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Effect of lignin/water-borne polyurethane composite coatings on tensile strength and UV protection properties of PET/PA6 bicomponent nonwoven fabrics

Lignin/su bazlı poliüretan kompozit kaplamaların PET/PA6 bikomponent dokunmamış kumaşların kopma mukavemeti ve UV koruma özelliklerine etkisi

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Abstract

This study involves the preparation of water-borne polyurethane (WPU)/lignin composite coating formulations at four distinct unmodified alkali lignin concentrations (1%, 3%, 5%, and 10%) and their application to polyester/polyamide (PET/PA6) bicomponent nonwoven fabrics. These formulations were applied to PET/PA6 bicomponent nonwoven fabrics using a coating applicator and subsequently thermally cured. The properties of the coated and thermally cured fabrics, including tensile strength, hydrophobicity, and ultraviolet light (UV) protection, were investigated. Furthermore, Fourier Transform Infrared (FTIR) spectroscopy was employed to analyze the cured films prepared from formulations with varying lignin concentrations. As the lignin concentration increased, there was a notable enhancement in both tensile strength and UV protection factors (UPF). While the hydrophobicity of the surface diminished due to the presence of WPU, higher lignin concentrations resulted in increased surface contact angle values. Despite the decrease in surface hydrophobicity due to the water-based polyurethane, elevated lignin concentrations contributed to higher surface contact angle values. The UV protection values of coated fabrics exhibited a significant improvement compared to untreated nonwoven fabric. The highest UPF value of 30.16 was achieved with the formulation having the highest lignin concentration (10%). This research introduces a straightforward method for creating environmentally friendly and sustainable multifunctional WPU/lignin coatings, offering promising applications in the textile industry.

Keywords: Bicomponent nonwoven, Water-borne polyurethane, Lignin, Ultraviolet protection.

Öz

Bu çalışma, dört farklı modifiye edilmemiş alkali lignin konsantrasyonunda (%1, %3, %5 ve %10) su bazlı poliüretan (WPU)/lignin kompozit kaplama formülasyonlarının hazırlanmasını ve poliester/poliamid (PET/PA6) bikomponent dokunmamış kumaşlara uygulanmasını içermektedir. Bu formülasyonlar, bir kaplama aplikatörü kullanılarak PET/PA6 bikomponent dokunmamış kumaşlara uygulanmış ve ardından ısı ile fikse edilmiştir. Kaplanmış ve ısıl olarak fikse edilen kumaşların kopma mukavemeti, hidrofobiklik ve ultraviyole ışığa (UV) karşı koruma özellikleri araştırılmıştır. Ayrıca, farklı lignin konsantrasyonlarına sahip formülasyonlarla hazırlanan kürlenmiş filmlerin karakterizasyonlarının analizi için Fourier Dönüşümü Kızılötesi (FTIR) spektroskopisi kullanılmıştır. Lignin konsantrasyonu arttıkça hem kopma mukavemetinde hem de UV koruma faktörlerinde (UPF) dikkate değer bir artış olmuştur. Su bazlı poliüretanın varlığı nedeniyle yüzeyin hidrofobikliği azalırken, yüksek lignin konsantrasyonları yüzey temas açısı değerlerinin artmasına neden olmuştur. Su bazlı poliüretan nedeniyle yüzey hidrofobikliğinin azalmasına rağmen, yüksek lignin konsantrasyonları daha yüksek yüzey temas açısı değerlerine katkıda bulunmuştur. Kaplamalı kumaşların UV koruma değerlerinde, işlem görmemiş dokunmamış kumaşlara göre önemli bir gelişme görülmüştür. En yüksek UPF değeri olan 30.16, en yüksek lignin konsantrasyonuna (%10) sahip olan formülasyonda elde edilmiştir. Bu araştırma, tekstil endüstrisinde umut verici uygulamalar sunan, çevre dostu ve sürdürülebilir çok işlevli WPU/lignin kaplamaları oluşturmak için basit bir yöntem sunmaktadır.

Anahtar kelimeler: Bikomponent nonwoven, Su bazlı poliüretan, Lignin, Ultraviyole koruma.

1 Introduction

Nonwoven fabrics (NWFs) are composed of individual fibers intricately entangled, bonded, or felted together. These fibers are joined through heat, chemical or creating fiber entanglement with mechanical treatments. Nonwovens boast shorter production times and lower costs due to fewer manufacturing steps compared to woven or knit fabrics and widely used in applications not requiring traditional apparel construction. Nonwovens, being cost-effective, find suitability in disposable items like wipes, feminine hygiene products, and diapers. Additionally, they exhibit versatility in aerospace, providing acoustic and thermal insulation, composite materials for industrial use and vehicle seats [1],[2]. Nonwovens are engineered fibrous assemblies with planned structural integrity, excluding weaving, knitting, or papermaking. They compete with traditional textiles and paper products and are known for their versatility in fiber composition, structure, and performance. The nonwoven manufacturing industry is profitable and sophisticated, holding a crucial role in the global fiber products sector. Despite its success, environmental concerns arise due to the prevalent use of petrochemical-based materials, particularly concerning microplastic generation. Bi-component fibers like polyester/polyamide 6 (PET/PA6) have

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become dominant in nonwoven fabrics, finding diverse applications and widespread use in this category [3]. Bicomponent technology utilizes high-pressure water jets to disentangle split-type fibers, creating environmentally friendly, high-strength and lightweight bicomponent filament microfiber nonwovens. An example of this technology is seen in the development of PET/PA6 microfiber nonwoven material [4]. These nonwovens have gained global prominence for their eco-friendly, lightweight, and high-strength properties [5].

The rapid progress in the technical textile sector has heightened the demand for functional textiles. With growing environmental concerns linked to the use of toxic chemicals in modification processes, there is a noticeable shift towards adopting biodegradable coating systems [6]. When applied to a surface, coating materials transform into a solid film, taking the form of liquid, paste, or powder. This film possesses desired properties, whether protective, decorative, or aligned with material content. Polyurethanes (PUs) stand out as a crucial polymer class in the coatings industry, celebrated for their outstanding mechanical, chemical, and physical attributes [7]. Research has intensified in the development of water-borne polyurethane (WPU) coated fabrics with waterproofing and high mechanical performance, leveraging benefits like non-toxicity and biodegradability. However, challenges arise as many WPU-coated fabrics experience reduced functionality due to structural issues induced by high temperatures, UV radiation, rain, and oxygen. This poses a significant hurdle in creating robust UV protective materials for textiles. Critical studies explore sustainable textile surface functionality while minimizing environmental impact. On the other hand, commercially available antioxidants and organic/inorganic UV absorbers aim to shield polymeric materials and human skin from UV radiation, but their limited biodegradability restricts applications and generate free radicals with potential health effects [8].

In the past decade, "lignin" has become a focal point in discussions about renewable polymers and related materials. Lignin is a vital component in the forest industry and with its amphiphilic structure, lignin exhibits surface-active properties, strengthening interfaces, particularly in adhesive applications. Its abundant availability from renewable sources and unique physicochemical properties make lignin a subject of increasing attention in both fundamental and applied fields across various disciplines [9]. Global lignin production, exceeding 50 million tons annually, mainly comes as a byproduct from biorefineries. Approximately 98% of this lignin is incinerated for energy, with only a minimal 2% applied in areas like dispersants, adhesives, and fillers. Despite challenges, lignin, when unmodified, can be directly incorporated into polymeric matrices, serving various purposes like antioxidant, flame retardant, UV stabilizer and plasticizer. This integration reduces production costs and dependence on traditional plastics, offering potential for enhanced material properties. It acts as a compatibilizer, reinforcing the interface between hydrophilic fibers and hydrophobic matrix polymers [10]. Different lignin types, with kraft lignin being a standout choice, can be incorporated into composites. Kraft lignin is easily accessible and abundant, can be fractionated to produce materials with diverse functional groups, offering advantages across various applications. The carbon-rich composition of lignin imparts natural hydrophobicity, protecting wood against pathogens and aiding water transportation within the wood structure. Apart from hydrophobicity, lignin's chemical attributes like solubility, stability and small particle size make it suitable for developing lignin-based coatings [11]. Lignin, with its aromatic structure, enhances the mechanical strength and thermal properties of different materials such as blends, copolymers, and composites. The final properties of adhesives are influenced by the quantity and chemical composition of lignin. Incorporating lignin into a polyurethane matrix has demonstrated substantial enhancements in thermal stability, resistance to delamination, and abrasion resistance [12]. Lignin research currently explores two primary avenues: direct utilization without chemical modification and pre-treatment involving chemical modification, functionalization, or fractionation to yield various intermediates, fine chemicals, and polymers [13]. WPUs have advantages such as excellent abrasion resistance and mechanical properties, along with environmental friendliness, safety, and reliability. Lignin, with its benzene rings, carbonyl groups, and phenolic hydroxyl groups, is used in modified polyurethane through two methods: blending lignin as filler with WPU or using lignin as a reactant in WPU synthesis. The incorporation of lignin provides UV protective properties to polyurethane-based materials, as lignin can scavenge free radicals and exhibit UV absorption characteristics [14].

In recent years, researchers have explored the application of lignin-based coatings in diverse fields such as nonwoven materials, textiles, wood products, and packaging [11]. Lignin nanoparticles with a protective coating are gaining prominence as the upcoming generation of sustainable nanomaterials within the realm of functional and intelligent materials derived from lignin [9]. The increasing focus on investigating the potential of lignin as a textile coating with UV-absorbing and antibacterial properties [15]-[17]. Baysal [18] conducted a recent study where functional polylactic acid (PLA) spunlace nonwoven fabrics were developed. These fabrics featured composite coatings comprising lignin, zinc oxide, and WPU. Following coating and thermal curing, the fabrics underwent a comprehensive analysis. The incorporation of lignin and zinc oxide into the WPU coating provided antibacterial activity and ultraviolet protection of PLA nonwoven fabric. In a follow-up investigation, it was aimed to produce biodegradable, mechanically robust, and UV-protective textile materials. Five lignin/WPU coating pastes with varying concentrations of modified quaternized lignin were applied to PLA nonwoven fabric using an applicator and thermally cured. The resulting fabrics showed outstanding UV protection, with UV protection factor (UPF) values exceeding 100 for all formulations. Additionally, the lignin/WPU coatings improved tensile strength and abrasion resistance compared to the uncoated fabric [8]. In another study, Zhao et al. reported hydrophilic modification of PET/PA6 through the application of UV/TiO_2/H_2O_2 [5]. Sunthornvarabhas et al. [17] created a fabric with antimicrobial properties by coating it with lignin extracts from sugarcane bagasse. The lignin extracts obtained through an alkali treatment process, were dissolved in dimethyl sulfoxide and mixed with a volatile solvent for efficient drying. The chemical characteristics of the extracts were analyzed using FTIR. The nonwoven glass fiber sheets were coated with lignin extracts and tested for potential use in sanitary masks, demonstrating antimicrobial activity against *Staphylococcus epidermidis*. The lignin extracts showed positive, dose-dependent antimicrobial activity making it suitable for sanitary mask use.

Numerous studies have explored lignin's UV protection in polymeric matrices, but this research pioneers the enhancement of both mechanical performance and UV protection in bicomponent PET/PA6 nonwoven fabrics (NWFs) through unmodified lignin-containing WPU coatings. Formulations with varying unmodified lignin concentrations were prepared and applied to NWFs using a film applicator, followed by thermal curing. The study assessed the applicability of water-borne coatings on bicomponent NWFs, examining the impact of different lignin concentrations on hydrophobicity, tensile strength, and UV absorption properties.

2 Experimental

2.1 Materials

PET/PA6 hollow segmented pie 120 g/m^2 bicomponent Madaline® NWF (Mogul Tekstil, Türkiye) was used as substrate. Madaline® represents an innovative hybrid nonwoven technology, incorporating a patented bicomponent system comprising PET and PA6. In this case, the fusion of PET and PA6 suggests a composite that potentially delivers a harmonious blend of strength, durability, and other advantageous properties. Madaline® is free from volatile organic compounds, mitigating the risk of air pollution, degradation of air quality, and potential health hazards [19].

Water-borne coating paste formulations were prepared using a water-borne PU dispersion (Witcobond® 358-90, Lanxess, Germany). A UV absorber unmodified industrial alkali lignin (AL, Merck, Germany) and a crosslinker (Trixene® Aqua BI 201, Lanxess, Germany) were utilized. The coating formulation also included additives like synthetic thickener, defoamer, wetting agent, deionized water and an ammonium hydroxide solution as in previous study [8].

2.2 Methods

2.2.1 Preparation of coating pastes

Water-borne composite coating pastes (solid content: 45%), including WPU binder, unmodified alkali lignin with four different concentrations (1%, 3%, 5% and 10%) as reported in previous study [8]. Water-borne formulations (Table 1) are coded as WPU/L-X, where “L” denotes lignin and “X” denotes the unmodified lignin concentrations. The pure WPU formulation, which does not contain lignin, is defined as WPU-R. After preparing the formulations, the coating process was applied to the nonwoven fabrics in two passes using a film applicator (BGD 206/4, Hedef Kimya, Türkiye). The coated fabric samples were thermally cured at 135 °C for 5 minutes (Figure 1).

2.2.2 FTIR spectroscopy

For FTIR analysis of the chemical groups in the structures of the coating formulations, coating pastes were applied to glass plates as a film with a thickness of approximately 120 µm, and then thermally cured. The examination of the thermally cured films was carried out using FTIR spectroscopy (VERTEX 70v Bruker, Germany) at the wavelengths from 400 to 4000 cm^{-1}, with resolution of 4 cm^{-1}.

2.2.3 Tensile strength measurements

Tensile tests were conducted with tensile testing machine (Shimadzu AGS-X, Japan) following the EN ISO 1421:2000 standard, TS 2008. Measurements were performed on both uncoated and coated nonwoven NWFs prepared as 20 cm × 5 cm to examine the influence of unmodified lignin concentration in the formulations.

Table 1. Water-borne coating formulations.

Formulation	DI Water (%)	WPU binder (%)	Unmodified lignin (%)	Blocked isocyanate (%)	Thickener (%)	Dispersing agent (%)	Defoamer (%)	NH_4OH solution (%)
WPU-R	18.61	75	0	2	2.63	0.75	0.46	0.55
WPU/L- 1%	18.61	75	1	2	2.63	0.75	0.46	0.55
WPU/L- 3%	18.61	75	3	2	2.63	0.75	0.46	0.55
WPU/L- 5%	18.61	75	5	2	2.63	0.75	0.46	0.55
WPU/L- 10%	18.61	75	10	2	2.63	0.75	0.46	0.55

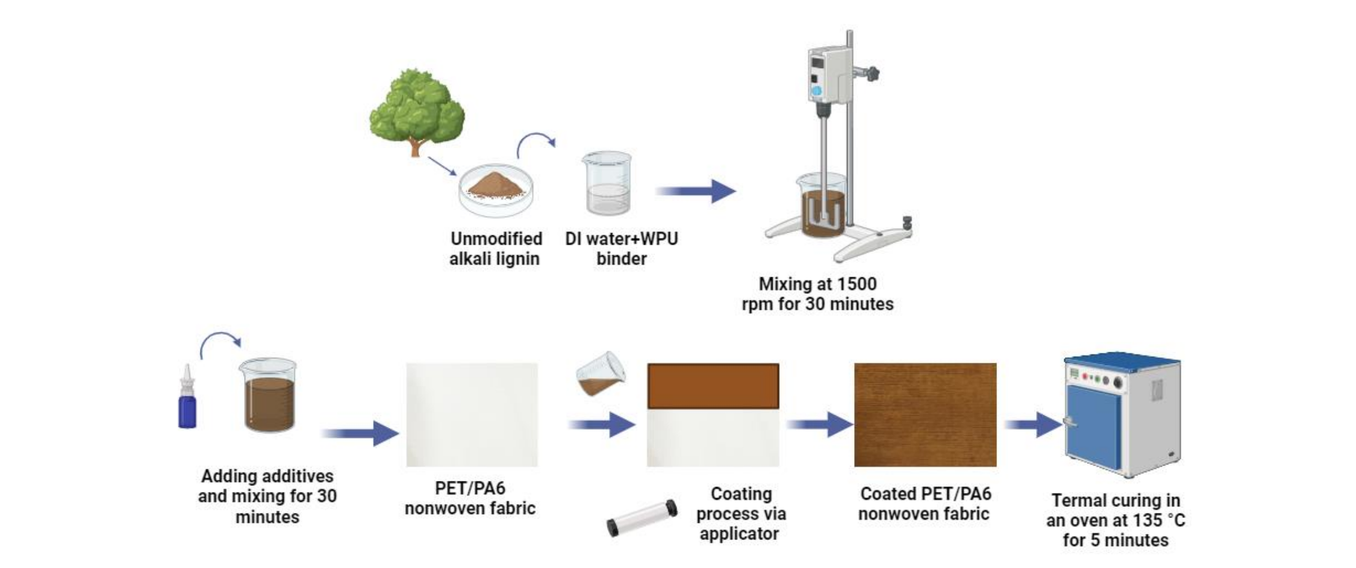

Figure 1. The preparation and application stages of composite coatings.

2.2.4 UV protection measurements

The UV transmission properties of NWFs were evaluated with a UV-VIS-NIR spectrometer (Shimadzu UV-3600 Plus) and the UV protection ranges for the coated and uncoated NWFs were determined as outlined in Table 2 [20].

Table 2. UV protection category according to ASTM D6603 [20].

Protection Category	UPF Range	UV Ttransmission (%)
Good	14-26	4.3-6.6
Very good	24-38	2.7-4
Excellent	38-52+	Less than 2.4

2.2.5 Water contact angles (WCAs) measurements

The WCA values were measured using an optical tensiometer device (Attension Theta Flex, Biolin Scientific, Sweden) to assess the hydrophobicity of uncoated nonwoven fabric, WPU-R, and WPU/L coated NWFs. The measurements for the left and right contact angles were performed after the drop release (CA-$T_{0\text{-}5}$ sn) and subsequently, the mean contact angle values were computed.

3 Results and discussion

3.1 FTIR spectroscopy results

FTIR analysis of cured films was given in Figure 2. The introduction of various concentrations of lignin into the pure WPU dispersion does not induce alterations in the principal functional groups of the WPUs, as evidenced by the FTIR spectra depicted in Figure 2.

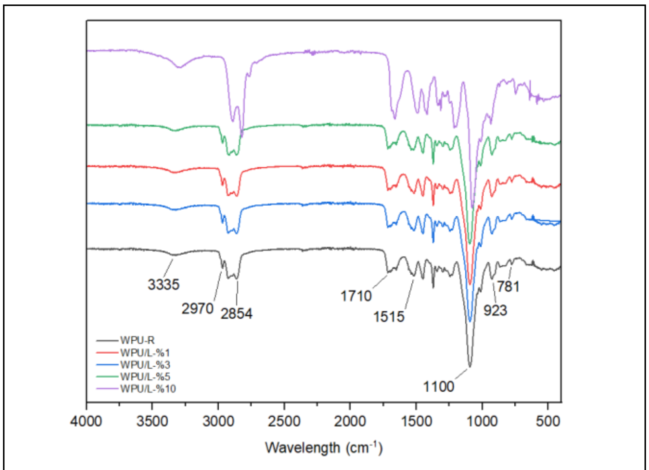

Figure 2. FTIR spectra of thermally cured films.

The spectra reveal that the characteristic absorption peaks associated with C-H stretching and C-O-C stretching of the WPU polymer chains were observed at 2930 cm^{-1} and 1235 cm^{-1}, respectively [8], [18], [21]. In all films includes lignin, a broad absorption band ranging from 3500 to 3000 cm^{-1} was identified, which can be attributed to the O–H stretching signal originating from hydrogen-bonded hydroxyl groups. In addition, the C=C stretching vibration of the aromatic skeleton at 1515 cm^{-1} is discernible. Furthermore, the wavelength at 1710 cm^{-1} corresponds to the C=O stretch in unconjugated carbonyl groups [13]. The elevation in lignin concentration, particularly evident in the cured film with 10% lignin, led to a pronounced intensification of the O-H stretching signal from hydrogen-bonded hydroxyl groups at the wavelength of 3335 cm^{-1}.

Simultaneously, there was an observable increase in the C=O stretching peak, which manifested at the wavelength of 1707 cm^{-1}. The spectral feature centered around 2970 cm^{-1} can be attributed to the C–H stretching of the aliphatic chains. Additionally, the peak at approximately~ 2970 cm^{-1} is indicative of the C–H stretching vibration associated with lignin. The urea absorption peak was identified at the wavenumber of 1100 cm^{-1}. Furthermore, the wavenumber of 781 cm^{-1} corresponds to the C–H deformation of the aromatic groups [8].

3.2 Tensile strength results

The tensile strengths of coated and cured fabrics were analyzed, and the results are presented in Table 3, also images taken from the samples during testing were shown in Figure 3. The coated NWF using the WPU/L-10% formulation exhibited a maximum breaking strength of 620 N. The addition of lignin contributed to an augmentation in breaking strength through the formation of additional hydrogen bonds [8].

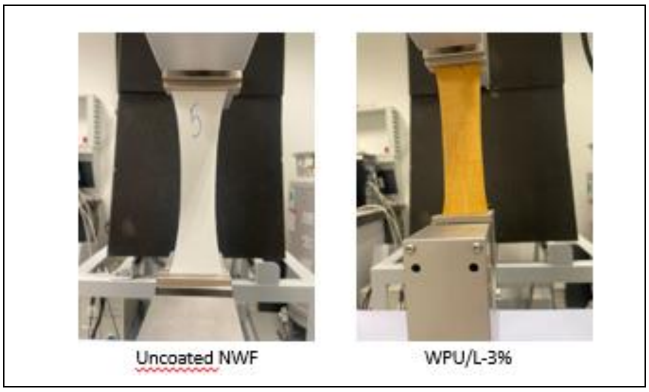

Figure 3. Photographic images of NWFs during tensile test.

The fabric achieved a maximum breaking strength and extension at break of 620 N and 76%, surpassing the values of pure NWF fabric, which had a breaking strength and extension of 550 N and 68.5%, respectively. The escalating lignin content in the coating material correlated with a substantial increase in fabric breaking strength. This enhancement can be attributed to the filling of gaps between fibers, facilitated by the coating, preventing slippage and stretching of fibers by enhancing fiber adhesion [8]. The hydroxyl groups within the chemical structure of lignin enable robust binding to fibers, establishing interfacial interaction that imparts mechanical properties [22].

Table 3. Tensile strength measurement results of NWFs.

Sample code	Uncoated NWFs	WPU-R	WPU/L-%1	WPU/L-%3	WPU/L-%5	WPU/L-%10
Breaking strength (N)	550	555	570	590	590	620
± STD	8.66	10.40	7.64	10.0	5.77	12.58
CV (%)	9.3	5.3	4.2	4.5	9.2	5.5
Breaking extension (%)	68.5	70.5	71.0	76.0	78.0	76.0
CV (%)	10.8	10.5	8.2	8.2	12.6	4.5

3.3 UV-VIS transmittance results

According to the UV permeability results (Table 4), with the increase in lignin in the formulations, the amount of UV permeability decreased and UPF values increased. Incorporating lignin into materials primarily serves as a strengthening agent, enhancing the mechanical characteristics of the end product and functioning as an additive to bolster UV protection properties. Lignin has emerged as a compelling substance for reinforcing fillers in the formulation of polymer-based composites. This is primarily attributed to its abundant functional groups, fostering the creation of both covalent and non-covalent interactions between the filler material and the polymer matrix. Beyond advancements in tensile strength properties, research has demonstrated that employing lignin nanoparticles as a reinforcement agent enhances the UV radiation resistance of WPU coatings [23]. The inherent characteristics of lignin particles, encompassing UV protection, antioxidant capacity, and biocompatibility, along with their abundant phenolic hydroxyl groups on the surface, contribute to enhancing UV absorption capabilities [23], [24]. Therefore, directly adding lignin in WPU formulations can be good promise in obtaining UV-blocking functional coating materials. According to the results obtained in Table 4, the uncoated NWF has high UV transmittance and consequently a low UPF factor (1.27). Similarly, the fabric coated with the WPU-R formulation also exhibited high UV transmittance. The effect of coatings obtained by adding lignin at different concentrations to the WPU coating formulation on the level of UV protection was determined and presented in Table 4. As defined in Table 2, the UV protection category is defined in three different levels. Accordingly, surfaces should have a UPF factor of 14 or higher to be considered to have UV protection. The UPF values calculated based on the UV transmittance of fabrics coated with coating formulations containing 1% and 3% lignin concentrations are 10.80 and 12.20, respectively, and since the values are below 14, a level for UV protection is not defined in the ASTM D6603 standard. The UPF values calculated based on the UV transmittance of fabrics coated with coating formulations containing 5% and 10% lignin concentrations are 18.43 and 30.16, respectively. Accordingly, good to very good UV protection levels were achieved according to the protection levels specified in Table 2.

3.4 Surface wettability results

In WCA measurements, the wetting characteristics of uncoated NWF and thermally cured NWFs, treated with WPU/lignin formulations featuring varying lignin concentrations, were examined, with the corresponding WCA results provided in Table 5. The images, captured using an optical tensiometer device, are illustrated in Figure 4.

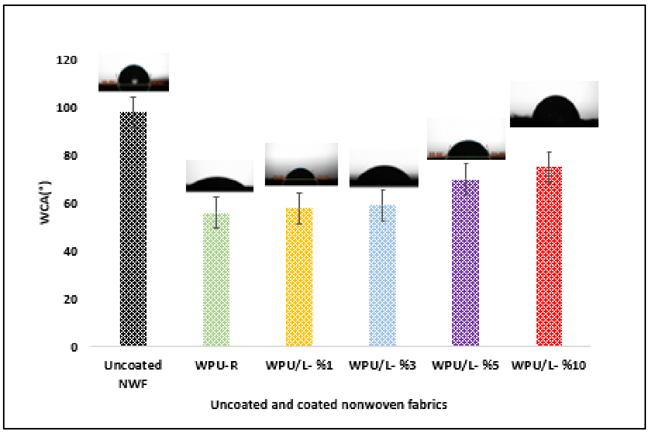

Figure 4. Surface wettability analysis results of NWFs with WCA images.

Wetting properties of fabric surfaces coated with WPU/lignin composite coating formulations were assessed through WCA measurements. In the analysis, water droplets deposited on the surface of fabric were evaluated based on the WCA angle formed on the surface within T_{0-5} seconds.

The uncoated fabric surface was tested and the WCA value obtained as 98°. In fabrics coated with formulations containing various lignin concentrations, the coating with 1% lignin exhibited the lowest WCA as 58° due to the presence of WPU polymer, while the hydrophobic nature of the surface increased with higher lignin concentrations. In the case of a pure WPU coating, it can be noted that the coating demonstrates wettability owing to the presence of hydrophilic groups within the WPU structure [25].

Table 4. UV-VIS transmittance results of NWFs.

Sample Code	T(UVB) %	T(UVA) %	UPF	UVA Blocking	UVB Blocking	± STD	Protection Level
Uncoated NWF	78.22	79.23	1.27	21.79	20.77	0.,31	-
WPU-R	71.11	74.44	2.55	25.55	28.88	1.17	-
WPU/L-1%	16.92	18.96	10.80	81.03	83.07	0.44	-
WPU/L-3%	7.93	9.50	12.20	90.43	92.06	0.24	-
WPU/L-5%	4.36	7.49	18.43	92.50	95.63	0.21	Good
WPU/L-10%	4.05	7.41	30.16	92.58	95.94	0.56	Very Good

Table 5. WCA measurement results of uncoated and coated NWFs.

Sample code	WCA (°)	±STD
Uncoated NWF	98	6.12
WPU-R	56	5.04
WPU/L-%1	58	9.60
WPU/L-%3	59	4.61
WPU/L-%5	70	7.01
WPU/L-%10	75	6.02

The attainment of a WCA value using WPU/L-%10 at 75° implies that integrating lignin into coating formulations decreases surface free energy and improves hydrophobicity of coated fabric, thereby hindering droplet diffusion on the surface [26]. Within a pure WPU coating, the presence of hydrophilic groups in the WPU structure suggests that the coating demonstrates high wettability [25].

Lignin can create a moisture-resistant, hydrophobic surface by encapsulating the hydrophilic groups present in WPU [27]. WCAs for coatings containing lignin typically range around 80°, with the commonly accepted limit for classifying a surface as hydrophobic being 90° [28]. The inherent hydrophobicity of unmodified lignin was constrained; therefore, enhancing lignin's hydrophobic properties through diverse methods proves advantageous for augmenting its application in the realm of hydrophobic coatings [29].

These findings offer insights for future hydrophobic modifications of other filament microfiber nonwovens using biopolymers to create a hydrophobic surface structure.

4 Conclusion

Nonwovens exhibit distinct structures and properties compared to woven fabrics, including softness, porosity, bulkiness, fiber arrangement, and packing. Woven and knitted fabrics often struggle with poor coating coverage, requiring numerous dips to achieve sufficient add-on for specific functions. Nonwoven fabrics, thanks to their highly porous nature, offer a better alternative by allowing adequate add-on with fewer coating passes compared to woven fabrics. Given the growing demand for research on UV protection of composite coatings, this work focused on the potential of coated PET/PA6 nonwovens with lignin/WPU composite coatings for UV blocking and tensile strength properties.

In this study, composite coatings including lignin and WPU were successfully administered to bicomponent NWFs made of PET/PA6, with varying concentrations of unmodified alkali lignin (1, 3, 5, and 10 wt.%). The study delves into the impact of unmodified alkali lignin concentration on key properties such as hydrophobicity, tensile strength, and UV protection of the coated and thermally cured NWFs. UV-VIS measurements revealed that the formulation with the highest lignin concentration (10 wt.%) achieved the highest UPF value of 30.16. Additionally, formulations with 5 and 10 wt.% lignin concentrations exhibited UPF values exceeding 15, signifying good to very good UV protection. Comparative analysis with uncoated NWFs indicated a notable increase in breaking strength, reaching 620 N, for lignin/WPU coated NWFs with a 10 wt.% lignin concentration in the WPU/L-10% coating formulation. WCA measurements demonstrated the highest value of 75° for NWFs coated with WPU/L-10%. Overall, the results suggest that incorporating 10 wt.% lignin into WPU dispersion enhances UV light blocking performance and tensile strength in coated NWFs. For optimal coating efficiency, UV protection, and tensile strength properties, the WPU/L-10% formulation is recommended.

There have been increasing efforts to use antioxidants and UV blockers to protect polymeric materials and human skin from UV radiation. Synthetic organic UV protectants like homosalate, oxybenzone, octinoxate, and avobenzone lack stability and can generate free radicals when exposed to UV light, posing health risks. Therefore, their limited biodegradability restricts their broader use. Biodegradable, cost-effective, non-toxic materials with excellent properties could replace traditional synthetic UV blocker materials. Lignin is a biopolymer with UV protective and antioxidant properties that has gained attention due to its biodegradability, renewability, wide availability, and strong stability. Lignin-coated textiles could notably decrease carbon emissions and reduce reliance on petroleum-based materials, thus reducing microplastic pollution. This study provides important insights for creating strong and UV-protective coated nonwoven fabrics, commonly used in the textile industry for advanced protective textiles due to their flexibility and functionality.

This research underscores the potential of lignin-based coatings, emphasizing the need for further exploration of lignin's viability as a functional filler in multifunctional coating materials, particularly on nonwoven fabrics. Lignin, with unique attributes such as hydrophobicity, UV absorption, and mechanical properties, plays a crucial role in diverse industries and applications when incorporated into coatings. Despite its evident potential, the existing research on utilizing lignin-based coatings on nonwoven fabrics is currently limited. Further studies are essential to substantiate the effectiveness of lignin in serving as a key component in multifunctional coating materials. The findings of this study hold promise for industries in search of sustainable and functional coatings, particularly in textile sectors. This is especially relevant to produce protective outdoor materials, such as tent fabrics requiring both high strength and UV protective properties. PET/PA6 nonwoven fabrics are suitable for various applications like home textiles, clothing, technical packaging, automotive, and aerospace.

The results imply that incorporating lignin into WPU could expand the practical applications of WPU-based coatings in textile industry. This research underscores the distinctive qualities of biodegradable natural biopolymer lignin that render it a promising material for applications in this context. Future studies can explore lignin-based composite coating structures to improve other functional textile properties for specific applications.

5 Author contribution statement

Gülçin BAYSAL is accountable for conceiving and executing the study, analyzing the results, and composing the article.

6 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”.

“There is no conflict of interest with any person/institution in the article prepared”.

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8 References

[1] Venkataraman D, Shabani E, Park JH. "Advancement of nonwoven fabrics in personal protective equipment". *Materials*, 16(11), 3964, 2023.

[2] Das D, Pradhan AK, Chattopadhyay R, Singh SN. "Composite nonwovens". *Textile Progress*, 44(1), 1-84, 2012.

[3] Yen MS, Kuo MC, Chen CW, Yeh CW. "Fabrication of novel multifunctional hybrid materials for PET/PA6 nonwoven fabrics finishing". *Fibers and Polymers*, 14, 772-780, 2013.

[4] Duo Y, Qian X, Zhao B, Gao L, Guo X, Zhang S, Bai H, Tang L. "Easily splittable hollow segmented-pie microfiber nonwoven material with excellent filtration and thermal-wet comfort for energy savings". *Journal of Materials Research and Technology*, 17, 876-887, 2022.

[5] Zhao B, Han X, Hu C, Qian X, Duo Y, Wang Z, Feng Q, Yang Q, Han, D. "Hydrophilic modification of polyester/polyamide 6 hollow segmented pie microfiber nonwovens by UV/TiO_2/H_2O_2". *Molecules*, 28(9), 3826, 2023.

[6] Gupta M, Sheikh J, Annu, Singh A. "An eco-friendly route to develop cellulose-based multifunctional finished linen fabric using ZnO NPs and CS network". *Journal of Industrial and Engineering Chemistry*, 97, 383-389, 2021.

[7] Bergamasco S, Tamantini S, Zikeli F, Vinciguerra V, Mugnozza GS, Romagnoli M. "Synthesis and characterizations of eco-friendly organosolv lignin-based polyurethane coating films for the coating industry". *Polymers*, 14(3), 416, 2022.

[8] Baysal G. "Mechanical and UV protection performances of polylactic acid spunlace nonwoven fabrics coated by eco-friendly lignin/water-borne polyurethane composite coatings". *Journal of Textile Institute*, 115(11), 2185-2197, 2024.

[9] Lizundia E, Sipponen MH, Greca LG, Balakshin M, Tardy BL, Rojas OL, Puglia D. "Multifunctional lignin-based nanocomposites and nanohybrids". *Green Chemistry*, 23(18), 6698-6760, 2021.

[10] Tanase-opedal M, Espinosa E, Rodr A, Chinga-carrasco G. "Lignin : A biopolymer from forestry biomass for biocomposites and 3D printing". *Materials*, 12(18), 3006, 2019.

[11] Gaynor JG, Szlek DB, Kwon S, Tiller PS, Byington MS, Argyropoulos DS. "Lignin use in nonwovens: A review". *BioResources*, 17(2), 3445-3488, 2022.

[12] Alinejad M, Henry C, Nikafshar S, Gondaliya A, Bagheri S, Chen N, Singh SK, Hodge DB, Nejad M. "Lignin-based polyurethanes: opportunities for bio-based foams, elastomers, coatings and adhesives". *Polymers*, 11(7), 1202, 2019.

[13] Klein SE, Rumpf J, Kusch P, Albach R, Rehahn M, Witzleben S, Schulze M. "Unmodified kraft lignin isolated at room temperature from aqueous solution for preparation of highly flexible transparent polyurethane coatings". *RSC Advances*, 8, 40765-40777, 2018.

[14] Lai Y, Qian Y, Yang D, Qiu X, Zhou M. "Preparation and performance of lignin-based waterborne polyurethane emulsion". *Industrial Crops and Products*, 170, 113739, 2021.

[15] Zimniewska M, Batog J, Bogacz E, Romanowska B. "Functionalization of natural fibres textiles by improvement of nanoparticles fixation on their surface". *Journal of Fiber Bioengineering & Informatics*, 5, 321-322, 2012.

[16] Zimniewska M, Kozłowski R, Batog, J. "Nanolignin modified linen fabric as a multifunctional product". *Molecular Crystals and Liquid Crystals*, 484(1), 43-50, 2008.

[17] Sunthornvarabhas J, Liengprayoon S, Suwonsichon T. "Antimicrobial kinetic activities of lignin from sugarcane bagasse for textile product". *Industrial Crops and Products*, 109, 857-861, 2017.

[18] Baysal G. "Sustainable polylactic acid spunlace nonwoven fabrics with lignin/zinc oxide/water-based polyurethane composite coatings", *International Journal of Biological Macromolecules*, 254, 127678, 2024.

[19] Mogul Nonwoven. "Polyester/Polyamide (PET/PA) Bicomponent TCS®, Trilobal Splittable Microfilament Spunbond Hydroentangeld Fabrics". https://mogulsb.com/en/microfilaments/madaline-multilobal-pet-pa (02.12.2023).

[20] Ray A, Singha K, Pandit P, Maity S. *Advances in Functional and Protective Textiles*. Editors: Ul-Islam S, Butola BS. Advanced Ultraviolet Protective Agents for Textiles and Clothing, 243-260, Cambridge, USA, Woodhead Publishing, 2020.

[21] Ng QY, Low, JH, Pang MM, Idumah CI. "Properties enhancement of waterborne polyurethane bio-composite films with 3-aminopropyltriethoxy silane functionalized lignin". *Journal of Polymers and the Environment,* 31, 688-697, 2022.

[22] Ridho MR, Agustiany EA, Rahmi Dn M, Windra EM, Ghozali M, Restu WK, Falah F, Adly M, Lubis R, Syamani FA, Nurhamiyah Y, Hidayati S, Sohail A. "Lignin as green filler in polymer composites: development methods, characteristics, and potential applications". *Advances in Materials Science & Engineering*, 1363481, 2022.

[23] Zhang Z, Terrasson V, Guénin E. "Lignin nanoparticles and their nanocomposites". *Nanomaterials*, 11(5), 1336, 2021.

[24] Ma X, Chen J, Zhu J, Yan N. "Lignin-based polyurethane: recent advances and future perspectives". *Macromolecular Rapid Communications*, 42(3), 2000492, 2021.

[25] Pandya H, Mahanwar P. "Fundamental insight into anionic aqueous polyurethane dispersions". *Advanced Industrial and Engineering Polymer Research*, 3(3), 102-110, 2020.

[26] Zhang N, Liu P, Yi Y, Gibril ME, Wang S, Kong F. "Application of polyvinyl acetate/lignin copolymer as bio-based coating material and its effects on paper properties", *Coatings*, 11 (2), 192, 2021.

[27] Wang W, Guo T, Sun K, Jin Y, Gu F, Xiao H. "Lignin redistribution for enhancing barrier properties of cellulose-based materials". *Polymers(Basel)*, 11(12), 1929, 2019.

[28] Henn KA, Forsman N, Zou T, Österberg M. "Colloidal lignin particles and epoxies for bio-based, durable, and multiresistant nanostructured coatings". *ACS Applied Materials & Interfaces*. 13(29), 34793-34806, 2021.

[29] Chen J, Fan X, Zhang L, Chen X, Sun S, Sun RC. "Research progress in lignin-based slow/controlled release fertilizer". *ChemSusChem*, 13(17), 4356-4366, 2020.