THE STABILITY OF SILVER NANOWIRE COATED POPLAR NONWOVENS UNDER WASHING CONDITIONS

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Abstract

Poplar fibers, known for their high cellulose content and hollow structure, are primarily discarded as waste in the wood industry despite the tree's abundance. Recent advancements have enabled the utilization of poplar fibers in the textile industry, specifically in the production of nonwoven fabrics. This study explores the potential of valorizing poplar fibers by functionalizing them with silver nanowires (AgNWs) for technical applications. The focus is on enhancing the durability of conductive poplar nonwovens against washing procedures. Initially, silver nanowires were synthesized via the NaCl-mediated polyol method and subsequently coated onto a blend of poplar and polyester (PET) nonwoven fabric. The conductive fabric samples underwent a series of washing cycles to assess their durability. Post-washing analyses included morphological characterization and conductivity measurements to evaluate the performance and resilience of the coatings. This study provides insights into the wash durability of conductive poplar nonwovens, contributing to their potential application in electronic wearables, where compliance and comfort are critical.

Keywords: Poplar fiber, sustainable textiles, silver nanowire, washing durability, wearable electronics

1. INTRODUCTION

The development of conductive textiles has gained considerable attention in recent years, particularly in response to the growing demand for wearable, flexible electronics and smart fabrics. These textiles offer promising applications in areas ranging from healthcare monitoring to interactive garments, owing to their ability to conduct electricity through incorporating conductive elements such as metal nanowires, intrinsically conductive polymers (ICPs), or carbon-related materials [1]. Among the materials explored for conductive textiles, silver nanowires (AgNWs) have emerged as a prominent candidate due to their exceptional electrical conductivity, flexibility, and ease of integration into fibrous structures [2, 3]. Silver as a component and silver nanoparticles have found use in textiles due to their antimicrobial activity in various applications, recently AgNW-coated fabrics have demonstrated notable performance in wearable applications as well [3, 4].

Beyond the choice of conductive materials and fabrication techniques, the selection of substrate plays a crucial role in the development of conductive surfaces, particularly when sustainable materials are considered for achieving both performance and environmental responsibility. Therefore, functionalization of natural fibers, particularly for technical and smart applications, represents a growing area of interest due to the increasing demand for sustainable and high-performance materials. The environmental impact of synthetic fibers, coupled with the vast quantities of natural fibers discarded as waste, has led to increased interest in valorizing renewable, biodegradable fibers. Poplar fibers belonging to the family of Populus genus, with their high cellulose content, large hollow lumen combined with a thin cell wall [5, 6], offer a promising alternative in this regard. Despite their abundance, poplar fibers are largely discarded as waste in the wood industry. Characterized by its large hollow lumen occupying about 80-90% of the cross-section, it offers a lightweight, fluffy texture with excellent thermal and sound insulation properties [7]. As a renewable, biodegradable resource, poplar fiber has gained increasing attention for various applications, including thermal [7] and acoustic insulation [8], oil sorbents for water cleanup [5, 9], composite reinforcement [10], aerogel formation [11] and as a natural substrate for wearable electronics [12, 13, 14]. Having the focus on the incorporation of poplar fibers for electronic wearables, this area of use requires materials that combine conductivity with softness, breathability, and durability, particularly in environments where washing and repeated handling are inevitable. However, the challenge of maintaining electrical conductivity after exposure to mechanical stresses, such as washing and repeated use, remains a significant hurdle in bringing these smart textiles to mass uses [15]. Washing can degrade the conductive coating by removing or altering the distribution of nanowires, which diminishes the fabric's electrical performance. The wash durability of such conductive fabrics is critical for their practical use in smart textiles and wearable devices. Research has thus focused on optimizing both the materials used and the processes involved in manufacturing conductive textiles to enhance their durability and washability.

The aim of this study is to explore the potential of poplar fibers as a sustainable substrate for conductive textiles. Using the NaCl-mediated polyol method, silver nanowires were synthesized and coated onto poplar-polyester (PET) nonwoven blends. The durability of these conductive nonwoven fabrics was evaluated by subjecting the samples to a series of washing cycles, followed by conductivity assessments to determine the performance of the AgNW coatings post-wash. This work aims to contribute to the growing body of research on sustainable, multifunctional textiles by providing insights into the wash durability of conductive poplar nonwovens, with particular relevance to electronic wearables where both comfort and compliance are essential.

2. EXPERIMENTAL STUDY

2.1. Materials

Poplar fibers belonging to nigra italica trees were collected from ground using a modified leaf-blower during the blooming season in Türkiye. Prior to the preparation of the nonwoven samples, seeds, dust, leaves, and other contaminants were meticulously removed manually to ensure clean poplar fibers. Hollow polyethylene terephthalate (PET) fibers (~64 mm in length) were generously provided by SASA Polyester Sanayi A.Ş., Türkiye. Silver nitrate ($AgNO_3$, ≥99.8%, Sigma-Aldrich), polyvinylpyrrolidone (PVP, average molecular weight of 40,000, Sigma-Aldrich), ethylene glycol (EG, Merck), ethanol (Merck), and acetone (99.5% purity, TEKKİM) were sourced from Labor-Teknik Laboratuvar Malzemeleri Sanayi Ve Ticaret A.Ş., Türkiye. All chemical reagents were used without further purification.

2.2. Nonwoven production

The cleaned poplar fibers were blended with PET fibers in three distinct weight ratios (0:100, 30:100, and 60:100) without any chemical pre-treatment. The resulting nonwoven fabrics were designated as sPET, popPET-30, and popPET-60, corresponding to blend ratios of 0/100, 30/100, and 60/100 (w/w) for poplar and PET fibers, respectively. A two-step process was employed to fabricate these blends. Initially, the fibers were processed through a carding machine (Mesdan 337A laboratory carding machine) to achieve uniform distribution. Subsequently, the carded webs were subjected to needle-punching (DILO needle-punching machine) to mechanically bond the fibers and produce stable nonwoven fabrics. The produced fabrics have similar basis weight of 243, 263 and 279 gsm along with 3 mm of thickness for sPET, popPET-30, and popPET-60, respectively as stated in the previous study [6].

2.3. Silver nanowire synthesis and coating

A NaCl-mediated polyol synthesis was carried out to produce silver nanowires. The capping agent, PVP, was dissolved in ethylene glycol in a three-necked glass flask. The flask was placed in an oil bath to provide homogenous heating over a hot plate at 180°C. The solution was stirred until homogenization for 45 minutes. Preparation of silver nitrate solution was carried out by dissolving silver nitrate in ethylene glycol at room temperature under continuous stirring in a aluminum foil covered beaker, simultaneously. After PVP solution is mixed, a 1M NaCl-EG solution was added and it was allowed to react for an additional 10 minutes. The silver nitrate solution was then fed into the system at a rate of 1 mL/min by a syringe pump. The resulting solution was stirred at 180°C for an additional 20 minutes and then allowed to cool to room temperature. After cooling, acetone was added to dilute the mixture, and silver nanowires (AgNWs) were precipitated through centrifugation.

The precipitated AgNWs were then re-dispersed in ethanol at a concentration of 50 mg/mL to prepare the coating solution. Nonwoven fabrics were cut into pieces having dimensions of 2.5 cm x 5 cm to prepare samples for coating procedure. They were then immersed in 15 mL of the AgNW dispersion to facilitate uniform coating, as schematized in **Figure 1**. Each cycle of dip-coating lasted for 10s. After each cycle an oven- drying step was performed at 60℃ for 30 minutes. Consecutive coatings were performed to decrease the electrical resistance of the samples. The number of dip-coating cycles was completed at 5 after a resistance value of below 20 Ohm was achieved for each fabric. AgNW functionalized poplar blend nonwovens were produced.

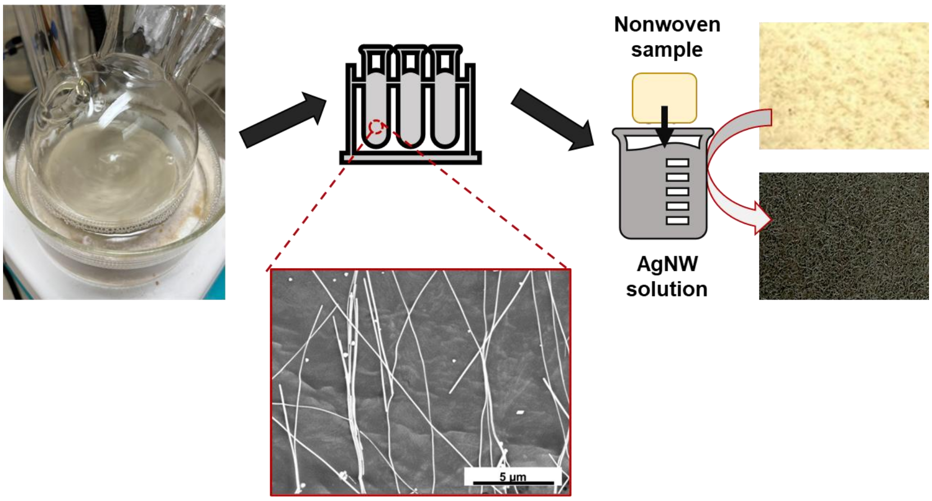

Figure 1 NaCl-mediated silver nanowire synthesis and dip-coating application on poplar blend nonwoven samples

2.4. Washing of AgNW coated poplar blend nonwovens

A gentle washing procedure was conducted as described [16]. Each fabric sample of 2.5 cm x 5 cm was placed in a beaker containing 50 mL of a tap water. The AgNW-coated sPET, popPET-30 and popPET-60 nonwoven fabrics underwent five washing cycles. Each cycle was performed at 40°C for 30 minutes. The washing was conducted under continuous stirring at 40 rpm with help of a magnetic stirrer, as demonstrated in **Figure 2**. After each washing cycle, the samples were rinsed using distilled water. Following each washing cycle, samples were oven-dried at 60 °C for 45 minutes and were subjected to resistance measurement in-between cycles.

2.5. Characterization

The surface electrical resistance values of the nonwoven samples were measured using a Digital Multimeter (FLUKE 17B+) having an accuracy of ±0.5%. The morphology of the silver was imaged using scanning electron microscopy (SEM, TESCAN VEGA3). The length of the nanowires was assessed with help of the ImageJ software using the SEM images as base for measurements. An average of 50 samples were taken into account. A Perkin Elmer Spectrum Two IR was used for the spectral analysis. Spectra were recorded with a resolution of 4 cm^{-1} across the range of 4000–50 cm^{-1}, with an average taken over 16 scans.

3. RESULTS AND DISCUSSION

The washing performance of conductive nonwovens was evaluated as focus of this study. Conductive nonwoven substrates were produced by a common dip-coating method. To impart conductivity, AgNWs were fabricated through polyol synthesis. After synthesis, a small fraction of nanowire dispersion was deposited on a smooth substrate and the excess ethanol was removed by oven-drying. This substrate was then subjected by scanning electron microscopy to analyze the produced silver nanowires. As represented in **Figure 1,** AgNWs having an average length of 10.9±5 μm has been synthesized and used for coating of nonwovens.

The dip-coating procedure lasted for 5 consecutive cycles. Increasing the dip-coating cycles to five significantly reduced electrical resistance, reaching below 20 Ω/cm, as each cycle imparted more silver nanowires onto the fabric surface. Although increased deposition has its advantages, the drawbacks may include increased cost, excessive coating without adhesion, which may be released during mechanical resistance or washing. Therefore, it is critical to achieve low resistivity at fewer deposition steps. The original fabrics have the colors white and a soft yellow for virgin PET (sPET) and poplar blends (popPET-30 and popPET-60), respectively. After full impregnation of the nonwoven fabrics with the AgNW ethanol suspension, the fabric colors shifted from their original appearance to a dark grey, signifying successful and complete AgNW deposition to create conductive network on the surface, as demonstrated in **Figure 1**.

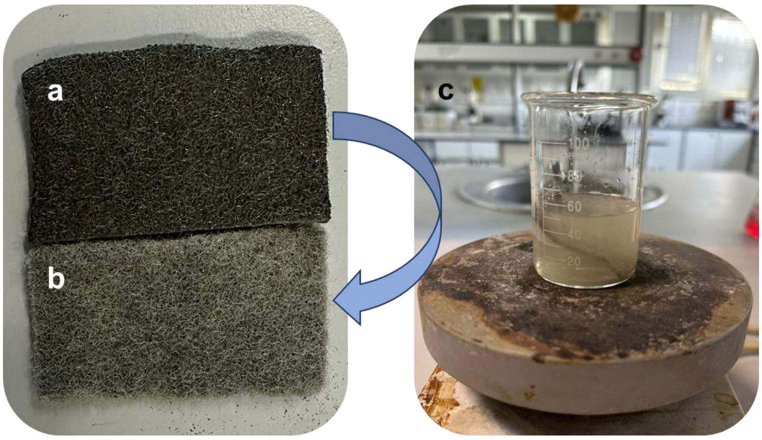

Figure 2 Silver nanowire-coated nonwoven fabric samples before (a) and after (b) being subjected to washing procedure 5 times (c)

The initial electrical resistance values of the fabric samples were given in **Table 1.** The slight difference in resistivity of synthetic and blend samples may be attributed to physical and chemical characteristics of the poplar fiber. For which, the surface roughness and abundant hydroxyl groups deriving from cellulose content have significant role. After first resistance measurements, all samples have been subjected to washing in a laboratory environment, as demonstrated in **Figure 2.** A gentle washing procedure has been conducted to observe the washing stability of the samples, which have been neither pre-treated nor post-cured. As seen in the color difference between **Figure 2a** and **Figure 2b,** a total washing procedure having 5 cycles have significantly affected the conductive network created by AgNW coating. The disruption of this network became also apparent in terms of electrical resistance activity recorded by multimeter measurement in **Table 1.** It reveals a clear trend in the washing durability of silver nanowire-coated nonwoven fabrics composed of varying proportions of poplar and PET fibers. Initially (Cyc.0), all samples exhibit relatively low electrical resistance, with sPET having a resistance of 18 Ω/cm, popPET-30 at 7.5 Ω/cm, and popPET-60 at 10.4 Ω/cm. As the fabrics are subjected to washing cycles, the sPET sample shows a sharp and dramatic increase in resistance, rising to 80 Ω/cm after just one cycle and reaching a significant 1100 Ω/cm by the third cycle. In contrast, the poplar-blended fabrics (popPET-30 and popPET-60) show much slower increases in resistance, rising by 9.3% and 5.7%, respectively. This indicates that poplar fibers contribute to greater stability of the silver nanowire coating after initial washing, particularly when compared to the pure polyester fabric. After five washing cycles, the electrical resistance of popPET-30 reaches 88 Ω/cm, and popPET-60 stabilizes at 20 Ω/cm, while the sPET sample is no longer measurable after three cycles due to its extremely high resistance.

Table 1 Electrical resistance measurements of nonwoven fabric samples at initial stage and after each washing cycle

Washing Cycle	**Electrical Resistance (Ω/cm)**		
	sPET	**popPET-30**	**popPET-60**
Cyc.0	18	7.5	10.4
Cyc.1	80	8.2	11
Cyc.2	138	9	12.2
Cyc.3	1100	16	13
Cyc.4	-	33	15.8
Cyc.5	-	88	20

The trend continues over subsequent washing cycles. After two washing cycles, sPET's resistance further surges to 138 Ω/cm, reflecting a 666% total rise from the initial value. Meanwhile, popPET-30 increased slightly to 9 Ω/cm and popPET-60 to 12.2 Ω/cm. By the third cycle, sPET experienced a dramatic increase to 1100 Ω/cm, indicating a near-total loss of conductivity. Conversely, popPET-30 reached 16 Ω/cm and popPET-60 only 13 Ω/cm showing much better retention of conductive properties. After five washing cycles, popPET-30 and popPET-60 had final resistances of 88 Ω/cm and 20 Ω/cm, respectively. Overall, popPET-60 demonstrated the best wash resistance, with only a 92.3% increase over five cycles, while sPET became non-conductive after three cycles. These findings suggest that increasing the poplar fiber content significantly improves the fabric's durability and conductivity retention after repeated washing, offering substantial advantages over pure polyester fabrics.

4. CONCLUSION

Conductive nonwoven fabrics were produced from hollow PET and poplar fibers decorated with silver nanowires. PET and poplar fibers have been carded and needle-punched to achieve a mechanically stable nonwoven fabric. In order to impart conductivity to these fabrics, AgNWs were synthesized according to NaCl-mediated polyols synthesis. Nanowires were deposited on the fabric substrates by consecutive dip coating. Their ability to conduct electricity has been investigated in context of washing durability. The results suggest that adding poplar fibers to polyester nonwovens significantly improves the wash durability of silver nanowire coatings, with higher poplar content offering even better performance. This makes poplar-blended nonwovens a more promising material for applications requiring conductive textiles.

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