

Engineering UV-Protective Polyamide Sportswear through Fabric Structure Optimization and Hybrid ZnO/TiO₂ NPs/Benzotriazole Finishing

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ABSTRACT: Prolonged exposure to solar ultraviolet (UV) radiation during outdoor sports activities necessitates sportswear capable of providing effective UV protection without compromising functional performance. This study investigates the effects of knitted fabric architecture, UV-protective finishing formulation, and curing technology on the performance of polyamide sports fabrics. Three knitted structures with different Lycra incorporation levels; without Lycra, half-Lycra, and full-Lycra were treated with ZnO/TiO₂ nanoparticles (NPs), sonicated benzotriazole, and their hybrid system using thermal and microwave curing. The resulting fabrics were evaluated for ultraviolet protection factor (UPF), wettability, whiteness, mass change, and dimensional stability. The results demonstrated that both fabric structure and finishing formulation substantially influenced UV-protection performance and associated fabric properties. The hybrid ZnO/TiO₂ NPs/benzotriazole treatment produced the highest UV protection, reflecting the complementary effects of nanoparticle-mediated UV scattering and benzotriazole absorption. Thermal curing generally achieved the highest UPF values, whereas microwave curing delivered comparable protection with markedly shorter processing time, indicating its potential as a more efficient finishing route. These findings highlight the potential of structure finish optimization for developing high performance UV protective sportswear.

KEYWORDS - benzotriazole, hybrid UV protection, polyamide sportswear, ultraviolet protection factor (UPF), ZnO/TiO₂ nanoparticles

Date of Submission: 07-10-2026

Date of acceptance: 19-10-2026

I. Introduction

Solar ultraviolet radiation (UVR) is a major environmental factor associated with acute and cumulative skin damage. Excessive exposure can induce erythema and photoaging and contribute to carcinogenesis through oxidative stress, immune suppression, and direct DNA damage [1-3]. The global burden is substantial, with more than 1.5 million skin cancer cases reported worldwide in 2020 [4]. Because solar UV exposure is particularly relevant during prolonged outdoor activities, effective and practical protection is essential for individuals who spend extended periods under direct sunlight.

Athletes engaged in outdoor training and competition represent an important target group because exposure may be repeated over long periods and often occurs under high solar radiance. Exercise induced sweating and moisture accumulation can alter the optical and physical characteristics of clothing and the skin fabric interface, potentially affecting UV transmission [5]. Repeated exposure may therefore increase the likelihood of both acute responses, such as sunburn, and long-term UV-related skin disorders [6]. In this context, protective sportswear offers an important passive barrier because it can provide continuous coverage during athletic activity without requiring repeated application, as is necessary with topical products.

The UV-protective performance of a textile is commonly quantified by the ultraviolet protection factor (UPF), which reflects the extent to which a fabric attenuates ultraviolet transmission. UPF is governed by several interacting parameters, including fiber composition, yarn and fabric construction, thickness, porosity, coloration, moisture condition, and functional finishing [7]. Consequently, optimization of the textile structure is as important as the selection of an effective UV-blocking treatment. For sportswear, high UV protection must be achieved

while maintaining properties essential for movement and comfort, particularly flexibility, moisture interaction, dimensional stability and an appropriate fabric handle.

Functional finishing provides an effective route for increasing the UV shielding capability of textile substrates. Organic UV absorbers can attenuate UV radiation through molecular absorption and subsequent energy dissipation, whereas inorganic particles such as TiO₂ and ZnO can contribute through a combination of absorption, reflection and scattering [8–10]. Organic absorbers, including hydroxyphenyl benzotriazoles, are particularly attractive because of their strong UV absorption and photostability associated with their conjugated aromatic structures and intramolecular hydrogen bonding [11,12]. Their performance can depend on fixation efficiency, photostability, and durability during textile use and laundering. Inorganic metal oxide nanoparticles, especially TiO₂ and ZnO, have consequently received considerable attention because of their optical activity, thermal stability, and potential to provide multifunctional performance [13,14]. TiO₂ nanoparticles are effective UV attenuators because of their strong interaction with UV radiation, while ZnO provides broad UV absorption together with additional functional characteristics [15–20].

Although organic UV absorbers and metal oxide nanoparticles have each been extensively investigated, combining materials with different UV attenuation mechanisms provides an opportunity to obtain more efficient protection. A hybrid ZnO/TiO₂ NPs/benzotriazole system may provide complementary molecular absorption and nanoparticle mediated scattering, thereby reducing UV transmission more effectively than an individual finishing component. The performance of such treatments cannot be considered independently of fabric architecture, particularly in stretchable knitted sportswear in which changes in structure and Lycra incorporation may influence porosity, thickness, and the extent of fabric deformation [21–26].

Another important consideration is the efficiency of the finishing process. Conventional thermal curing is widely used for fixing functional finishes but may require relatively long processing times and substantial thermal energy. Microwave assisted processing has emerged as a potential alternative because volumetric heating can accelerate energy transfer and shorten treatment time [27–31]. The combined effects of knitted structure, hybrid UV finishing chemistry, and curing method on the resulting UV protection and key fabric properties require further systematic investigation.

This study evaluates polyamide knitted sports fabrics with different Lycra incorporation levels, without Lycra, half Lycra and full Lycra. Also, three UV protective finishing systems based on ZnO/TiO₂ nanoparticles, benzotriazole, and their hybrid combination are investigated. Thermal and microwave curing are studied comparatively, with particular emphasis on UPF, wettability, whiteness, weight change and dimensional stability. The objective is to identify the structure finish processing combination capable of maximizing UV protection while preserving the functional and dimensional characteristics required for high performance sportswear.

II. Materials and Experimental Methodology

2.1 Materials

2.1.1 Fabric

Nylon 6 knitted fabric was used as the substrate for the functional finishing treatment. The fabric was supplied by a local textile manufacturer. The fabric specifications, including yarn characteristics, fabric construction, and other relevant physical properties, are presented in Table 1 [26].

Table 1: Yarn specifications and structural configurations of investigated nylon 6 knitted fabrics

Fabric configuration	Face-layer yarn (dtex)	Back-layer yarn (dtex)
Without Lycra	70/68 × 2	70/68 × 1
Full Lycra	70/68 × 2	20/40/34 × 1 (Lycra)
Half Lycra	70/68 × 2	20/40/34 × 1 (Lycra) + 70/68 × 1 (Nylon 6)

2.1.2 Chemicals

Zinc oxide nanoparticles (ZnO NPs) and titanium dioxide nanoparticles (TiO₂ NPs) of high-purity grade were used as functional finishing agents. ZnO and TiO₂ NPs were supplied by Orchid. Benzotriazole (Biotirizole), obtained from Biotex, was used as a UV stabilizing agent. Sodium carbonate (Na₂CO₃) was used for pretreatment of the fabric. Distilled water was used for the preparation of all treatment baths. All chemicals were of analytical grade and were used as received without further purification.

2.2 Methods

2.2.1 Pretreatment of Nylon 6 Fabric

Prior to functional finishing, nylon 6 fabric samples were subjected to alkaline pretreatment. The fabric was treated with an aqueous sodium carbonate solution at a concentration of 3 g/L using a material to liquor ratio of 1:20. Pretreatment was carried out at 45 °C for 25 min under ultrasonic agitation. The treated samples were subsequently washed thoroughly with distilled water to remove residual alkali and loosely attached impurities, then squeezed and air dried before further treatment [27, 28].

2.2.2 Preparation of the Nanoparticle Treatment Bath

The treatment bath was prepared by dispersing ZnO and TiO₂ NPs at 0.5 g each per 100 g of fabric, corresponding to a 1:1 mass ratio of ZnO:TiO₂. Biotriazole was added at a concentration of 0.3 g/L. The components were dispersed in distilled water and subjected to ultrasonic treatment for one cycle of 7 min at 100% amplitude to improve dispersion and reduce particle agglomeration.

2.2.3 Application of the Treatment Reagents

The pretreated Nylon 6 fabric samples were divided into the corresponding treatment groups: (i) ZnO/TiO₂ nanoparticles alone, (ii) Biotriazole alone, and (iii) ZnO/TiO₂ nanoparticles in combination with Biotriazole. An untreated fabric sample was maintained as the control. For each treatment, the fabric samples were immersed in the respective treatment bath for 30 min at room temperature. The samples were subsequently passed through a padding unit and squeezed to achieve a wet pick-up of 100%. The padded samples were then dried at 105 °C for 30 min. This experimental design enabled the effects of the nanoparticle treatment and Biotriazole to be assessed separately, while also allowing evaluation of the combined treatment to determine whether the simultaneous application of the two systems provided enhanced functional performance compared with their individual applications. After drying, the treated and untreated fabric samples were conditioned under standard laboratory conditions before characterization.

2.2.4 Curing Treatment

After padding and drying, the treated nylon 6 fabric samples were subjected to two different curing methods. Thermal curing was performed in a laboratory oven at 160 °C for different curing times of 1- 5 min. In parallel, microwave curing was applied at different irradiation times of 30- 90 s under the selected microwave operating conditions. The curing treatments were applied to each of the three treatment systems, namely ZnO/TiO₂ nanoparticles alone, Biotriazole alone, and the combined ZnO/TiO₂-Biotriazole treatment. An untreated fabric was maintained as the control. The cured samples were subsequently conditioned under standard atmospheric conditions before characterization and performance evaluation.

2.3 Characterization of Treated Fabrics

The untreated and finished nylon 6 fabric samples were evaluated to determine the effect of the applied treatments and curing conditions on their dimensional stability, mass change, optical properties, wettability, and ultraviolet (UV) protection. The following evaluation methods were used.

2.3.1 Change in Weight

The change in fabric mass resulting from the application of the treatment agents was determined by weighing the nylon 6 specimens before and after treatment. The samples were weighed under controlled conditions, considering the moisture acquired by the specimens from the surrounding atmosphere. The percentage change in weight was calculated using the following equation:

$$\text{Weight change \%} = \frac{W_0 - W}{W_0} \times 100 \quad (1)$$

where W_0 represents the initial weight of the untreated fabric specimen (g), and W is the dry weight of the corresponding treated specimen (g) [29].

2.3.2 Area Shrinkage

The dimensional stability of the nylon 6 fabric was assessed by measuring the fabric dimensions before and after treatment. The length and width of each specimen were recorded, and the corresponding fabric area was calculated. The percentage shrinkage was determined from the change in fabric area according to the following equation:

$$\text{Shrinkage \%} = \frac{A_0 - A}{A_0} \times 100 \quad (2)$$

where A_0 is the original area of the fabric specimen before treatment (cm²), and A is the area measured after treatment (cm²). The calculation was performed according to the reported method [29].

2.3.3 Whiteness Index

The optical properties of the Nylon 6 fabrics were evaluated by measuring the changes in whiteness and yellowness resulting from the applied treatments. The measurements were performed using an Ultra Scan PRO

Hunter Lab spectrophotometer. The untreated fabric was used as a reference, and the changes in the corresponding whiteness indices were used to assess the influence of the treatment agents and curing conditions on the fabric appearance.

2.3.4 Wettability

The surface wettability of the untreated and treated nylon 6 fabrics was evaluated by determining the wetting time using the AATCC 39 method. A drop of distilled water was placed on the fabric surface from a fixed height, and the time required for the water droplet to disappear completely from the fabric surface was recorded. A shorter wetting time indicates greater surface wettability, whereas a longer time reflects increased hydrophobicity. Five measurements were performed for each specimen, and the mean value was reported [30, 31].

2.3.5 Ultraviolet Protection Factor (UPF)

The UV-protective performance of the untreated and treated nylon 6 fabrics was assessed by measuring their ultraviolet transmission using a JASCO U-750 UV/Vis spectrophotometer. The measurements were conducted across the UVA wavelength region of 315 - 400 nm and the UVB region of 280 - 315 nm. The ultraviolet protection factor (UPF) was subsequently determined from the spectral transmission data according to the AS/NZS 4399:1996 standard method, as described in the relevant AATCC procedure [29]. The UPF value was used to quantify the ability of the treated fabric to attenuate ultraviolet radiation compared with the untreated control.

III. Results and Discussion

3.1 Change in Weight

3.1.1 Before Curing

Weight change was measured after finishing and drying but before curing. All nylon 6 (PA6) fabric constructions were first subjected to the same Na_2CO_3 ultrasonic pretreatment before the application of the UV protective treatments. This pretreatment was maintained as a common processing condition rather than an experimental variable. Positive values represent weight gain, whereas negative values indicate weight loss. The results reflect the net mass change during finishing and drying and cannot be directly interpreted as a measure of finish fixation.

3.1.1.1 Effect of Fabric Structure and Treatment Formulation

The results in Tables 2–4 demonstrate that the precuring mass response depended on both fabric construction and treatment formulation. The ZnO/TiO_2 NPs treatment resulted in weight loss across all three structures, with mean values of -0.73% (SD = 0.113, CV = 15.51%) for full Lycra, -1.575% (SD = 0.601, CV = 38.16%) for half Lycra, and -0.715% (SD = 0.187, CV = 26.20%) for the fabric without Lycra. The greatest loss occurred in the half Lycra fabric, which also exhibited the highest variability among the nanoparticle treated specimens. These findings indicate that the nanoparticle treatment did not necessarily produce a net mass increase, despite introducing inorganic material. The observed losses may reflect the balance between material deposition and the removal of residual or loosely retained substances during processing; however, the individual contributions cannot be distinguished from weight measurements alone.

Biotriazole only treatment produced weight gain in all three constructions, with mean values of 0.485% (SD = 0.12, CV = 24.79%) for full Lycra, 0.44% (SD = 0.24, CV = 54.60%) for half Lycra, and 0.88% (SD = 0.40, CV = 45.45%) for the fabric without Lycra. The greatest gain was observed in the Lycra free fabric, whereas the half Lycra construction exhibited the highest relative variability. These positive values indicate that the specimens gained mass after treatment and drying. Such gains are consistent with the retention of finishing constituents, although the measured values cannot establish the actual quantity of Biotriazole deposited independently of other mass changes.

The combined ZnO/TiO_2 NPs/ biotriazole treatment exhibited a structure dependent response. The full Lycra fabric showed a mean weight loss of -1.01% (SD = 0.127, CV = 12.60%), whereas the half Lycra and Lycra free fabrics exhibited weight gains of 0.80% (SD = 0.141, CV = 17.68%) and 1.00% (SD = 0.141, CV = 14.14%), respectively. The opposite response of the full Lycra construction indicates that the combined formulation did not produce a uniform mass change pattern across the three fabric structures. The combined treatment resulted in the greatest weight gain for the Lycra free fabric, while the full Lycra fabric showed a net loss.

Table 2: Effect of treatment agents on change in weight of full Lycra PA6 fabric after drying

Type of sample	Change in weight (%)	Mean value %	σ	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	-0.81	-0.73	0.113	15.51
	-0.65			

Type of sample	Change in weight (%)	Mean value %	σ	CV (%)
Untreated sample	0	0	0	0
Treated with NPs & Bio triazole	-0.92	-1.01	0.127	12.60
	-1.1			
Treated with Bio triazole	0.4	0.485	0.12	24.79
	0.57			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105°C, 30 min.

Table 3: Effect of treatment agents on change in weight of half Lycra PA6 fabric after drying

Type of sample	Change in weight (%)	Mean value	σ	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	-1.15	-1.575	0.601	38.16
	-2			
Treated with NPs & Bio triazole	0.9	0.8	0.141	17.68
	0.7			
Treated with Bio triazole	0.61	0.44	0.24	54.6
	0.27			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105 °C, 30 min.

Table 4: Effect of treatment agents on change in weight of PA6 fabric without Lycra after drying

Type of sample	Change in weight (%)	Mean value	σ	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	-0.65	- 0.715	0.187	26.2
	-0.52			
	-0.96			
	-0.73			
Treated with NPs & Bio triazole	0.9	1	0.141	14.14
	1.1			
Treated with Bio triazole	1.16	0.88	0.40	45.45
	0.6			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105

This behaviour suggests that the mass response was influenced by the interaction between the finishing formulation and fabric construction during padding and drying, although the underlying mechanism was not directly established. Fabric structure and treatment formulation influenced slightly precuring mass changes. These reflect net mass balance, not fixation efficiency; durability should be assessed through post curing performance and UPF retention after washing.

3.1.2 Effect of Thermal Curing Time on Weight Change of PA6/Lycra Fabrics

Thermal curing at 160 °C was investigated to evaluate the weight change behavior of PA6 fabrics with different Lycra contents after treatment with ZnO/TiO₂ NPs, Biotriazole, and their combined formulation. All fabrics were padded at 100% pickup, treated with sonicated agent, and then dried at 105 °C for 30 min before curing. Figs. 1–3 show that weight change varies with curing duration, finishing formulation, and fabric construction. These results describe the mass response of the treated fabrics under thermal conditions but cannot alone establish chemical fixation, coating adhesion, or thermal degradation.

3.1.2.1 Effect of Finishing Formulation and Curing Duration

ZnO/TiO₂ treatment produced the highest weight change values. For full Lycra PA6, weight change increased from approximately 1.60% at 1 min to 2.15% at 5 min, with an excellent quadratic fit ($R^2 = 0.9999$), indicating

rapid mass increase followed by near stabilization. Half Lycra fabric showed a similar but more gradual increase to approximately 2.00% ($R^2 = 0.9257$), whereas PA6 without Lycra exhibited only a weak curing time dependence ($R^2 = 0.1829$). The relatively high response of the ZnO/TiO₂ system is consistent with the retention of nonvolatile inorganic nanoparticles on the fabric surface.

Incorporation of biotriazole reduced the overall weight change response compared with ZnO/TiO₂ alone and produced more formulation dependent behavior. The combined ZnO/TiO₂ NPs/biotriazole treatment increased from approximately 1.20 -1.50% to 1.40 -1.70% over the curing period, with strong linear relationships for half Lycra ($R^2 = 0.9143$) and PA6 without Lycra ($R^2 = 0.9878$), but greater fluctuation for full Lycra ($R^2 = 0.4346$). Biotriazole alone showed a progressive increase in full Lycra and PA6 without Lycra ($R^2 = 0.9938$ and 0.9806 , respectively), while the half Lycra fabric remained nearly unchanged ($R^2 = 0.0857$). Thus, ZnO/TiO₂ primarily contributed to mass retention through its nonvolatile inorganic content, whereas biotriazole introduced a more formulation and curing dependent response.

3.1.2.2 Influence of Lycra Content and Possible Mechanisms

Figs. 1–3 demonstrate that fabric construction influenced weight change behavior during thermal curing. Full Lycra fabrics generally exhibited more pronounced variations, whereas half Lycra fabrics showed comparatively gradual or stable responses. PA6 without Lycra displayed distinct trends, including stronger increases under certain treatments. These differences may be associated with variations in elastomeric content, yarn arrangement, and fabric structure, although the individual contribution of each factor cannot be isolated from the present data. The differences in weight change behavior may be associated with variations in fabric construction and the relative proportions of PA6 and elastomeric yarns. Full, half and free Lycra fabrics may differ in their response to heating and finishing agent retention. However, these effects cannot be attributed solely to Lycra content, as yarn arrangement and fabric structure may also contribute. The relationship between weight change and UV protection will be discussed later in conjunction with UPF and durability results, as weight change alone cannot establish UV-protective performance or finish retention. So, thermal curing affected the weight change behavior of PA6 fabrics, depending on Lycra content and finishing formulation. ZnO/TiO₂ generally produced the highest values, while the other treatments showed construction dependent trends.

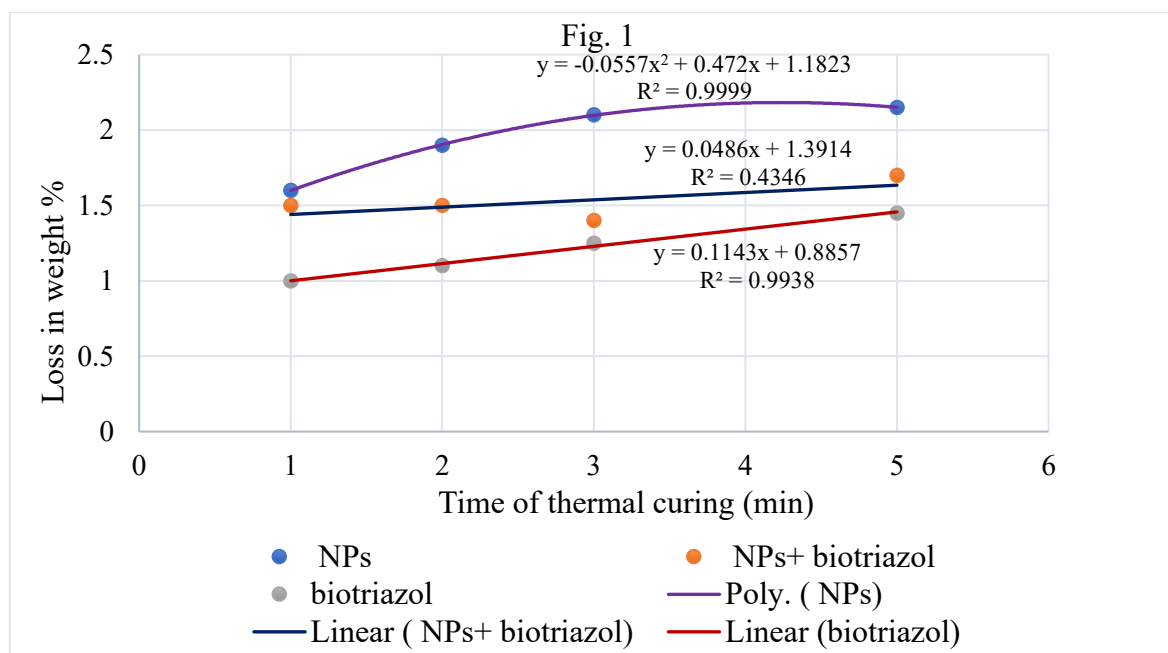


Fig. 1: Effect of thermal curing time on treated fabrics weight for full PA6/Lycra

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105 °C, 30 min. curing: 160 °C

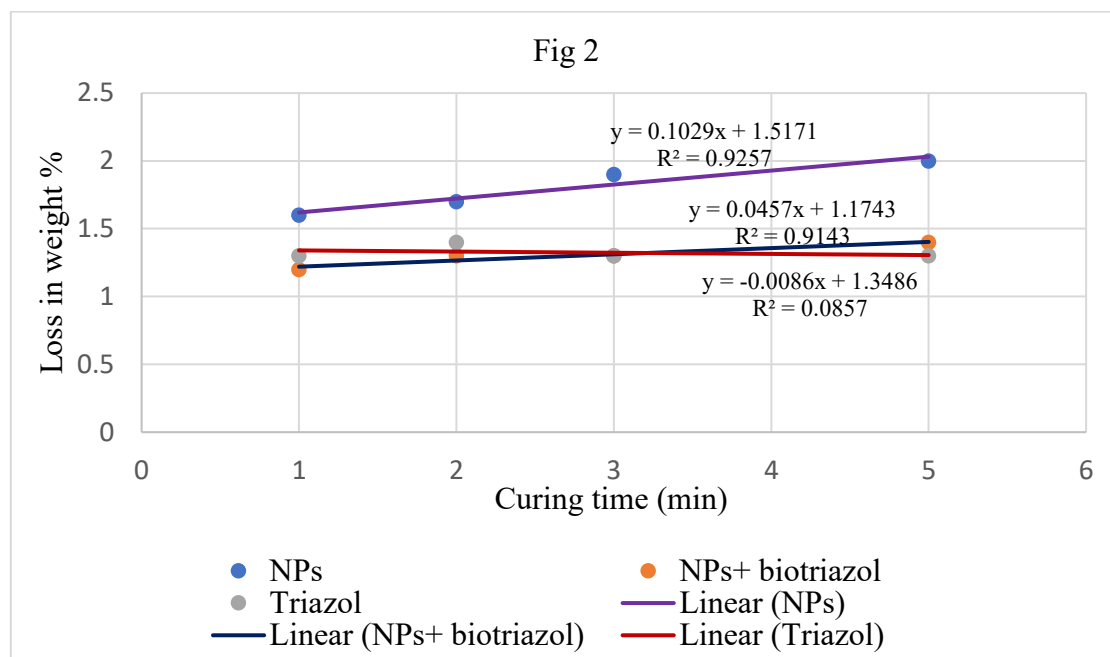


Fig. 2: Effect of thermal curing time on the treated fabric's weight for PA/ half Lycra
Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105 °C, 30 min. curing: 160 °C

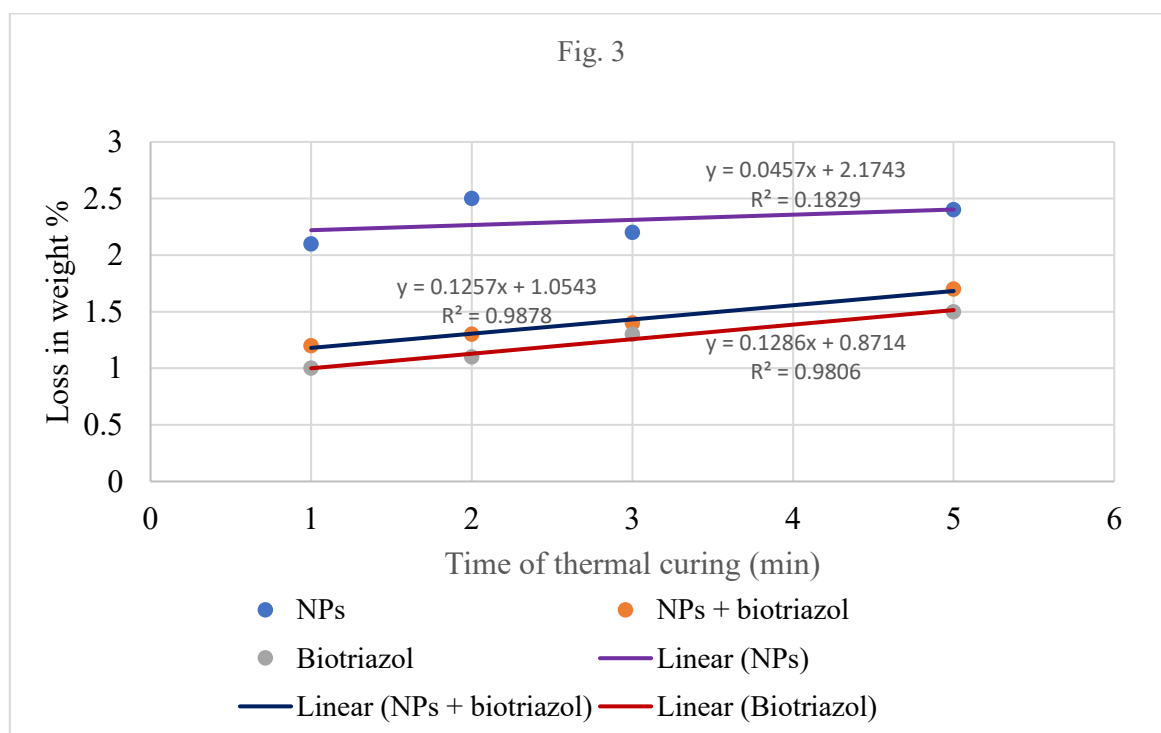


Fig. 3: Effect of thermal curing time on the treated fabric's weight for PA6 without Lycra
Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105 °C, 30 min. curing: 160 °C

3.1.3 Effect of Finishing Formulation and Microwave Curing Duration

After curing the microwave, the fabrics were washed to remove loosely adhered finishing components and then dried weight measured. ZnO/TiO₂ treatment produced negative weight changes (−1.10 to −2.30%), indicating a mass loss. The loss was most pronounced in half Lycra fabric and generally increased with curing duration, suggesting that prolonged microwave exposure promoted greater removal of volatile or weakly retained components. Because ZnO and TiO₂ are inorganic and nonvolatile under these conditions, the negative values reflect the mass balance rather than direct loss of nanoparticles alone (Table 5).

Biotriazole containing formulations produced positive weight changes, indicating net mass retention after washing. The combined ZnO/TiO₂NPs/biotriazole system remained relatively consistent at shorter curing times but increased to about 1.3% at 90 s, suggesting improved retention of the finishing system with extended microwave treatment. Biotriazole alone showed a similar positive response, with the most pronounced increase occurring for half Lycra fabric, reaching 2.50% at 90 s. This indicates that the organic biotriazole component contributed substantially to the retained mass following curing and washing. Microwave curing caused weight loss with ZnO/TiO₂ alone but weight gain with biotriazole containing treatments, indicating greater post washing mass retention. However, weight change alone cannot confirm fixation or finish durability.

Table 5: Effect of microwave curing duration on the weight change of treated PA6/Lycra fabrics

Type of sample	Microwave curing time (s)	Change in weight (%)		
		Full lycra	Half lycra	No lycra
Treated with ZnO/TiO ₂ NPs	30	-1.25	-1.6	-1.23
	45	-1.1	-1.8	-1.26
	60	-1.3	-2.1	-1.84
	90	-1.36	-2.3	-1.34
Treated with ZnO/TiO ₂ NPs + Biotriazole	30	0.8	1.2	0.8
	60	1.1	0.8	1.1
	90	1.29	1.3	1.29
Treated with Bio triazole	30	1.6	0.8	1.1
	60	1.3	1.92	1.3
	90	1.4	2.5	1.3

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min.

3.2 Area Shrinkage Before Curing

3.2.1 Effect of Fabric Structure and Finishing Formulation

Tables 6–8 show that area shrinkage after padding and drying at 105 °C for 30 min depending on both fabric construction and finishing formulation. The untreated fabrics exhibited no shrinkage, whereas all treated samples showed dimensional contraction, with responses varying according to the presence of Lycra and the applied treatment agent. ZnO/TiO₂ NPs treatment produced the lowest shrinkage in full Lycra fabric (3.45%), compared with 4.82% for half Lycra and 3.20% for PA6 without Lycra. Biotriazole treatment resulted in shrinkage of 4.60% in both Lycra containing fabrics, but only 2.75% in PA6 without Lycra. The combined treatment showed a distinct structure dependent response: shrinkage was highest in full Lycra fabric (5.05%), intermediate in half Lycra (4.30%), and 4.50% in the fabric without Lycra.

These results indicate that the effect of finishing agents on dimensional stability was dependent on fabric construction. The greater shrinkage of Lycra containing fabrics may be associated with elastic relaxation and changes in knitted loop geometry during wet processing and drying. ZnO/TiO₂ treatment was associated with lower shrinkage in full Lycra fabric, whereas the combined formulation produced the highest value for this structure. The proposed mechanisms remain tentative because loop geometry, finish distribution, and relaxation were not directly characterized. Variability was generally low, particularly for half Lycra samples (CV = 0.75-3.29%), indicating good repeatability. The combined treatment showed structure dependent shrinkage, reflecting fabric architecture and formulation rather than finish fixation (Table 7).

Table 6: Effect of treatment agents on area shrinkage of full Lycra PA6 fabric after drying

Type of sample	Area shrinkage (%)	Mean value	St. deviation (σ)	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	3.81	3.45	0.34	9.8
	3.44			
	3.55			
	3			

Type of sample	Area shrinkage (%)	Mean value	St. deviation (σ)	CV (%)
Untreated sample	0	0	0	0
Treated with NPs / Biotriazole	5	5.05	0.07	1.4
	5.1			
Treated with Biotriazole	4.5	4.6	0.14	3.07
	4.7			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105 °C, 30 min.

Table 7: Effect of treatment agents on area shrinkage of half Lycra PA6 fabric after drying

Type of sample	Area shrinkage (%)	Mean value	St. deviation (σ)	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	4.8	4.82	0.036	0.75
	4.85			
Treated with NPs & Bio triazole	4.2	4.3	0.141	3.29
	4.4			
Treated with Bio triazole	4.5	4.6	0.141	3.07
	4.7			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105 °C, 30 min.

Table 8: Effect of treatment agents on area shrinkage of PA6 fabric without Lycra after drying

Type of sample	Area shrinkage (%)	Mean value	St. deviation (σ)	CV (%)
Untreated sample	0	0	0	0
Treated with NPs	3.1	3.2	0.183	5.71
	3			
	3.3			
	3.4			
Treated with NPs & Bio triazole	4.7	4.5	0.28	6.29
	4.3			
Treated with Bio triazole	2.9	2.75	0.21	7.7
	2.6			

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105 °C, 30 min.

3.2.2 Effect of Thermal Curing on the Dimensional Stability of PA6/Lycra Fabrics

Fig. 4 illustrates the effect of thermal curing duration on area shrinkage of PA6 fabrics with different Lycra contents. Shrinkage increased with curing time across all formulations, indicating progressive thermally induced dimensional contraction. This behavior is consistent with heat induced relaxation of knitted loops and changes in yarn configuration, particularly in elastane containing structures. Similar effects of heat setting conditions on knitted fabric dimensions have been reported in the literature [32, 33].

Biotriazole treated fabrics exhibited the highest shrinkage, reaching approximately 2.9% for full Lycra, 2.7% for half Lycra, and 1.7% for non-Lycra fabric at 5 min. The combined ZnO/TiO₂ NPs/ biotriazole treatment showed intermediate to high values, while ZnO/TiO₂ alone generally produced lower shrinkage. This suggests that the finishing formulation influenced the fabric's dimensional response during heating. Across all treatments, fabrics without Lycra showed substantially lower shrinkage than Lycra containing fabrics, highlighting the contribution of fabric construction and elastomeric yarns to thermal dimensional behavior. Heat induced shrinkage in knitted fabrics is also associated with changes in loop geometry and yarn relaxation. Longer curing increased area shrinkage, depending on the finish and fabric construction, highlighting the importance of curing duration for dimensional stability.

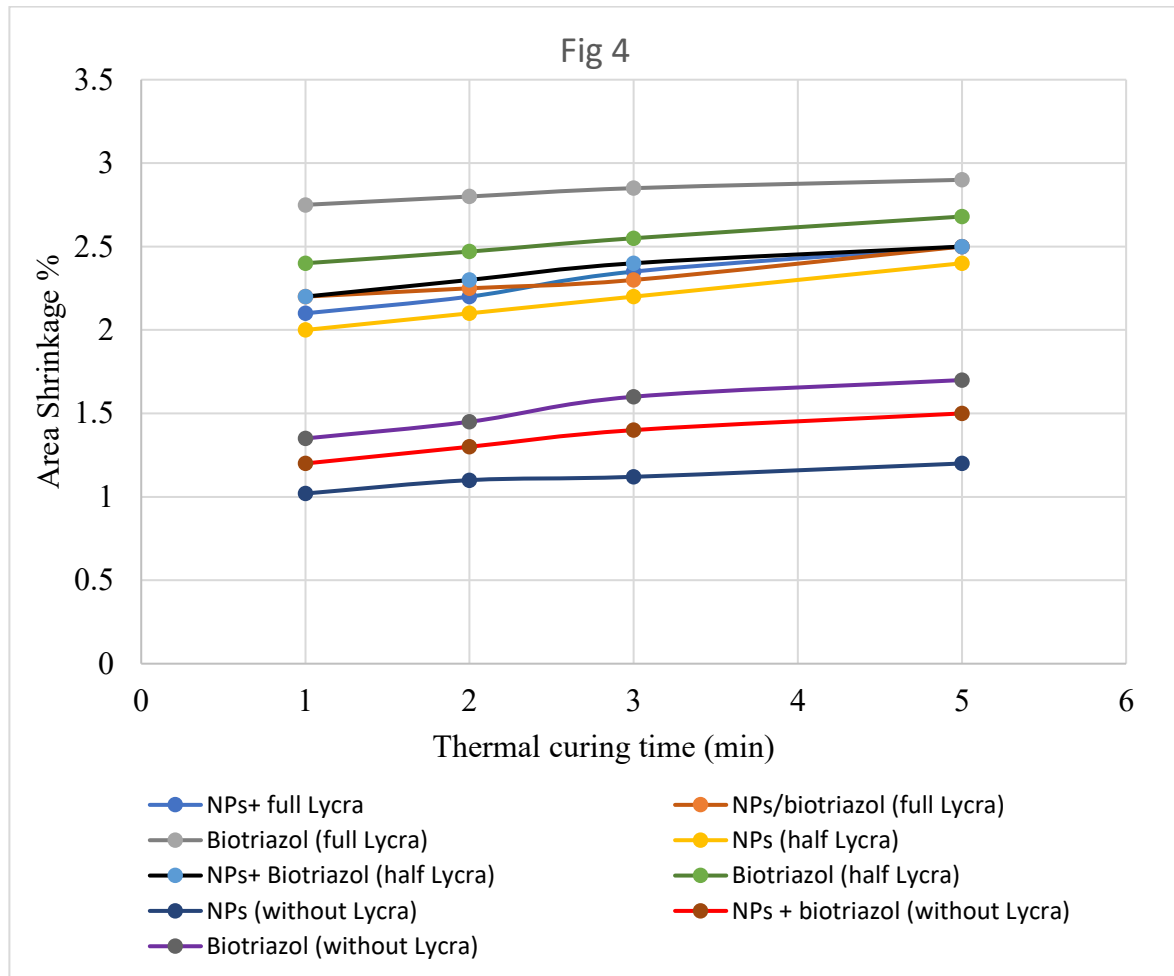


Fig. 4: Thermal curing-induced area shrinkage of PA6 fabrics with varying Lycra contents and UV-protective finishes.
 Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), 3% (owf) Biotriazole, sonication: 7 min, drying: 105 °C, 30 min., Curing: 160°C

3.2.3 Effect of Microwave Curing Time on the Dimensional Stability of PA6/Lycra Fabrics

As shown in Table 9, extending microwave curing generally increased area shrinkage, with the extent of dimensional change influenced by fabric construction and finishing formulation. ZnO/TiO₂ NPs treated fabrics exhibited shrinkage increases from 1.9 to 2.5% (full Lycra), 1.8 to 2.1% (half Lycra), and 0.9 to 1.15% (no Lycra) as curing time increased from 30 to 90 s. The hybrid treatment showed a similar response, whereas biotriazole treated fabrics displayed a slight irregularity in the no Lycra samples. Full Lycra fabrics generally showed greater shrinkage, while no Lycra fabrics exhibited comparatively limited dimensional changes. These findings suggest that prolonged microwave exposure promotes dimensional changes, potentially through moisture removal, polymer-chain relaxation, and the response of the elastic component [32- 35].

Table 9: Effect of microwave curing duration on area shrinkage of treated PA6/Lycra fabrics

Type of sample	Microwave curing time (s)	Area Shrinkage (%)		
		Full Lycra	Half Lycra	No Lycra
Treated with ZnO/TiO ₂ NPs	30	1.9	1.8	0.9
	45	1.95	1.86	1
	60	2.1	1.9	1.1
	90	2.5	2.1	1.15
Treated with ZnO/TiO ₂ NPs / Biotriazole	30	2	2.1	1.2
	60	2.2	2.19	1.3
	90	2.3	2.22	1.39

Type of sample	Microwave curing time (s)	Area Shrinkage (%)		
		Full Lycra	Half Lycra	No Lycra
Treated with Bio triazole	30	2.4	2	1.1
	60	2.5	2.1	1.7
	90	2.6	2.2	1.22

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min.

3.3 Wettability

Tables 10 and 11 demonstrate that curing conditions, finishing formulation, and fabric construction jointly influenced the wetting time of the PA6/Lycra fabrics. Since wettability time represents the time required for water to penetrate the fabric surface, lower values indicate more rapid wetting and, consequently, greater surface affinity for water. Fabric architecture can substantially affect liquid transport because yarn arrangement, pore geometry, and surface characteristics govern capillary flow in knitted materials [36, 37].

3.3.1 Thermal Curing

The untreated fabrics exhibited wetting times of 3.0, 2.1, and 1.9 s for full-, half-, and no-Lycra constructions, respectively, providing the reference condition for evaluating the finishing treatments. ZnO/TiO₂ treatment reduced the wetting time relative to the untreated fabric, with the reduction becoming more pronounced as thermal curing increased from 1 to 5 min. At 5 min, wetting times reached 2.20, 1.80, and 1.68 s for full-, half-, and no-Lycra fabrics, corresponding to reductions of approximately 26.7%, 14.3%, and 11.6%, respectively, relative to their untreated counterparts. The ZnO/TiO₂ NPs/Biotriazole formulation produced an even shorter wetting time for the full Lycra fabric, reaching 1.50 s, equivalent to a 50% reduction compared with the untreated sample. Half - Lycra and no - Lycra fabrics reached 1.85 and 1.70 s, representing reductions of 11.9% and 10.5%, respectively. Biotriazole alone caused comparatively smaller changes, with reductions of 30.0%, 9.5%, and 5.3% in full -, half-, and no-Lycra fabrics, respectively, at 5 min. The comparison with the untreated controls therefore demonstrates that the finishing treatments generally shortened the wetting time, although the magnitude of change depended on both formulation and fabric construction.

Table 10: Effect of thermal curing duration on wettability of treated PA6/Lycra fabrics

Type of sample	Thermal curing time (min)	Wettability (s)		
		Full Lycra	Half Lycra	No Lycra
Untreated sample	0	3	2.1	1.9
Treated with ZnO/TiO ₂ NPs	1	2.8	2.1	1.9
	2	2.65	1.94	1.8
	3	2.46	1.84	1.7
	5	2.2	1.8	1.68
Treated with ZnO/TiO ₂ NPs + Biotriazole	1	1.5	2.1	1.8
	3	1.5	1.9	1.7
	5	1.5	1.85	1.7
Treated with Bio triazole	1	2.2	2.1	1.9
	3	2.2	1.95	1.9
	5	2.1	1.9	1.8

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min., curing: 160 °C

3.3.2 Microwave Curing

Microwave curing generally reduced wetting time with increasing exposure from 30 to 90 s, although the magnitude of change varied with treatment and fabric construction. Relative to the untreated controls (3.00, 2.10, and 1.90 s for full-, half-, and no-Lycra fabrics), ZnO/TiO₂ treatment reduced wetting time to 1.60, 1.74, and 1.40 s at 90 s, corresponding to reductions of 46.7%, 17.1%, and 26.3%, respectively. The ZnO/TiO₂ NPs/Biotriazole treatment produced final values of 2.10, 1.80, and 1.40 s, while biotriazole alone reached 1.50, 1.60, and approximately 1.50 s for the same constructions. Hence, all treatments generally produced shorter wetting

times than the untreated fabrics, with the response depending on both finishing formulation and knitted structure. The reduction in wetting time may reflect changes in finish distribution and surface characteristics during microwave curing, together with differences in capillary pathways within the knitted substrates [36 - 39]. The consistently shorter wetting times observed for non-Lycra fabrics should therefore be interpreted as a combined effect of fabric architecture and finishing treatment rather than as an intrinsic effect of Lycra absence. Yarn arrangement, pore geometry, and accessible surface characteristics can substantially influence liquid transport in knitted fabrics [36, 37].

Both curing methods shortened wetting time, with the response determined by the finishing formulation and fabric construction. Microwave curing showed a more pronounced time dependent reduction, highlighting the combined influence of curing conditions and textile structure on wettability.

Table 11: Effect of microwave curing duration on wettability of treated PA6/Lycra fabrics

Type of sample	Microwave curing time (s)	Wettability (s)		
		Full Lycra	Half Lycra	No Lycra
Untreated sample	0	3	2.1	1.9
Treated with ZnO/TiO ₂ NPs	30	1.95	2.1	1.5
	45	1.77	2.0	1.5
	60	1.72	1.8	1.5
	90	1.6	1.74	1.4
Treated with ZnO/TiO ₂ NPs / Biotriazole	30	2.3	1.9	1.5
	60	2.3	1.85	1.5
	90	2.1	1.8	1.4
Treated with Biotriazole	30	1.6	1.8	1.6
	60	1.5	1.76	1.6
	90	1.5	1.6	1.5

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min.

3.4 Whiteness Index (W.I.)

The influence of curing method, duration, and formulation type on the whiteness index (W.I.) of PA6 fabrics with varying Lycra contents (0%, 50%, and 100%) is presented in Tables 12 and 13. The treatment type and thermal energy delivery mechanism significantly dictate the visual brightness of the functionalized substrates.

Table 12: Effect of thermal curing duration on whiteness of treated PA6/Lycra fabrics

Type of sample	Thermal curing time (min)	Whiteness index (W.I)		
		Full Lycra	Half Lycra	No Lycra
Untreated sample	0	90.35	90.0	89.5
Treated with ZnO/TiO ₂ NPs	1	93.94	99.7	93.95
	2	92.46	93.5	93.86
	3	91.64	92.1	92.06
	5	89.03	87.45	89.65
Treated with ZnO/TiO ₂ NPs / Biotriazole	1	92.72	95.1	78.29
	3	91.7	82.17	68.65
	5	91.1	80.93	65.59
Treated with Biotriazole	1	79.4	82.1	77.38
	3	76.71	80.93	68.34
	5	73.96	78.5	67.62

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min., curing: 160 °C

Table 13: Effect of microwave curing duration on whiteness of treated PA6/Lycra fabrics

Type of sample	Microwave curing time (s)	Whiteness index (W.I)		
		Full Lycra	Half Lycra	No Lycra
Untreated sample	0	90.35	90.0	89.5
Treated with ZnO/TiO ₂ NPs	30	94.91	90.6	99.1
	45	90.84	90.44	96.45
	60	82.81	90.16	95.01
	90	65.03	87.11	92.99
Treated with ZnO/TiO ₂ NPs + Biotriazole	30	76.58	83.2	77.82
	60	71.65	80.1	77.13
	90	77.44	79.2	71.58
Treated with Bio triazole	30	76.7	82.8	74.76
	60	73.99	76.76	68.34
	90	72	73.96	67.62

Padding, 100% pick up, 1% (owf) ZnO: TiO₂ (1:1), Biotriazole 3% (owf), sonication: 7 min, drying: 105°C, 30 min.

3.4.1 Effect of Formulation Type

Across both curing methods, fabrics treated with pure inorganic nanoparticles ZnO/TiO NPs exhibited the highest initial whiteness index values (reaching up to 99.70 for half Lycra under thermal curing and 99.10 for no Lycra under microwave curing), noticeably exceeding the untreated baseline controls (~89.5 - 90.35). This optical enhancement is attributed to the high refractive index and light scattering capability of TiO and ZnO NPs on the fiber surfaces. The introduction of biotriazole, either alone or in combination with the NPs, resulted in a lower whiteness index (ranging between ~65.59 and 95.10). This reduction stems from the intrinsic light absorption and subtle yellowish hue imparted by organic triazole based UV absorbers [36-39].

3.4.2 Effect of Curing Method and Duration

The optical properties of the functionalized fabrics were strongly influenced by both the energy application method and the exposure duration during the fixation process. Across all evaluated substrates, expanding the curing timeframe continuously compromised fabric brightness, resulting in a steady decline in the whiteness index for both thermal processing at 160 °C and microwave radiation. Conventional thermal heating over an extended period from 1 to 5 minutes promoted progressive thermal browning, a phenomenon primarily attributed to the localized thermo-oxidative breakdown of the polymeric structure, with the sensitive soft polyurethane domains in the Lycra component being particularly susceptible. Microwave radiation facilitated rapid fixation that preserved maximum whiteness at brief durations, such as 30 seconds. However, extending microwave exposure up to 90 seconds induced a significantly sharper degradation in whiteness compared to conductive heating, an effect most prominently observed in the full Lycra substrate treated with ZnO/TiO NPs, where the index dropped drastically from 94.91 to 65.03. This heightened sensitivity under prolonged microwave exposure stems from rapid, core to surface volumetric heating combined with localized dielectric hot spot formation, which together accelerate the thermal yellowing kinetics of the elastomeric fibers far more aggressively than standard thermal methods [36-39].

3.4.3 Substrate Composition Influence

The elastomeric content plays a crucial role in thermal stability. Samples with higher polyamide 6 ratios (no Lycra and half Lycra) maintained superior whiteness stability during extended heating compared to full Lycra. The combination treatment ZnO/TiO NPs / biotriazole under short thermal curing (1 min) demonstrated the most balanced tradeoff between functional UV finish loading and aesthetic brightness retention across all substrate blends [35-39].

3.5 Ultraviolet Protection Factor (UPF) Performance

The ultraviolet protection properties of functionalized polyamide 6 (nylon 6) knitted fabrics were systematically evaluated across three distinct blend configurations: Full Lycra (Table 14), half Lycra (Table 15), and no Lycra (Table 16). The percentage improvement in UPF compared to the pristine, untreated control substrate was calculated using the following equation:

$$\% \text{ increase in UPF} = [(\text{UPF treated} - \text{UPF untreated}) / \text{UPF untreated}] \times 100 \quad (3)$$

UPF enhancement across all treatments was strongly governed by chemical composition, Lycra content, curing technology, and exposure duration.

3.5.1 Influence of Lycra Content

The intrinsic UPF of the untreated controls scaled directly with the proportion of Lycra present in the knit construction, yielding values of 355, 272 and 172 for untreated full, half, and no Lycra substrates respectively. This result may be due to the differences in fabric tightness factor, mass per unit area, and fiber cross-sectional geometry. Elastomeric Lycra (polyurethane) yarns contract after knitting, increasing fabric density and reducing inter yarn cover factor pores. Consequently, the denser full Lycra construction physically blocks UV radiation transmission more effectively than the more open, un-elastomer PA6 structure prior to chemical finishing [35].

3.5.2 Performance of ZnO/TiO₂ NPs Finish

ZnO/TiO₂ NPs substantially enhanced the UV protective performance of the treated fabrics compared with the untreated materials. The improvement is primarily attributed to the complementary optical properties of ZnO and TiO₂, which can attenuate ultraviolet radiation through strong absorption and scattering [35]. Their wide band gap semiconductor structures enable efficient interaction with incident UV radiation, while the deposited nanoparticles can increase the probability of UV interception at the fabric surface. The highest enhancement recorded was a UPF of 3893, corresponding to a 2163.37% increase relative to the untreated fabric. Other treated samples also exhibited substantial improvements, including a UPF of 1670 (+370.42%) and 1500 (+322.54%). Although the magnitude of protection varied among the measured samples, all these values demonstrate the strong UV screening capability imparted by the ZnO/TiO₂ treatment. The reduction in UPF observed in some specimens indicates that the UV protective efficiency of ZnO/TiO₂ is also influenced by the stability and distribution of the nanoparticle layer.

Table 14: Effect of curing method and duration on UPF and percentage improvement relative to untreated nylon 6 - full Lycra knitted fabric

Type of sample	Curing time		UPF		% Increase in UPF	
	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)
Untreated sample	0	0	355	355	0.00	0.00
Treated with ZnO/TiO ₂ NPs	1	30	1670	1500	370.42	322.54
	2	45	1500	1498	322.54	321.97
	3	60	1270	1277	257.75	259.72
	5	90	1120	1214	215.49	242.00
Treated with ZnO/TiO ₂ NPs / Biotriazole	1	30	3560	1570	902.82	342.25
	3	60	3380	1940	852.11	446.48
	5	90	6500	1620	1730.99	356.34
Treated with Biotriazole	1	30	1100	2458	209.86	592.39
	3	60	2300	3055	547.89	760.56
	5	90	2520	2450	609.86	590.14

3.5.3 Effect of the hybrid ZnO / TiO₂ / benzotriazole treatment

The hybrid treatment substantially enhanced UV protection, particularly under thermal curing. UPF increased from 355 for the untreated fabric to 3560 after 1 min and reached 6500 after 5 min, corresponding to increases of 902.82% and 1730.99%, respectively. While microwave curing produced a maximum UPF of 1940 at 60 s (446.48%), which decreased to 1620 at 90 s. The higher UPF values obtained with thermal curing indicate that the performance of the hybrid finish depended strongly on the curing method and duration. The improvement may reflect the combined UV attenuation mechanisms of benzotriazole, which absorbs UV radiation, and ZnO/TiO₂ NPs, which contribute through absorption and scattering. The present results demonstrate enhanced performance of the combined treatment [38, 39]. The ZnO/TiO₂ NPs / biotriazole hybrid treatment produced a marked improvement in UV protection. For full Lycra fabric, UPF increased from 355 for the untreated sample to 3560 after 1 min and 6500 after 5 min of thermal curing, corresponding to increases of 902.82% and 1730.99%, respectively. Microwave curing produced a maximum UPF of 1940 at 60 s (+446.48%), which decreased to 1620 at 90 s. Substantial improvements were also obtained for the half- and no-Lycra fabrics, with thermal curing reaching maximum UPF values of 1706 and 2514, respectively. These results demonstrate the strong UV screening capability of combining ZnO/TiO₂ NPs with Biotriazole, arising from the complementary absorption and scattering functions of the inorganic nanoparticles and the UV-absorbing triazole component [35].

Table 15: Effect of curing method and duration on UPF and percentage improvement relative to untreated nylon 6 - half Lycra knitted fabric

Type of sample	Curing time		UPF		% increase in UPF	
	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)
Untreated sample	0	0	272	272	0.00	0.00
Treated with ZnO/TiO ₂ NPs	1	30	444	380	63.24	39.70
	2	45	379	386	39.33	41.91
	3	60	552	386	102.94	41.91
	5	90	475	357	74.63	31.25
Treated with ZnO/TiO ₂ NPs + Biotriazole	1	30	1706	1045	527.20	284.19
	3	60	1268	1100	366.17	304.41
	5	90	1563	1200	474.63	341.17
Treated with Bio triazole	1	30	1100	2458	304.41	803.67
	3	60	2300	3055	745.59	1023.16
	5	90	2520	2450	826.47	800.74

Table 16: Effect of curing method and curing time on the UPF of nylon 6 knitted fabric without Lycra

Type of sample	Curing time		UPF		% increase in UPF	
	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)	Thermal (min)	Microwave (s)
Untreated sample	0	0	172	172	0.00	0.00
Treated with ZnO/TiO ₂ NPs	1	30	333	3893	93.60	2163.37
	2	45	526	498	205.81	189.53
	3	60	633	543	268.02	215.70
	5	90	630	597	266.28	247.09
Treated with ZnO/TiO ₂ NPs + Biotriazole	1	30	2004	982	1065.12	470.93
	3	60	1826	901	961.63	423.84
	5	90	2514	807	1361.63	369.19
Treated with Bio triazole	1	30	1000	1200	481.40	597.67
	3	60	1835	2050	966.86	1091.86
	5	90	2500	2450	1353.49	1324.42

3.5.4 Effect of Benzotriazole Treatment

Benzotriazole treatment markedly enhanced the UV protective performance of the knitted fabric, with the magnitude of improvement governed by both curing method and duration. Thermal curing produced a continuous increase in UPF with increasing treatment time, whereas microwave curing showed an optimum at 60 s, followed by a decline at 90 s. The higher maximum UPF obtained by microwave curing (3055) compared with thermal curing (2520), together with its shorter processing time, demonstrates the potential of microwave assisted fixation for achieving efficient benzotriazole based UV protection. The decline at prolonged microwave exposure indicates that excessive treatment time may adversely affect the resulting UV protective performance.

3.5.5 Comparative Evaluation of Curing Technologies

The effect of curing technology was strongly dependent on the chemical system and treatment duration. ZnO/TiO₂ showed a transition from better performance under thermal curing at shorter durations to slightly higher UPF under microwave curing at longer durations. The hybrid treatment responded more favorably to thermal curing throughout the investigated conditions, whereas benzotriazole generally benefited from microwave curing at shorter and intermediate durations.

The results suggest that curing method, duration, and finishing formulation interact to determine the final UV protective performance. Microwave curing offers an important processing advantage through its shorter exposure time, but this benefit does not necessarily translate into the highest UPF for every formulation. So, curing

conditions should be optimized specifically for each finishing system by considering the combined effects of UPF enhancement, treatment duration, and process efficiency.

IV. Conclusion

This study established the relationship between knitted fabric structure, functional finishing chemistry, and fixing technology for the development of UV protective polyamide 6 sportswear. Elastomeric yarn incorporation significantly influenced the baseline UV protection, with untreated full Lycra fabric exhibiting a UPF of 355, compared with 272 for half-Lycra and 172 for the Lycra-free structure. This improvement is associated with greater fabric compactness and reduced inter-yarn porosity. Although ZnO/TiO₂ NPs and Biotriazole individually enhanced UV protection, the hybrid ZnO/TiO₂ NPs/Biotriazole treatment provided the strongest shielding through complementary UV absorption and scattering mechanisms.

Fixing conditions strongly influenced the performance of the applied reagents. Thermal curing at 160 °C was particularly effective for the hybrid system, with full Lycra fabric reaching a maximum UPF of 6500 after 5 min, corresponding to a 1730.99% increase over the untreated fabric. Microwave curing also provided high UV protection within substantially shorter processing times, with the Biotriazole treatment reaching a maximum UPF of 3055 after 60 s. Combining an appropriate fabric architecture with multifunctional finishing and optimized curing conditions provides an effective approach for producing lightweight sportswear with enhanced UV protection.

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