BIO-INNOVATIVE FUNCTIONALIZATION OF KNITTED POLYESTER FABRICS USING ENZYME, TiO_2 AND FLUORESCENT WHITENING AGENTS FOR SUSTAINABLE ARCHITECTURAL TEXTILES

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ABSTRACT

This paper has investigated the development of sustainable textiles for architectural applications using TiO_2 nanoparticles and fluorescent whitening agents on knitted polyester fabrics. The implementation of TiO_2 improved photocatalytic self-cleaning and UV protection properties of fabric, while the addition of fluorescent whitening agents enhanced fabric whiteness and optical appeal, while optimizing the UV blocking effect. The enzymatic pretreatment of polyester fabric increased hydrophilicity, ensuring uniform deposition of TiO_2 nanoparticles and improved the functional properties. The self-cleaning performance tested by degradation of blackcurrant dye under UV/VIS light showed up to 79 % stain removal after 2 hours, confirming the photocatalytic efficacy of TiO_2-treated fabrics. The obtained results show the potential of modified polyester fabrics as multifunctional materials for sustainable architecture, offering high UV protection, improved aesthetics and enhanced self-care. These textiles are suitable for use in tensioned structures, shading systems and building façades, contributing to energy efficiency, durability and sustainability. Additionally, the possible applications of such knitted functionalized fabrics as textile patterns in architectural environments are presented and visualized by artificial intelligence (Leonardo.Ai) based on sketches and photos of the design author (T. Frasonski).

Keywords: *textile architecture, sustainable architecture, titanium dioxide (TiO_2), enzyme, fluorescent whitening agents, UV protection, self-cleaning, nanotechnology*

INTRODUCTION

In the face of increasing urbanisation and environmental crises, the need for sustainable development in architecture is more urgent than ever. Built environments must evolve to reduce energy consumption, mitigate climate impact and prioritise human well-being. One promising solution lies in architectural textiles - lightweight, multifunctional materials that offer energy efficiency, visual appeal and environmental protection [1 - 3]. Fabric structures maximise the use of large spaces to meet specific needs and functions that require the least amount of supporting elements (materials) to create "hard structures" while providing large amounts of natural daylight [4].

Textiles used in architectural spaces, both indoors and outdoors, must meet requirements that go beyond aesthetics. They must offer protection from UV (ultraviolet) radiation, support self-cleaning and be weather-resistant. The shift towards environmentally friendly textiles, particularly through functional finishing and innovative nanotechnology, can also be observed in European legislation. Current efforts to increase sustainability in the textile sector include the use of organic cotton and recycled polyester, the introduction of production technologies that reduce water consumption and minimise pollution, and the transition to renewable energy sources to reduce overall energy consumption. Other measures include the development of recycling programmes to manage textile waste and the promotion of more environmentally conscious consumer behaviour. In this context, the European Union (EU) adopted the EU Strategy for Sustainable and Circular Textiles in March 2022, which aims to create a clear vision and a coherent framework for the green transformation of the textile ecosystem. According to this strategy, by 2030, textile products on the EU market should be durable and recyclable, largely made from recycled fibres, free from hazardous substances and produced in compliance with social rights [5].

The European Green Deal (EGD) is a series of policy initiatives launched by the European Commission in 2020 to make the economies of EU countries sustainable and tackle critical challenges such as climate change and environmental degradation. One of the EGD's particular concerns is improving the energy efficiency of buildings. This is not only about new sustainable buildings, but also about modernising the existing building stock in Europe. This is a burning issue and the current renovation rates of public and private buildings should be at least doubled [6].

Nanotechnology is already being used in many areas of the construction industry. Functional coatings such as low-E coatings are applied to membranes to transmit light, absorb UV and IR (infrared) rays and even reduce CO_2 emissions to less than 40 %. Nanocoatings, such as titanium dioxide (TiO_2) coatings, and other photocatalytic materials can also be used as topcoats on the outer layers of textile membranes to create a clean surface with self-cleaning properties [7 - 9]. Nano-sized TiO_2 is considered an important alternative due to its photocatalytic properties which contribute to the purification of air and water, as well as its self-cleaning ability, chemical stability and antimicrobial activity [9 - 14]. The use of nanomaterials in the construction sector is increasingly being considered as a strategy to improve the environmental performance of buildings [14 - 16].

This study investigates an innovative approach to the development of sustainable textiles for architectural applications by combining TiO_2 and fluorescent whitening agents (FWAs) on knitted polyester fabrics. Building on previous studies with standard TiO_2, the current work investigates the improved photocatalytic self-cleaning properties and UV protection performance of TiO_2, including UV-A (315 - 400 nm) and UV-B (280 - 315 nm) range [17]. The application of fluorescent whitening agents (FWA) to textiles improves the degree of whiteness and the optical attractiveness of textiles, especially when used in an optimal concentration range [18, 19]. Textile designs can be tailored to specific production conditions, allowing for greater flexibility in manufacturing. In addition, the integration of fluorescent yarns improves the aesthetic value of textiles under UV light, as optically brightened fibres contribute to the decorative quality of interiors [20, 21]. The synergy between light conversion by FWAs and scattering by nanoparticles is used for high-performance UV protection [19, 22, 23].

To improve hydrophilicity and facilitate uniform, stable deposition of TiO_2 nanoparticles, the polyester knitted fabric can be pre-treated, usually hydrolysed [19]. The enzyme modification of polyester fibres with esterases and lipases (ester hydrolases) increases the hydrophilicity of polyester and improves the functional parameters through the formation of new reactive groups (—OH and —COOH) by selective breaking of ester bonds. Lipases are among the hydrolysates that are able to hydrolyse amides and carboxyl esters, which can be used for the surface modification of polyester hydrolysis [24 - 27].

EXPERIMENTAL

Material

Knitted textured multifilament yarn made of 100 % polyester with a linear mass density of 78 dtex, with combined piqué weave, was produced on a MAYER&Cie double circular knitting machine with the following technical parameters: knock-over depth for cylinder needles: 25, knock-over depth for dial needles: 20, straight line distance between the dial and the cylinder: 3.5 mm, knitting speed: 11 rot/min. Fabric parameters are: thickness - 1 mm, mass per unit area: 134 g/m^2, number of courses/wales per cm: 22/12.

Texazym PES (INOTEX Ltd.), a special enzymatic agent containing ester hydrolase - lipolase with activity EC 3.1.1.3, was used for environmentally friendly modification of polyester fabric.

CCA 100BS Cinkarna (Celje, Slovenia), a stabilised aqueous suspension of ultrafine titanium dioxide (UF TiO_2) with excellent photocatalytic properties in the presence of natural or artificial UV light (anatase crystal structure, TiO_2 content 20 - 22 %, density ~ 1.2 g/cm^3, pH 7 - 9, crystallite size ~10 nm and specific surface area > 250 m^2/g) was used. PERSOFTAL® NANO-SIL (Tanatex Chemicals B.V), a softener based on nanoemulsion of amino-modified silicone, was used as a crosslinking agent. Tuboblanc ERN (CHT-Bezema), a benzoxazol derivative, was used as an optical brightener.

Treatments

Knitted polyester fabric (PES) was desized by washing and rinsing twice with distilled water (Label N).

The enzymatic pretreatment was carried out by exhaustion process in a bath containing 2 % owf Texazym PES at 35 °C, pH 4.5, for 45 minutes in a Mathis Polymat machine (Label E). After pretreatment, the degraded residues and oligomers were removed by rinsing in hot and cold distilled water.

Knitted PES fabric was functionalized under laboratory conditions using the pad-dry-cure method. The fabric was padded in a laboratory padding squeeze machine (E. Benz) in a bath containing 5 or 10 g/l CCA 100BS and 20 g/l PERSOFTAL® NANO-SIL with a wet pick-up, WP 90 %. It was dried for 4 min at 110 °C and cured for 2 min at 150 °C in open-form with a laboratory stenter drying-curing machine (E. Benz).

One set of chosen PES fabrics (enzyme pretreated and functionalized with 5 g/l CCA 100BS) was optically brightened by exhaustion method in the Linitest (Original Hanau) at 100 °C for 30 min with LR 1:20. Tuboblanc ERN was used in a wide range of concentrations: 0.1 %, 0.5 %, 1.0 % or 5.0 % owf. After treatment, the fabrics were air-dried.

Another set of PET fabrics was stained with blackcurrant nectar containing 30 % blackcurrant juice to evaluate the self-cleaning properties. Juice staining was applied to the surface of fabric using a stamp printing process. Printed samples were dried in the dark. One-half of stained samples (control and modified) were irradiated for 2 h using a 160 W mercury lamp (Solar Glo PT2193, Exo Terra, Montreal, QC, Canada) with a spectrum similar to that of sunlight, with the distance of 30 cm above the sample surface. The samples were irradiated with light of different UV-A/B radiation intensities c.a. 400 and c.a. 1.4 mW/cm^2. The UV-A/B radiation intensity was monitored using a UV-AB ST513 SENTRY radiation meter (Sentry Optronics Corp., Taipei, Taiwan). The irradiated samples were sprayed with distilled water after 1 hour of irradiation. The other half of stained samples were stored in the dark.

The labels and treatments are listed in Table 1.

Table 1. The labels and sample treatments

Label	Treatment
N_	Start knitted polyester fabric
E_	Enzymatically pretreated polyester fabric with Texazym PES
…_5BS_...	Treatment with 5 g/l CCA 100BS in combination with 20 g/l PERSOFTAL® NANO-SIL
…_10BS_...	Treatment with 10 g/l CCA 100BS in combination with 20 g/l PERSOFTAL® NANO-SIL
…_FWA_...	Optical brightening with Tuboblanc ERN (Fluorescent Whitening Agent)
_01, 05, 1, 5	Concentration of applied FWA: 0.1, 0.5, 1 or 5 % owf

Characterisation methods

The spectral remission, R [%] was measured on a spectrophotometer Spectraflash SF 300, Datacolor at illuminant D65/10°. The degree of whiteness according to the International Commission on Illumination (Commission internationale de l'éclairage, CIE) was automatically calculated (W_{CIE}) according to ISO 105-J02:1997 (*Textiles - Tests for colour fastness, Part J02: Instrumental assessment of relative whiteness*) and Yellowing Index (YI) according to DIN 6167:1980-01 (*Description of yellowness of near-white or near-colourless materials*). Tint value (TV), tint deviation (TD) from the neutral white standard, and its coloristic meanings according to Griesser [28] were also determined.

The self-cleaning properties were also determined via spectral characterisation [12]. Colour depth and K/S values were calculated using the values of measured spectral remission. K/S values after staining and after 2 h of irradiation were compared and the difference in colour depth, ΔK/S, was calculated in % according to eq. 1:

$$\Delta K/S = \frac{K/S_0 - K/S_{2h}}{K/S_0} (\%) \qquad (1)$$

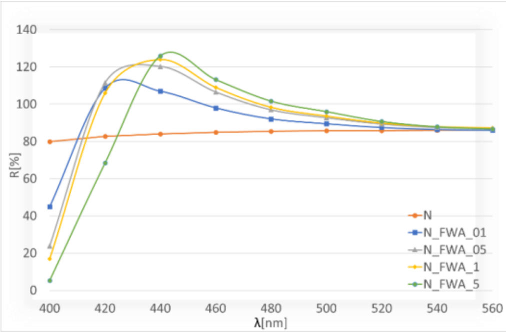
where K/S_0 is K/S value of the stained PES fabric and K/S_{2h} is K/S value of the stained PES fabric after 2 h of irradiation. The colour parameters (L*, a*, b*), difference in lightness (ΔL*) and total colour difference (ΔE*) were also determined between irradiated and stained knitted PES fabrics.

The UV protection was calculated from the UV transmittances in UV-A ($\tau_{UV\text{-}A}$) and UV-B ($\tau_{UV\text{-}B}$) range measured with the transmission spectrophotometer Cary 50/Solascreen (Varian) in accordance with AS/NZS 4399:2017 (*Sun protective clothing - Evaluation and classification*).

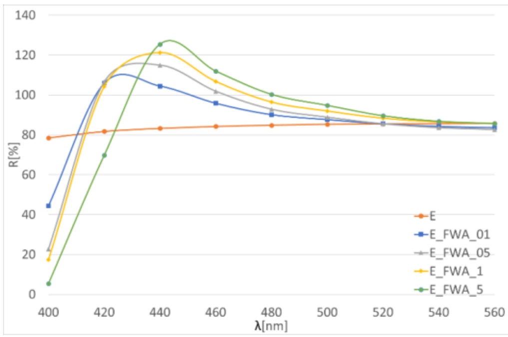
RESULTS AND DISCUSSION

This study investigated the UV protection properties and self-cleaning power of functionalized PES fabrics intended for architectural applications. Protection was achieved by light conversion using fluorescent whitening agents (FWAs) and/or light scattering by titanium dioxide nanoparticles (TiO_2 NPs). In order to improve hydrophilicity and enable uniform, stable deposition of TiO_2 nanoparticles, the polyester knitted fabric was pretreated with enzymes. Subsequently, one set of PES knitted fabrics was optically brightened for UV protection and another was stained with blackcurrant juice to evaluate the self-cleaning properties.

The results of spectral remission R [%], whiteness degree according to CIE (W_{CIE}), Yellowing Index (YI), Tint value (TV), Tint Deviation (TD) and its coloristic meaning of PES fabrics after enzyme pretreatment and treatment with NPs and/or FWAs are shown in Figure 1 and in Table 2.



a)



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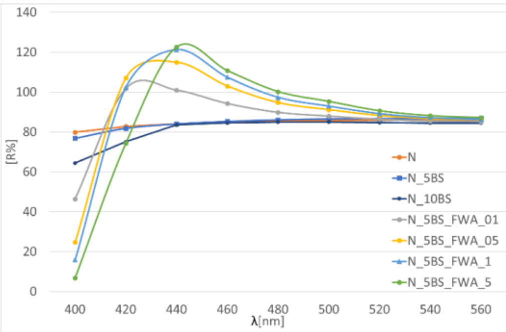
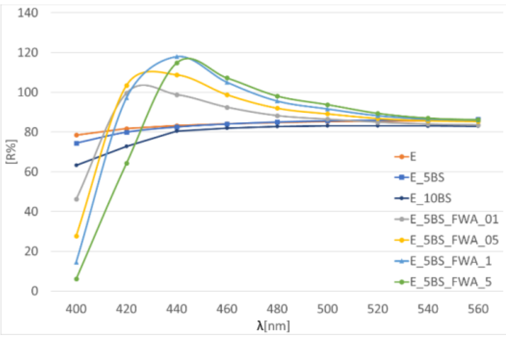


c)



d)

Figure 1. Remission spectra of polyester fabrics before and after optical brightening: a) untreated/start fabric, b) enzyme pretreated fabric; c) start fabric functionalized with TiO_2 NPs, d) enzyme pretreated fabric functionalized with TiO_2 NPs

The untreated/start polyester fabric (N) had a degree of whiteness 80.8, with no appreciable deviation in tint from the white scale. Both the enzymatic pretreatment (E) and the functionalization with TiO_2 nanoparticles lead to a slight reduction in the degree of whiteness, from to 78.9 (E) to 72.6 (E_10BS), but without any appreciable deviation in tint. This change can be attributed primarily to the increased light scattering since the enzyme treatment led to surface pilling, while TiO_2 nanoparticles contributed to surface roughness [22].

On the spectral remission curves for functionalized PES fabrics, a lower reflectance can be observed between 400 and 440 nm. This deficiency in the blue spectra is responsible for the yellowness of these fabrics. An increase in yellowing was observed after enzyme pretreatment and subsequent functionalization. This phenomenon is more pronounced at a higher concentration of the nanoemulsion, 10 g/l, resulting in the highest yellowing index of 4.11. Since the enzymatic modification of polyester fibres leads to the formation of new anionic reactive groups (—OH and —COOH) by selective breaking of ester bonds [24 - 26], this change could be the result of a higher adsorption of the cationic nanoemulsion of amino-modified silicone used as a crosslinking agent.

It should be noted that the lowest concentration of FWA (0.1 % owf) significantly improves the whiteness of the fabric. For this FWA - Tuboblanc ERN, the highest degree of whiteness (W_{CIE}) was found at 1 % owf, confirmed by maximum remission at 440 nm. At lower FWA concentrations, 0.1 and 0.5 % owf, the maximum of remission is at 430 nm indicating that hypsochromic shift to lower wavelengths occurs when low concentration of FWA is applied to fabrics.

The results of Tint value (TV), Tint Deviation (TD) and its coloristic meaning indicate a change in tint of PES fabric after FWA treatment. The more positive tint value is, the sample is more greenish having a higher tint deviation. On the other hand, the more negative tint value is, the sample is redder.

Based on the tint analysis, Tuboblanc ERN emits in the red-violet region, corresponding to a remission maximum at 430 nm. These fabrics are slightly redder than the white scale. As the whiteness increases, the yellowness decreases to the negative values. At the low FWA concentrations, the fluorescence neutralizes the yellowness.

At FWA concentrations above 1 %, the emission shifts further into the blue-green region of the spectrum. At a concentration of 5 %, the maximum of the remission shifts to 445 nm, which leads to a decrease in the degree of whiteness. As the concentration increases, the layering of the FWA occurs, leading to a quenching phenomenon, and the fabric are slightly greener than the white scale [18, 29]. Because of fluorescence quenching, a bathochromic shift to higher wavelengths is visible.

The highest degree of whiteness was found in the untreated polyester fabric (149.9). The reason for this is that the optical brightener, the benzoxazole derivative Tuboblanc ERN, has an affinity for polyester and does not exhibit ionogenicity. The enzyme treatment of PES fabric leads to a higher number of anionic groups (hydroxyl, carboxyl), but the affinity is the same, based on hydrophobic binding, so that the whiteness remains the same.

Table 2. Whiteness (W_{CIE}), Yellowing Index (YI), Tint Value (TV), Tint Deviation (TD) and its coloristic meaning of PES fabrics after enzyme pre-treatment and treatment with NPs and/or FWAs

Fabric	W_{CIE}	YI	TV	TD	Colour meaning
N	80.8	2.06	0		No appreciable deviation in tint from the white scale
N_FWA_01	128.4	-16.09	-1.3	R1	Slightly redder than the white scale
N_FWA_05	147.3	-23.86	-1.1	R1	Slightly redder than the white scale
N_FWA_1	149.9	-24.93	-0.7	R1	Slightly redder than the white scale
N_FWA_5	141.9	-22.91	2.6	G3	Appreciably greener than the white scale
E	78.9	2.67	-0.1		No appreciable deviation in tint from the white scale
E_FWA_01	126.8	-16.21	-1.5	R1	Slightly redder than the white scale
E_FWA_05	143.4	-23.68	-1.4	R1	Slightly redder than the white scale
E_FWA_1	147.3	-24.32	-1.0	R1	Slightly redder than the white scale
E_FWA_5	142.4	-23.35	2.1	G2	Slightly greener than the white scale
N_5BS	79.1	2.90	0.2		No appreciable deviation in tint from the white scale
N_10BS	78.2	2.49	0.2		No appreciable deviation in tint from the white scale
N_5BS_FWA_01	117.3	-11.85	-1.3	R1	Slightly redder than the white scale
N_5BS_FWA_05	138.7	-20.35	-1.2	R1	Slightly redder than the white scale
N_5BS_FWA_1	146.1	-23.67	-0.6	R1	Slightly redder than the white scale
N_5BS_FWA_5	137.8	-20.67	1.8	G2	Slightly greener than the white scale
E_5BS	76.0	3.85	0.1		No appreciable deviation in tint from the white scale
E_10BS	72.6	4.11	-0.1		No appreciable deviation in tint from the white scale
E_5BS_FWA_01	115.1	-11.47	-1.4	R1	Slightly redder than the white scale
E_5BS_FWA_05	129.1	-16.61	-1.3	R1	Slightly redder than the white scale
E_5BS_FWA_1	139.4	-20.96	-0.6	R1	Slightly redder than the white scale
E_5BS_FWA_5	125.0	-16.07	2.7	G3	Appreciably greener than the white scale

The observed reduction in the whiteness of fabrics after the functionalisation of TiO_2 nanoparticles (NP) appears to be due to an antagonistic interaction between surface modifications and optical effects. In particular, the pilling caused by hydrolysis, the TiO_2 nanoparticles and the increased light scattering impair the whiteness of the fabric. This can be attributed to the scattering behaviour of the TiO_2 particles, which disturbs the uniform light reflection, as well as to the reduced adsorption efficiency of fluorescent whitening agents (FWAs) on the roughened or modified surface. It should also be noted that the degree of whiteness decreased with the amount of TiO_2 applied, because scattering was higher.

The optical behaviour of the fabric whiteness and yellowness differs significantly between polyester and natural fibres i.e. cotton. As reported in previous studies [30], the degree of whiteness of cotton fabrics tends to increase after modification with TiO_2 nanoparticles. This improvement is primarily related to the removal of naturally occurring compounds such as pigments, waxes and pectins during the treatment process, which improves surface cleanliness and optical brightness. In addition, the increased TiO_2 content improves both the hydrophilicity and whiteness of cotton substrates. In contrast, this effect was not observed in the PES knitted fabrics investigated in this study, suggesting that TiO_2 functionalization interacts differently with synthetic fibre surfaces, likely due to the absence of active groups and different surface chemistry.

Benzoxazole derivatives, which are commonly used as FWAs for polyesters, can also serve as UV absorbers [19, 22, 23]. Therefore, UV protection was also investigated in this study. The results are shown in Table 3.

Table 2. Ultraviolet protection factor (UPF), UV-A and UV-B transmission (τ_{UV-A}, τ_{UV-B}), and UV protection rating according to AS/NZS 4399:2017 of PES knitted fabric

Fabric	Mean UPF	τ_{UV-A}	τ_{UV-B}	Standard deviations	Standard error	Calculated UPF	UPF rating
N	220.827	0.1	3.776	16.109	26.579	194.248	50+
N_FWA_01	1000	0.1	0.1	0	0	1000	50+
N_FWA_05	1000	0.1	0.1	0	0	1000	50+
N_FWA_1	1000	0.1	0.1	0	0	1000	50+
N_FWA_5	1000	0.1	0.1	0	0	1000	50+
E	203.859	0.1	3.929	7.983	13.172	190.687	50+
E_FWA_01	1000	0.1	0.1	0	0	1000	50+
E_FWA_05	1000	0.1	0.1	0	0	1000	50+
E_FWA_1	1000	0.1	0.1	0	0	1000	50+
E_FWA_5	1000	0.1	0.1	0	0	1000	50+
N_5BS	508.045	0.1	1.302	5.7	9.404	498.641	50+
N_10BS	625.631	0.1	0.85	22.494	37.115	588.516	50+
N_5BS_FWA_01	1000	0.1	0.1	0	0	1000	50+
N_5BS_FWA_05	1000	0.1	0.1	0	0	1000	50+
N_5BS_FWA_1	1000	0.1	0.1	0	0	1000	50+
N_5BS_FWA_5	1000	0.1	0.1	0	0	1000	50+
E_5BS	536.019	0.1	1.174	19.883	32.807	503.212	50+
E_10BS	698.669	0.1	0.657	23.412	38.629	660.04	50+
E_5BS_FWA_01	1000	0.1	0.1	0	0	1000	50+
E_5BS_FWA_05	1000	0.1	0.1	0	0	1000	50+
E_5BS_FWA_1	1000	0.1	0.1	0	0	1000	50+
E_5BS_FWA_5	1000	0.1	0.1	0	0	1000	50+

The UV protection performance of polyester (PES) knitted fabrics intended for architectural applications was evaluated in vitro by measuring the ultraviolet radiation transmittance (UV-R) in the UV-A and UV-B range, from which the Ultraviolet Protection Factor (UPF) was calculated. The results in Table 3 show that all fabrics offer excellent UV protection, with UPF values of over 50+. However, notable differences were found between the different fabric treatments.

The untreated PES fabric had a UPF of 220.827, which is primarily due to the intrinsic UV absorption by aromatic benzene rings in the polymer backbone. The enzymatic pre-treatment leads to localised breaks in the polymer chains, yet the material still retains a significant UV blocking capacity with a slightly reduced UPF of 203.859. Functionalization with TiO_2 nanoparticles significantly improved UV protection, achieving a UPF of 698.669. This improvement is more pronounced in enzyme pretreated samples due to increased TiO_2 adsorption (bigger surface area after hydrolysis), which enhances UV scattering.

Remarkably, treatment with fluorescent whitening agents (FWAs) resulted in the highest UPF value of 1000 with only 0.1 % owf, indicating maximum protection regardless of whether the fabric was pre-treated or functionalised with nanoparticles. The results indicate a synergistic interaction between TiO_2 nanoparticles and FWAs, which is consistent with the results of previous studies [12, 20].

The self-cleaning potential of PES knitted fabrics was evaluated by studying the degradation of blackcurrant nectar stains under UV/VIS light exposure. The spectrophotometric results to determine the photocatalytic activity of the TiO_2-modified PES knitted fabric are shown in Table 4.

Table 4. The spectrophotometric results of the photocatalytic activity of the TiO_2-modified PES knitted fabric

Fabric	t_{irrad} [h]	K/S	ΔK/S [%]	ΔE*	ΔL*	L*	a*	b*
N	0	0.11				84.90	7.60	-0.82
	2	0.18	-63.64	5.838	-3.274	81.63	12.43	-0.62
N_5BS	0	1.27				51.76	1.42	-9.83
	2	0.24	81.10	34.497	25.600	77.35	0.40	13.27
N_10BS	0	0.91				56.64	-0.42	-7.27
	2	0.20	78.02	33.580	23.273	79.91	0.77	16.9
E	0	0.11				84.11	7.56	-0.82
	2	0.19	-72.73	5.988	-2.684	81.42	12.23	-0.63
E_5BS	0	0.96				56.09	1.69	-9.86
	2	0.22	77.08	30.457	21.667	77.76	0.40	11.51
E_10BS	0	1.00				55.57	3.58	-12.06
	2	0.21	79.00	31.366	22.326	77.90	0.30	9.72

* time of irradiation - t_{irrad} [h], colour depth - K/S, difference in colour depth - ΔK/S [%], total colour difference - ΔE*; difference in lightness - ΔL*, colour parameters - L*, a*, b*

Unmodified PES fabrics showed no significant photodegradation of the adsorbed dye, indicating negligible photocatalytic activity. Similarly, enzymatically treated fabrics without TiO_2 coating exhibited minimal changes in dye concentration post-irradiation, with a visible darkening effect due to increased chromatic saturation, as shown by reduced ΔK/S and ΔL*. A significant increase in the L* parameter was observed in all modified TiO_2 samples. TiO_2-functionalized samples demonstrated notable lightening post-irradiation, evident from increased L* values and higher ΔE*, reflecting significant shade shifts. Chromatic parameters a* and b* shifted from red to yellow hues, confirming the photodegradation of anthocyanin-based dyes and validating the photocatalytic self-cleaning effect of TiO_2 coatings. The colour difference (ΔE*) provides a quantitative assessment of the visual disparity between a reference sample and a tested specimen. According to the Kubelka-Munk theory, the K/S value represents the ratio of the absorption (K) to scattering (S) coefficients; it is linearly proportional to the concentration of colorant present within the fabric, thus serving as a key indicator of dye uptake or stain intensity. This can be attributed to the greater roughness, the larger surface area and the higher number of active groups on the polyester fibre surface, which allow a greater deposition of TiO_2 particles on the fibre surface. The samples modified with enzymes show a greater colour difference compared to the unmodified samples. This is due to the formation of strong functional groups after amines, hydroxyl, thiol and phenol groups, which lead to the formation of a stronger stain and its stronger spread on the sample.

The highest self-cleaning efficiency was observed in fabrics treated with 10 g/l TiO_2 in combination with enzymatic surface modification. Enzyme-treated fabrics (E_10BS) and untreated fabrics with 5 g/l TiO_2 (N_5BS) achieved a dye removal efficiency of 79 % and 81 % respectively after only 2 hours of UV irradiation. The self-cleaning power of the modified knitted fabrics is promising for architectural applications.

POSSIBLE APPLICATION IN ARCHITECTURE AND FUTURE DESIGN CONSIDERATIONS

The knitted structure of the fabric can be adjusted to achieve different levels of transparency, flexibility, and strength, depending on the intended application.

TiO_2-modified knitted fabrics can be used as cladding material for building facades. Their self-cleaning properties ensure that the facade remains clean and free of pollutants, which reduces maintenance costs and enhances the aesthetics of the building. These fabrics can be integrated into shading systems to protect buildings from excessive solar radiation. The UV protection provided by TiO_2 and FWAs helps to reduce heat gain and therefore improve the energy efficiency of the building. Within buildings, TiO_2-modified fabrics can be used for partition walls and room dividers. Their self-cleaning, air-purifying and antimicrobial properties contribute to a healthier indoor climate.

FWAs improve the visual appeal of textiles by increasing their whiteness and brightness. In combination with TiO_2, FWAs can improve the aesthetic and functional properties of architectural fabrics. FWAs can be used to create visually striking decorative elements in architectural spaces. The increased whiteness and brightness of the fabrics can be used to create dynamic lighting effects, especially under UV light.

The versatility of TiO_2-modified, FWAs and self-cleaning knitted fabrics allows for customization to meet the specific needs and visions of architects and designers.

Figure 2 aims to visualize the possible applications of knitted fabrics functionalized with TiO_2 and FWAs as textile patterns in architectural environments. The visualization was created by artificial intelligence (Leonardo.Ai) based on sketches and photos by the design author (T. Frasonski).

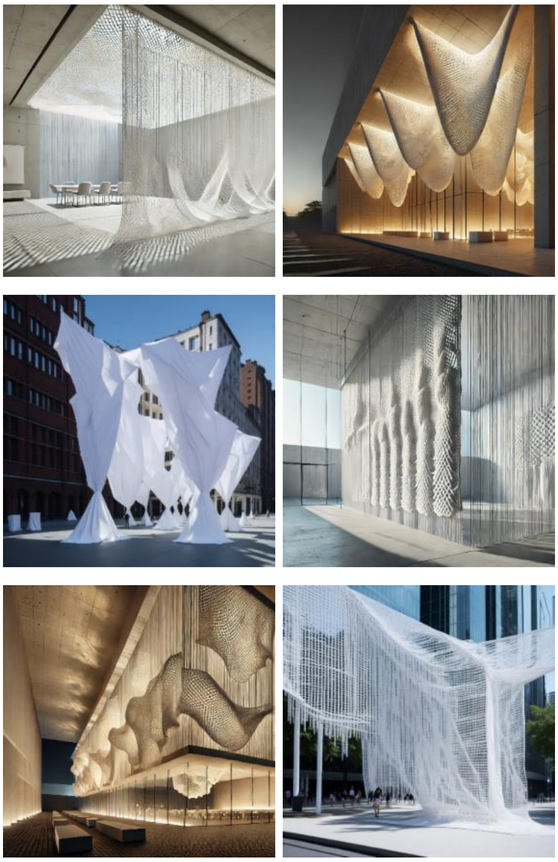


Figure 2. Visual representation of possible applications of TiO_2 and FWAs functionalized knitted fabrics generated with Leonardo.Ai based on sketches and photos of the design author (T. Frasonski)

CONCLUSION

This study shows the significant potential of functionalized polyester (PES) knitted fabrics for sustainable architectural applications. By combined use of enzymatic pretreatment, titanium dioxide (TiO_2) nanoparticles and fluorescent whitening agents (FWAs), multifunctional textile surfaces were developed that exhibit high UV protection, improved optical properties and effective photocatalytic self-cleaning capabilities.

The enzymatic surface activation significantly improved the hydrophilicity of PES fabrics and enabled a more uniform and stable deposition of TiO_2 nanoparticles. This not only improved UV protection (UPF 50+), but also increased photocatalytic efficiency. FWAs, especially at low concentrations (0.1 - 1 % owf), contributed to both improved whiteness and synergistic UV blocking behaviour through light conversion. Too high FWA concentration (> 1 %) resulted in fluorescence quenching and tinting.

Self-cleaning performance evaluated by blackcurrant dye degradation under UV/VIS irradiation confirmed the photocatalytic activity of TiO_2-treated samples, with enzyme-assisted fabrics removing up to 79 % of stain after 2 hours of irradiation. This photocatalytic efficiency is directly related to the increased surface roughness and the introduction of reactive groups that support better TiO_2 anchoring.

These results position the modified PES knitted fabrics as excellent candidates for architectural textiles, where the materials must meet stringent criteria in terms of durability, UV shielding, ecological self-maintenance and aesthetic quality. Their integration into tensile structures, shading systems, building envelopes or interior textile surfaces could support energy efficiency, extend lifespan and align with circular and sustainable building goals, especially in the context of the European Green Deal and the EU Sustainable and Circular Textiles Strategy. The methods used in this work have the potential to be used on a larger scale in industrial applications.

Future research should investigate the long-term stability of these treatments under outdoor conditions, potential recycling routes and integration with digital fabrication for architectural customization.

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