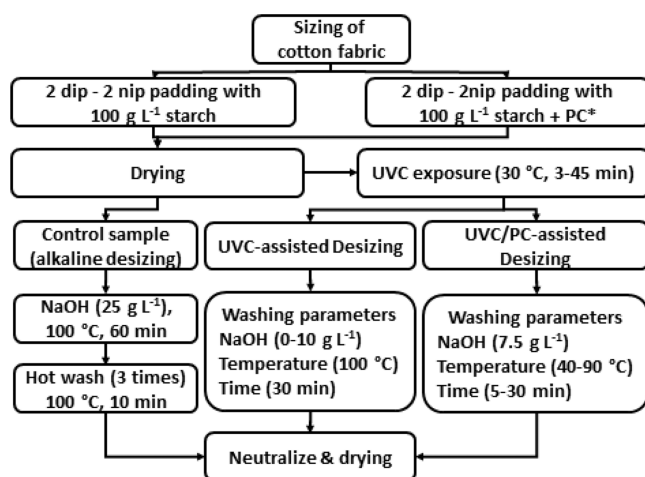

Figure 1. Process flowchart *(PC denotes photocatalyst).

Sizing. The cotton fabric was padded with 100 g L^{-1} starch and a mixture of starch and different oxidizing agents for the photocatalytic processes, such as NaNO$_2$ (PC I), K$_2$S$_2$O$_8$ (PC II), and NaBO$_3$·4H$_2$O (PC III), and dried. The expression in padding was set to 100%. The sized cotton fabric had a 10% nominal add-on of starch.

Conventional Desizing. A conventional desizing process involved washing with alkali (25 g L^{-1} NaOH) at 100 °C for 60 min, followed by three hot washes (100 °C) and neutralization with acetic acid.

UVC Exposure. The samples, including those sized with oxidizing agents, were exposed to UVC in an in-house-built UVC cabinet. The temperature inside the UVC cabinet was maintained at 30 °C. The energy on the fabric was recorded as 15 mW cm^{-2} using two banks of UVC lamps on both sides of the fabric. The time of exposure varied between 3 and 45 min. The equipment details were discussed in our previous work.[16]

UVC-Assisted Desizing. The UVC-exposed samples were desized with an aqueous alkaline solution containing 2.5−10 g L^{-1} NaOH at different washing times (5−30 min) and temperatures (40−100 °C). The material-to-liquid ratio was kept at 1:40. After desizing, the samples were neutralized, dried, and conditioned at 20 ± 2 °C and 65 ± 5% RH for 24 h for characterization.

■ CHARACTERIZATION

Viscosity Measurement. Viscosity is an estimate of the change in the molecular weight of a polymer. The viscosity of the 10% (w/v) starch was measured at 20 °C using spindle number 3 in a Brookfield RV viscometer with a 100 rpm rotational speed.

Efficiency and Degree of Desizing. The extent of size removal from the fabric after desizing was expressed as the efficiency of desizing and noted in percentage (eq 1).

$$\text{efficiency of desizing (\%)} = \frac{(W2 - W3)}{(W2 - W1)} \times 100 \tag{1}$$

where W_1 is the oven-dry weight before sizing, W_2 is the oven-dry weight after sizing, and W_3 is the oven-dry weight after desizing. The degree of desizing was determined by staining the fabric with an iodine solution. The detection of starch was observed by comparing the developed color stain with the Tegewa standard scale. The wicking height was measured using a potassium dichromate solution, as mentioned in the literature.[18]

Whiteness Index. Change in the whiteness index of the fabric affects the color value of fabric during further processes like bleaching, dyeing, and printing and is a measure of fabric appearance. The whiteness of the fabric was measured using a spectrophotometer (Premier Colorscan SS 5100H) using AATCC Test Method 110-2007.[19]

Tensile Strength. The tensile strength of the fabric may be altered during the pretreatment of fabric and a reduction in strength will affect the end user. The material's tensile strength was obtained from a Tinius Olsen tensile tester using the raveled strip ASTM D 5035 method.[20]

FTIR Spectroscopy. FTIR needs to be studied to see if any chemical changes occurred during the UVC treatment. The FTIR analysis of the fabric samples was conducted in ATR mode and analyzed from FTIR spectra using a Thermo Fisher Scientific Nicolet iS50 FTIR spectrometer.

Wide-Angle X-ray Diffraction. WAXD is conducted to see if the crystal structure of the cellulose is altered during the UVC-assisted desizing process. A Philips PANalytical X'pert Pro diffractometer (source: Cu Kα, λ = 1.54 Å) with Ni filter was used for wide-angle X-ray diffraction (WAXD). The analysis was carried out with a 2° min^{-1} scanning rate taking 2θ range from 10° to 40° Crystallinity, crystal size, dislocation

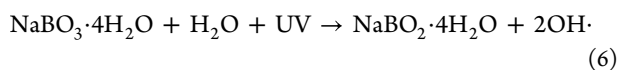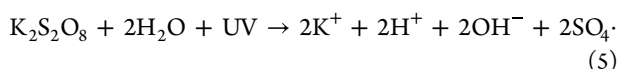density, and microstrains of the samples were calculated from the WXRD pattern using origin (OriginLab 2022b) software.[21]

Life Cycle Analysis. An LCA (cradle-to-gate) was conducted to determine the processes' environmental impact. A life cycle impact assessment database (Recipe 2016 (H)) was used for the LCA in OpenLCA 1.10.3. The main impacts generated by these processes are freshwater ecotoxicity (FWETC), freshwater eutrophication (FWETP), marine eutrophication (METP), terrestrial acidification (TA), and water consumption related to the aquatic ecosystem (WC, AE) measured with species year. The global warming effect on human health (GW, HH) and the ozone formation effect on human health (OF, HH) are measured with disability-adjusted life years (DALY). Mineral resource scarcity (MRS) is measured in USD2013.

■ RESULTS AND DISCUSSION

Effect of UVC on Film Viscosity of the Starch. Films were prepared from starch and mixtures of starch and photocatalysts and exposed under UVC to measure the effect of UVC exposure on viscosity. The possible mechanism of degradation is given in eq 2. UVC irradiation breaks the water molecule present in the film as moisture to produce free radicals ($\cdot$OH, H$\cdot$). The free radicals are responsible for the chain scission of starch molecules.

$$H_2O + UVC \rightarrow \cdot OH + H\cdot \tag{2}$$
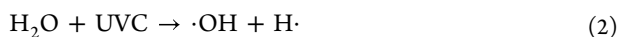
Starch degradation was also facilitated by embedding $NaNO_2$, $K_2S_2O_8$, and $NaBO_3\cdot4H_2O$. UVC generates free radicals ($\cdot$OH) from the moisture present in the film. The anions (NO_2^-) are formed by sodium nitrite, as shown in eq 3. NO_2^- in the presence of UV and free radicals ($\cdot$OH) converted to form $\cdot NO_2$ (eq 4), actively taking part in starch molecules' chain scission.[22] The photocatalysis action of $K_2S_2O_8$ is carried out by the generation of $\cdot S_2O_8$ (eq 5), which is responsible for starch degradation.[23] However, $NaBO_3\cdot4H_2O$ acts differently in the degradation process. In the presence of moisture, sodium perborate is converted to sodium metaborate, and hydrogen peroxide (H_2O_2) is released. UVC breaks H_2O_2 to generate enough free radicals ($\cdot$OH), as mentioned in eq 6.[24]

$$NaNO_2 \rightarrow Na^+ + NO_2^- \tag{3}$$

$$NO_2^- + \cdot OH \rightarrow OH^- + \cdot NO_2 \tag{4}$$

$$K_2S_2O_8 + 2H_2O + UV \rightarrow 2K^+ + 2H^+ + 2OH^- + 2SO_4\cdot \tag{5}$$

$$NaBO_3\cdot4H_2O + H_2O + UV \rightarrow NaBO_2\cdot4H_2O + 2OH\cdot \tag{6}$$

The film viscosity of the starch before UVC exposure and after a 15 min UVC exposure is presented in Table 2. The measured film viscosity confirmed the enhanced degradation of starch.

Table 2. Viscosity of Starch Film

polymer type	viscosity before UVC treatment (cP)	viscosity after 15 min UVC treatment (cP)
only starch	1400 ± 15	324 ± 7
starch + NaBO$_3$·4H$_2$O	1405 ± 21	206 ± 6
starch + NaNO$_2$	1420 ± 8	193 ± 6
starch + K$_2$–O$_8$	1412 ± 10	174 ± 5

Effect of UVC Exposure Time on Desizing Efficiency. The conventional sample with rigorous washing in the presence of highly concentrated alkali (25 g L^{-1}) was found to have a desizing efficiency of 81.44%. In contrast, desizing a control sample with hot water at 100 °C for 30 min without any alkali resulted in a desizing efficiency of 50.47% only. Starch-sized samples were exposed under UVC for 0−45 min to find out the optimum UVC exposure time. Then, the UVC-exposed samples were washed in hot water with similar conditions as that for the control and the results of the optimization are tabulated in Table 3.

Table 3. Desizing Efficiency at Different Exposure Times

sr. no.	exposure time (min)	desizing efficiency (%)
1	0	50.476 ± 0.61
2	5	71.58 ± 1.09
3	10	84.29 ± 1.74
4	15	94.42 ± 0.88
5	20	94.58 ± 0.80
6	25	95.01 ± 0.57
7	30	95.05 ± 0.79
8	35	95.13 ± 0.70
9	40	95.17 ± 0.50
10	45	95.18 ± 0.42
11^a	0	81.44 ± 0.73

^{a}Conventional sample.

Figure 2 shows that the UVC exposure has enhanced the desizing efficiency ranging from 72 to 95%. The desizing
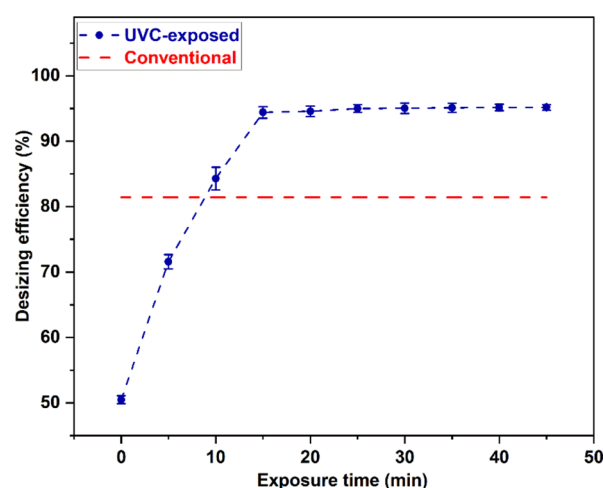

Figure 2. Effect of UVC exposure time on desizing efficiency (UVC energy = 15 mW cm^{-2}).

efficiency for samples exposed under UVC for 15 min and washed with one wash without alkali was 44% higher than the control and 13% higher than the conventionally processed sample.

The summary of the statistical analysis with polynomial fitting is given in Table 4. The equation for the desizing efficiency is shown in eq 7:

$$y = intercept + B1 \times x^1 + B2 \times x^2 + B3 \times x^3 \tag{7}$$

where intercept = 50.87 ± 1.21, $B1$ = 4.69 ± 0.28, $B2$ = −0.16 ± 0.02, and $B3$ = 0.002 ± 2.14 × 10^{-4}. The coefficient of determination (r^2) for the data plot is found to be 0.99.

Table 4. ANOVA of Desizing Efficiency at Different Exposure Times

|	DF	sum of squares	mean square	F value	prob > F
model	3	4957.19	1652.39	386.24	2.98×10^{-7}
error	6	25.67	4.28		
total	9	4982.86			

Effect of UVC Exposure on Desizing Efficiency with Alkali Washing. The UVC-assisted desizing method discussed in the previous section resulted in better efficacy than the conventional technique; however, the complete removal of starch was not accomplished. The free radicals (·OH, H·) generated by UVC are responsible for the chain scission of starch molecules on the fabric's surface. Alkali hydrolysis (Figure 3) during washing helps decrease the molecular weight and facilitate easy removal.

The sized samples were exposed under UVC for 15 min and washed with an aqueous solution of NaOH at 100 °C for 30 min. The desizing efficiency of fabric using alkaline washing (2.5−10 g L^{-1} NaOH) is plotted in Figure 4. The coefficient of determination (r^2) for the data plot is found to be 1.00. It may be noted that 100% removal of the size is achieved with 7.5 g L^{-1} NaOH solution. Tegewa scale rating of 9 for samples washed with 7.5 g L^{-1} NaOH solution is also evidence of 100% size removal (Table 5). A 15 min UVC exposure helped in a 70% reduction in alkali concentration compared to the conventional process.

Effect of Photocatalysis on Desizing Efficiency. The UVC-assisted desizing with alkaline wash was incorporated successfully to remove 100% of the size. However, the washing was carried out at 100 °C for 30 min. This was considered of interest if washing temperature and time could be reduced. Different concentrations of NaNO$_2$, a known oxidizing agent, were added to the sizing bath during sizing. These fabrics were exposed under UVC for 15 min to facilitate photocatalysis. Desizing was done with 7.5 g L^{-1} NaOH at 90 °C for 30 min. The results of the desizing are tabulated in Table 6, revealing that 10 mM of NaNO$_2$ is sufficient to achieve a desizing efficiency of 100% at a lower washing temperature. It may be noticed that an increase in the concentration of the oxidizing agent does not affect the whiteness index; however, the strength of the fabric is getting lowered.

In the next set of experiments, the sized fabric was prepared with a mixture of starch and 10 mM NaNO$_2$. Then, the fabric was exposed to UVC for 15 min and washed with 7.5 g L^{-1} NaOH at different washing temperatures (Figure 5). The summary of the statistical analysis with polynomial fitting is given in Table 7.

The coefficient of determination (r^2) for the data plot is found to be 0.97. It was noticed that the washing temperature was reduced by 40% of the conventional process by the combined action of photocatalytic exposure and alkaline hydrolysis during washing. This technique is adequate for
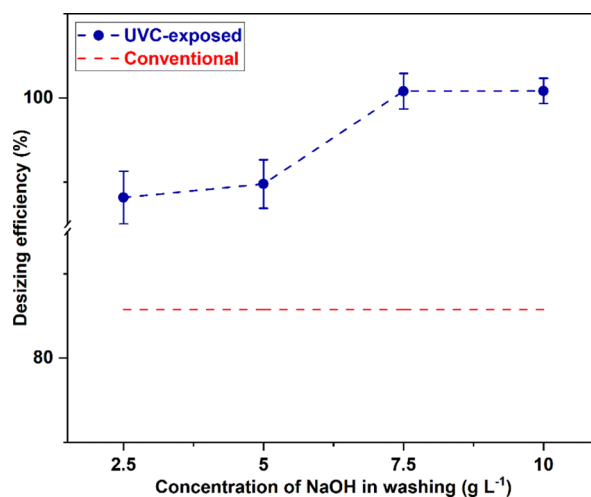
Figure 4. Effect of alkaline washing on desizing efficiency (UVC exposure = 15 min).

Table 5. Tegewa Test Results of Desized Samples

sr. no.	NaOH (g L^{-1})	Tegewa rating
1	2.5	6−7
2	5.0	7−8
3	7.5	9
4	10.0	9

Table 6. Effect of UVC in the Presence of NaNO$_2$ in Desizing

concentration of NaNO$_2$ (mM)	desizing efficiency (%)	CIE whiteness index	tensile strength (N)
0	84.35 ± 0.44	56 ± 0.51	765 ± 6.85
5	91.14 ± 1.42	55 ± 0.73	672 ± 11.82
10	100.20 ± 0.60	58 ± 0.51	638 ± 5.94
15	101.73 ± 0.42	59 ± 0.84	550 ± 14.80
20	101.01 ± 1.68	57 ± 1.25	442 ± 15.54

completely removing the starch at 60 °C of washing. The higher amount of free radicals generated by NaNO$_2$ in UVC increases starch molecules' degradation.

The desizing efficiency of the samples with NaNO$_2$ exposed under UVC and washed at different washing times is plotted in Figure 6. The summary of the statistical analysis with polynomial fitting is given in Table 8.

The coefficient of determination (r^2) for the data plot is found to be 0.99. It may be observed that photocatalytic desizing reduced the duration of washing to just 15 min.

After achieving reduced process time and a lowered washing temperature with NaNO$_2$ (PC I), the effect of a few other oxidizing agents was also studied. Potassium persulfate (K$_2$S$_2$O$_8$) and sodium perborate tetrahydrate (NaBO$_3$·4H$_2$O) were used for photocatalytic desizing processes, PC II and PC
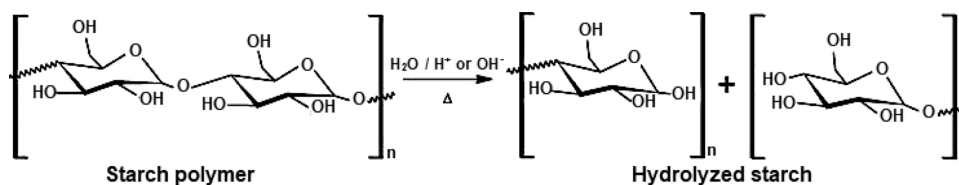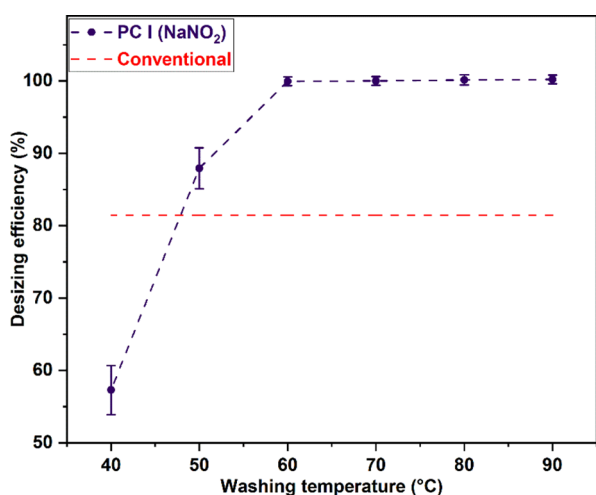

Figure 3. Alkali hydrolysis of starch.

Figure 5. Effect of photocatalysis on desizing efficiency at different washing temperatures (UVC exposure = 15 min, NaOH = 7.5 g L^{-1}).

Table 7. ANOVA of Desizing Efficiency at Different Washing Temperatures

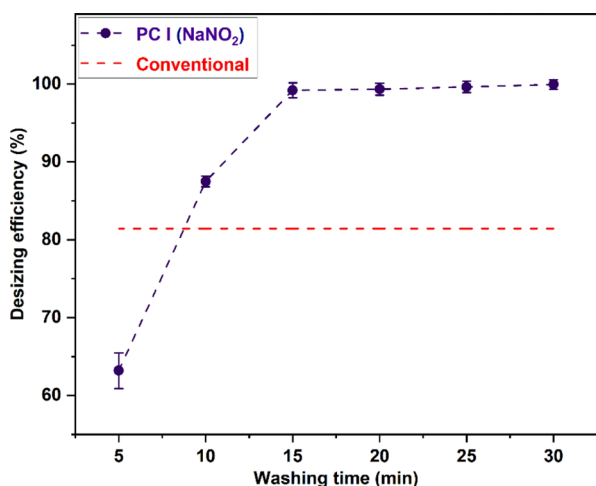|	DF	sum of squares	mean square	F value	prob > F
model	3	169.98	56.66	1.89×10^1	0.05
error	2	5.99	2.99		
total	5	175.97			

Figure 6. Effect of photocatalysis on desizing efficiency at different washing times (UVC exposure = 15 min, NaOH = 7.5 g L^{-1}, washing temperature = 60 °C).

Table 8. ANOVA of Desizing Efficiency at Different Washing Times

	DF	sum of squares	mean square	F value	prob > F
model	3	445.64	148.55	9.56×10^1	0.01
error	2	3.11	1.55		
total	5	448.75			

III. Different catalyst concentrations (2.5−10 mM) were added to the sizing paste. The sized samples were exposed under UVC for 15 min before washing. The desizing efficiencies of the samples have been plotted in Figure 7. According to the results, only 7.5 mM of K$_2$S$_2$O$_8$ is enough to completely desize the fabric, while the other two catalysts required at least 10
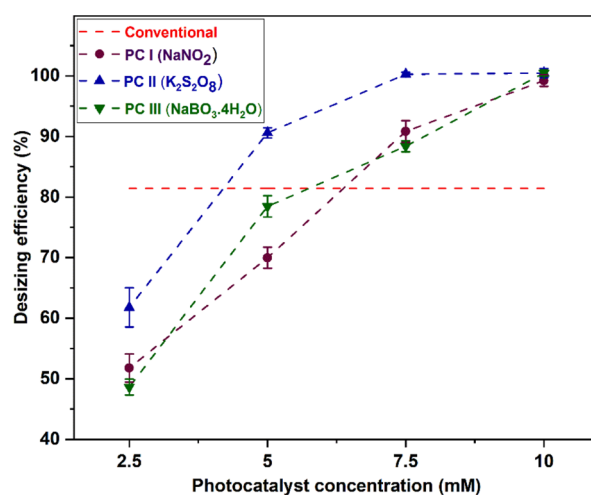

Figure 7. Effect of photocatalyst concentration on desizing efficiency (UVC exposure = 15 min, NaOH = 7.5 g L^{-1}, washing temperature = 60 °C, washing time = 15 min).

mM. The activity of the catalysts with optimum concentration was further studied to optimize the UVC exposure time. A plot of the results is shown in Figure 8. The times of exposure required to obtain 100% removal of the starch from the fabric for PC I, PC II, and PC III processes are 15, 9, and 12 min, respectively.
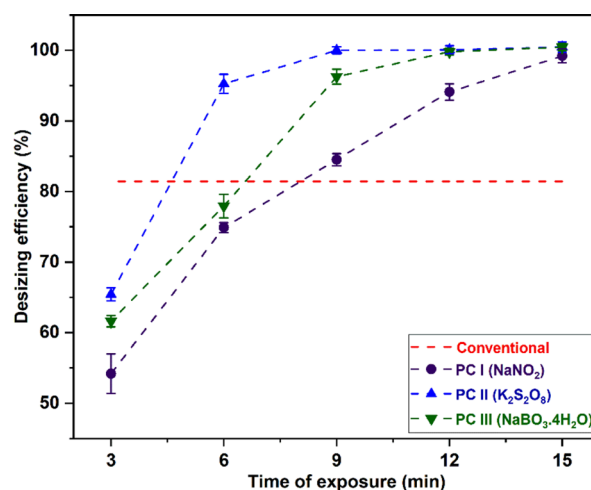

Figure 8. Effect of photocatalysis on desizing efficiency at different times of exposure (NaOH = 7.5 g L^{-1}, washing temperature = 60 °C, washing time = 15 min).

The desizing efficacy of the fabric processed with different photocatalysts was characterized by the whiteness index, wicking height, and Tegewa rating. The characterization results for the optimized samples washed at 60 °C for 15 min are summarized in Table 9. A Tegewa rating of 9 indicates the complete removal of starch from the fabric processed. The whiteness indices and wicking heights are better than the control sample. The obtained test results of the fabric processed with photocatalytic desizing confirmed that the process has no adverse effect on fabric quality. In summary, the UVC-treated fabrics produced significantly better results than the control fabrics.

The study of tensile strength retention is crucial for choosing the duration of UVC exposure in the presence of suitable

Table 9. Fabric Characterization Results

process	UVC exposure time (min)	washing temperature (°C)	Tegewa rating (1−9)	whiteness index (CIE)	wicking height (mm)
conventional	0	100	5−6	61 ± 1.53	98 ± 3.45
PC I	15	60	9	59 ± 0.83	110 ± 4.24
PC II	9	60	9	58 ± 0.86	115 ± 3.58
PC III	12	60	9	58 ± 1.22	118 ± 4.62

photocatalysts. The strength retention for PC I, PC II, and PC III processes was 84.8, 91.4, and 98.5% of untreated fabric strength (Figure 9), respectively. Among the other photocatalysts, $NaBO_3·4H_2O$ may be preferred because it retains the maximum strength of the fabric.
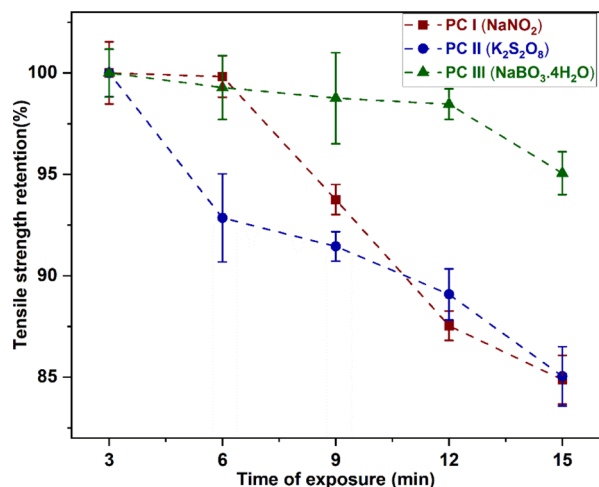

Figure 9. Effect of photocatalysts on tensile strength retention (TSR) at different times of exposure (NaOH = 7.5 g L^{-1}, washing temperature = 60 °C, washing time = 15 min).

FTIR Spectroscopy. FTIR analysis of untreated fabric, starch film, starch-sized fabric, and desized fabrics processed with different photocatalysis processes (PC I, PC II, PC III) was conducted to analyze their chemical structure. The absorbance spectra are depicted in Figure 10. The associated functional groups are mentioned in Table 10. The absorption ratio of desized fabrics with untreated fabric for major peaks is
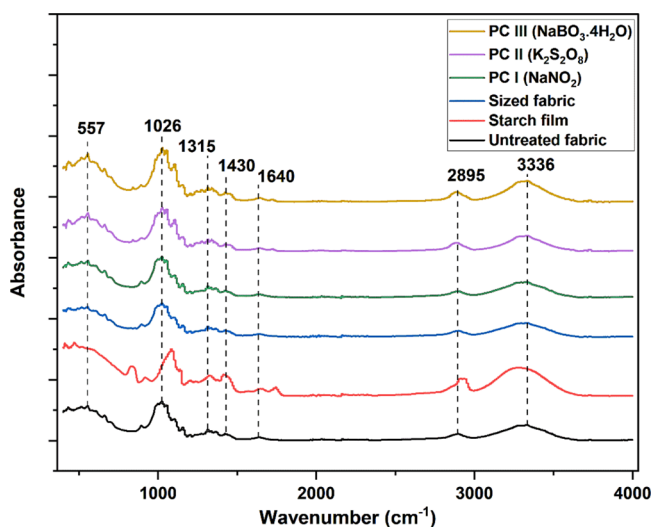

Figure 10. FTIR of starch film and fabrics with various treatments.

Table 10. IR Absorption for Different Chemical Groups

sr. no.	chemical groups	wavenumber (cm^{-1})	references
1	OH stretching	3336	25
2	CH stretching	2895	27
3	OH bending (for absorbed moisture)	1640	26
4	CH symmetric bending (CH$_2$)	1430	28
5	CH wagging (CH$_2$)	1315	29
6	CO stretching at C$_6$	1026	30
7	OH bending (out of plane)	557	31

tabulated in Table 11. The O−H groups' stretching vibrations were found at 3336 cm^{-1}.[25] The peak at 1640 cm^{-1} was

Table 11. Absorption Ratio of Desized Fabric with Untreated Fabric

wave no	untreated	PC I	PC II	PC III
557	1	1.08	1.11	1.40
1026	1	1.07	1.07	1.33
1315	1	1.08	1.10	1.35
1430	1	1.11	1.09	1.41
1640	1	1.16	0.98	1.25
2895	1	1.03	1.31	1.53
3336	1	1.92	1.16	1.14

attributed to the O−H bending vibration for the absorbed moisture.[26] Although the peak intensity of O−H in the starch film was higher than cellulose, it was found to be dominated by starch-sized fabric. However, the absorption intensity for washed fabrics increased at 3333 cm^{-1} and 1640 cm^{-1}. The absorbance peak intensity at wavenumber 1640 cm^{-1} was higher than the untreated fabric for all photocatalytically treated fabrics. This shows the UVC-assisted desized samples are more hydrophilic than the untreated fabric. The reason behind a higher moisture absorbance may be due to the maximum removal of hydrophobic impurities from the cellulose. Additionally, the increased wicking height of the UVC-assisted desizing samples indicated increased hydrophilicity. FTIR analysis also suggests that the material's chemical structure is not altered by UVC exposure.

Wide-Angle X-ray Diffraction. It was pertinent to check if the photocatalytic desizing process had any effect on the microstructure of cotton. The typical cellulose-I peaks were observed as 1−10, 110, 200, and 004, as shown in Figure 11.[32] The crystallinity for the UVC-treated and untreated fabrics is also depicted in Figure 11. The crystallinity for samples treated with UVC in PC I, PC II, and PC III processes was lowered by 7.9, 2.3, and 1.4% of the untreated sample, respectively. A minor decrease in the crystallinity of cellulose after UVC treatment may result in a slight reduction in strength. After analyzing the XRD data, the crystallite size, dislocation density, and microstrain for the untreated and desized fabrics are given in Table 12. All UVC-assisted desized fabrics exhibited nearly
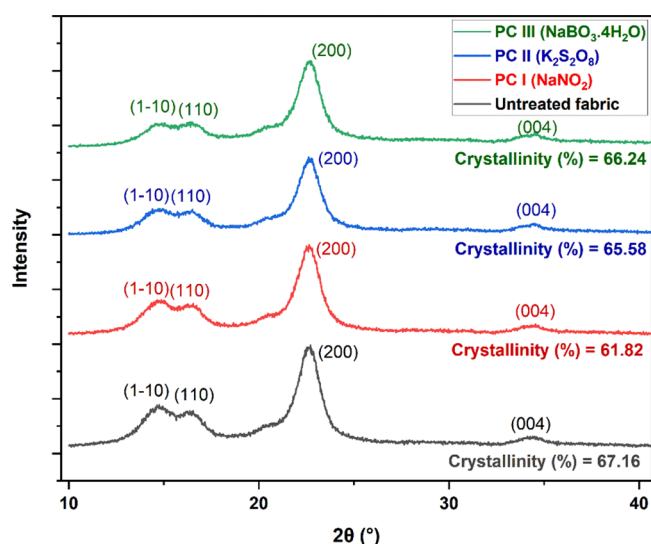
Figure 11. XRD for untreated and UVC desized fabric samples.

identical patterns to untreated fabric in WXRD. The UVC-aided desizing treatment does not affect the crystal structure of the cellulose. However, there was a slight change in the crystallinity of the desized fabrics after photocatalysis.

Evaluation of Process Benefits. The UVC-assisted photocatalyzed desizing process was compared with conventional desizing. Inlet water (temperature = 25 °C) quantity was calculated considering the material-to-liquid ratio as 1:40. The specific heat capacities (C_p) of fabric, starch, and water were taken as 1.34, 1.795, and 4.18 kJ kg^{-1} K^{-1}, respectively. The formula for calculating the heat energy is given in eq 8

$$(q) = (m) \times (C_p) \times (\Delta T) \tag{8}$$

where q is the heat energy, m is the mass, C_p is the specific heat capacity, and ΔT is the change in temperature. The consumption of energy, water, and time for 1 kg of fabric is given in Table 13. Analyzing the utility consumptions for different UVC-aided desizing processes, a comparison was made with the conventional process. The bar diagram is shown in Figure 12. According to the results, samples treated with PC I, PC II, and PC III consumed 29, 26, and 28% of the

conventional process, respectively. The water and energy consumption of the novel method was 40 and 10% of the conventional one, respectively.

Life Cycle Analysis. Table 14 shows the input of various processes for 1 kg of desized fabric.

Figure 13 shows the impact of various desizing processes. The relative impact of the conventional process is considered 100%. The impacts by UVC-assisted desizing processes PC I have a slightly higher impact on freshwater ecotoxicity, eutrophication, marine eutrophication, and global warming on human health compared to PC II, and PC III. Water consumption impact is similar for all three UVC processes using the oxidizing agents. The oxidizing agents' contribution toward the impact is not observed much as these are used in very minute quantities. It can be noticed from the LCA that the photocatalytic process drastically reduces the effect on the environment. The implementation of photocatalysts in the UVC-assisted process can reduce the impact on human health by approximately 85%. By adopting the new techniques, mineral resources can be saved by about 69%. Overall, the photocatalytic desizing processes are better environment-friendly techniques than conventional ones.

■ CONCLUSIONS

Removing starch from the fabric during desizing requires considerable heat and water. The novel photocatalytic technique was optimized with UVC exposure time, alkali concentration, catalyst concentration, washing temperature, and washing time. Starch-sized fabric can be desized to 100% desizing efficiency after 15 min UVC exposure. Adding a small quantity of catalysts in size, like NaNO$_2$, K$_2$S$_2$O$_8$, and NaBO$_3$·4H$_2$O, can reduce the washing temperature by 40 °C and process time by more than 70% of the conventional process. Furthermore, the novel desizing method showed that desizing efficacy was improved with comparable fabric strength, whiteness, or wettability. Compared to the conventional method, PC I (NaNO$_2$), PC II (K$_2$S$_2$O$_8$), and PC III (NaBO$_3$·4H$_2$O) desizing processes can save about 60% water and 90% energy. Life cycle analysis confirmed that the new techniques are eco-friendly. From an economic and environmental perspective, the process appears promising since it reduces the consumption of water, energy, and time.

Table 12. XRD for Untreated and UVC Desized Fabric Samples

sample type	Bragg angle 2θ (°)	FWHM β (°)	crystallite size D (nm)	dislocation density $\delta \times 10^{-3}$ (nm^{-2})	microstrain $\varepsilon \times 10^{-3}$
untreated	15.35	3.51	2.29	191.39	113.53
	22.01	4.63	1.75	327.07	103.87
	22.64	1.21	6.70	22.25	26.34
	34.33	1.92	4.33	53.28	27.11
PC I	15.37	3.47	2.31	186.87	112.03
	21.99	4.56	1.77	317.87	102.44
	22.63	1.22	6.64	22.66	26.59
	34.33	1.95	4.26	55.17	27.59
PC II	15.44	3.27	2.45	166.74	105.35
	22.11	4.41	1.83	297.28	98.61
	22.66	1.19	6.83	21.46	25.85
	34.36	1.96	4.25	55.41	27.62
PC III	15.62	3.13	2.56	152.06	99.45
	22.09	4.74	1.71	343.35	106.00
	22.65	1.22	6.67	22.50	26.47
	34.35	2.24	3.72	72.37	31.58

Table 13. Consumption of Time, Water, and Energy

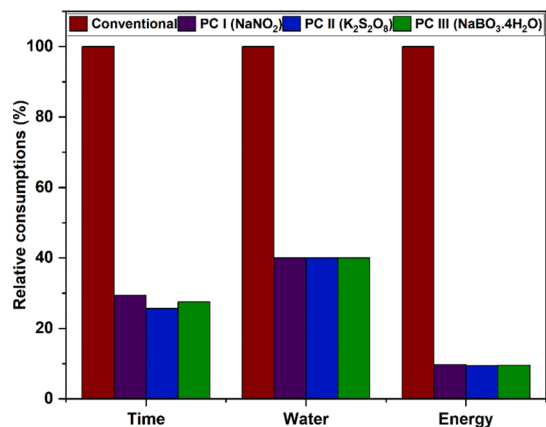| process	temperature of desizing (°C)	time (min)	water (L kg⁻¹)	energy (MJ kg⁻¹)
conventional	100	160	200	1167
PC I (NaNO$_2$)	60	47	80	114
PC II (K$_2$S$_2$O$_8$)	60	41	80	110
PC III (NaBO$_3$·4H$_2$O)	60	44	80	112

Figure 12. Comparison of utility consumptions of UVC-assisted desizing with conventional desizing.

Table 14. Process Input for Various Desizing Processes

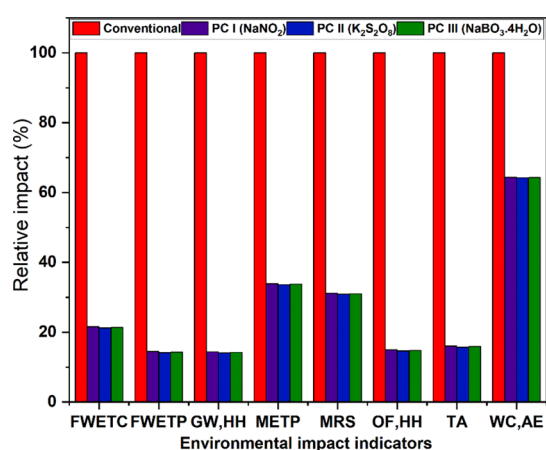| input	conventional	PC I	PC II	PC III
cotton fabric (kg)	1.000	1.000	1.000	1.000
starch (kg)	0.100	0.100	0.100	0.100
NaOH (kg)	1.000	0.300	0.300	0.300
acetic acid (kg)	0.040	0.040	0.040	0.040
NaNO$_2$ (kg)		0.001		
K$_2$S$_2$O$_8$ (kg)			0.001	
NaBO$_3$·4H$_2$O (kg)				0.002
water (L kg⁻¹)	200	80	80	80
energy (MJ kg⁻¹)	1167	104	104	104
UVC lamps (MJ kg⁻¹)	0	10	6	8

Figure 13. LCA of various desizing processes.

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have approved the final version of the manuscript. All authors contributed equally.

Notes

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■ ABBREVIATIONS

UVC, ultraviolet C; PC, photocatalyst; RH, relative humidity; FWHM, full-width half maxima

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