WEARABLE TEXTILE ELECTRODES BASED ON SILVER NANOWIRE COATED POPLAR/PET NONWOVEN FABRICS

[1]Canan USTA, [1]Ozgur ATALAY, [1]Alper GURARSLAN*

[1]ITU - Istanbul Technical University, Beyoglu, Istanbul, Turkiye, gurarslan@itu.edu.tr

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Abstract

With the advancement of the wearable electronics, there is a growing demand for the textile electrodes due to their compliance and comfortableness to wear. Hence, a thorough investigation of suitable materials, fabrication methodologies and sensing elements needs to be developed. While poplar trees are widely used in the wood industry, our group recently utilize the poplar fibers in the production of nonwoven fabrics for the first time. In this study, an electrically conductive web is formed via coating the poplar/polyester (PET) nonwoven fabric with silver nanowires (AgNWs). The coated poplar textile electrodes exhibited good electrical conductivity and superb flexibility. Therefore, they might have great potential in wearable electronic applications such as an ECG electrode.

Keywords: Poplar fiber, silver nanowire, textile electrode, wearable electronics, sustainable textiles

1. INTRODUCTION

Poplar fibers are highly lignified organic seed fiber that can grow in diverse regions across the world without the need for extensive irrigation, unlike cotton. It mainly composed of cellulose, lignin, hemicellulose and plant wax (41-44%, 28-29%, 19-21% and 4-9%, respectively). It has large hollow lumen, comprising nearly 90% of the fiber structure which is similar to kapok and milkweed fibers. The fiber lenght is usually in the range of 0.5 to 1.5 cm and fiber diameter varies from 8 to 12 μm [1]. Its superb physical properties can offer advantages in various applications, such as insulation, filtration, and lightweight materials. The presence of such an extensive hollow lumen can contribute to enhanced thermal and acoustic insulation properties, increased surface area for filtration, and reduced overall weight, making these fibers valuable in heat and sound insulation applications [2,3]. Besides, some studies in the literature demonstrated that poplar fiber has a hydrophobic surface attributed to the natural waxes on the fiber, reflected in a remarkable contact angle of 125°[1]. Moreover, studies by Liu et al. [4], Likon et al. [5] and Gurarslan et. al. [1] have showed that oil sorption capacity of poplar fiber is very high which is more than 30 times its own weight, indicating the fiber's capability to be effectively used in chemical such as oil and petroleum absorbtion studies. Narinc et. al. [6] presented a fundamental technique to fabricate flexible capacitors of a silver nanowire coated nonwoven poplar web. This study shows that nonwoven raw poplar fibre webs coated with AgNW exhibit acceptable electrical conductivity and flexibility, adding the high sensitivity to external loads.

As it is seen in the literature, studies mostly aim to benefit from physical properties of poplar fiber. Also, owing to the difficulty of obtaining yarn and fabric due to the shortness of the fiber, studies have generally focused on its utility in fiber form.

In the rapidly growing field of wearable electronics, the development of biocompatible and sustainable solutions is attracting substantial attention. To support this green transition, different approaches towards miniaturization and integration of functional materials with daily wear to realize electronic devices, such as capacitors, biosensors and electrodes need to be carried out. The adoption of electroconductive textiles offers several additional benefits, including enhanced flexibility, improved breathability and seamless integration [7].

Conventional wearable electronics typically depend on fabrication methods based on clean-room environments and/ or utilize supporting substrates made from nonbiodegradable and expensive polymers such as polyimide (PI), porous materials etc. [8-10]. Among these, the use of natural and biodegradable fibers have been widely explored as substrate material for flexible electronics [11,12]. Lignocellulosic fibers such as poplar fibers have various advantages, including easy accessibility, abundance, comfort, low density and cost-effectiveness [13].

By exploiting the properties of poplar fibers and integrating them with advanced conductive materials such as silver nanowires, a new approach is revealed. Here, we report a sustainable and green nonwoven fabric compose of poplar and PET fibers. The obtained nonwoven fabric is coated with silver nanowires. Within the scope of the study, nonwoven fabric is produced by needle-punching method. We analyzed the potential of these nonwoven fabrics to serve as an ECG electrode. In this context, poplar fibers which is a natural resource treated as waste despite its superior properties, were transformed into high- value added textile products, the best of nature is combined for the benefit of healthcare and the environment.

2. EXPERIMENTAL STUDY

2.1 Nonwoven Fabric Preparation

The raw poplar fiber (**Figure 1a**) was harvested during the middle of May in Kırklareli/ Istanbul using a gasoline leaf collecting machine. Collected poplar fibres contain some amount of undesired foreign particles such as seeds, dusk, leaves etc. Hence, mechanical cleaning with steel tweezers was applied prior to nonwoven fabric production due to obtain cleaned poplar fiber (**Figure 1b**).

Webs were initially created using a carding machine and subsequently mechanically bonded through a needle-punching process. In this process, a laboratory type carding machine (337A Mesdan) was utilized to form the webs (**Figure 1c**). The nonwoven fabric production involved several steps: weighing fibers, carding and blending, web bonding. Initially, 100 g polyester fiber and 60 g poplar fiber were weighed according to predetermined blending ratios. The weighed polyester fibers were fed to the carding machine twice. The first one was to open up and prepare the fibers, while the second one aimed to ensure a smooth and even distribution. Polyester web was obtained and were wound onto a rotating drum. Subsequently, the weighed poplar fiber was sandwiched between the polyester web and fed to the carding machine. Following the formation of blended poplar/polyester nonwoven fabric, the bonding of the web was conducted using an industrial-grade needle-punching machine equipped with barbed felting needles (**Figure 1d**).

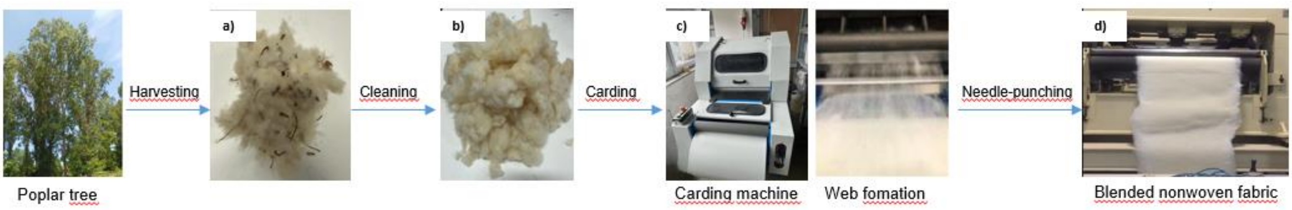

Figure 1 Schematic illustration of poplar/ PET blended nonwoven fabric

2.2 Synthesis of Silver Nanowire Solution

A crystallizing dish of 14 cm diameter, filled with silicone oil, was placed on a hot plate with a magnetic stirrer. In a three-necked round-bottomed glass flask, 0.5 g of polyvinyl pyrrolidone (PVP) was dissolved in 50 mL of ethylene glycol (EG) with a magnet at 180 °C for 40 minutes. Also, in a separate glass flask, 0.5 g of silver nitrate and 50 mL of EG were combined and stirred. After 40 minutes, 0.15 ml of 1 M NaCl- EG solution was added to the PVP solution and waited for another 10 minutes. Then, the silver nitrate solution was injected with a syringe pump at a rate of 1 ml/ min. Injection period took 50 minutes and during the process, the solution acquired a bright gray color. The solution was stirred at 185 ̊C for another 20 minutes, the heating was turned off and the solution was allowed to reach room temperature. Upon reaching room temperature, acetone was added to dilute the solution and AgNWs were precipitated in the centrifuge machine. The precipitated AgNWs were diluted in ethanol (EtOH) of 1 g/ 20 ml concentraton ratio (**Figure 2a**) due to be applied to nonwoven fabric.

2.3 Coating with Silver Nanowires

The poplar/ polyester blended nonwoven fabric is cut in size of 1 cm × 5 cm samples before the coating process. AgNW-EtOH solution was coated on both sides of the two fabric samples with a Pasteur pipette (**Figure 2b**). Then, the sample is dried in an oven for 1 h at 50°C. After drying, samples' resistance value was recorded with a multimeter (**Figure 2c**). This process is repeated for 5 times to decrease the electrical resistivity. The electrical resistance of all conductive fabric was assessed utilizing the TT Technic Digital Multimeter (Model VC97). After final coating procedure, resistivity value was measured as 5.20 ± 1.8 Ω/cm decrement of 35% ± 0.06% compared to first coating.

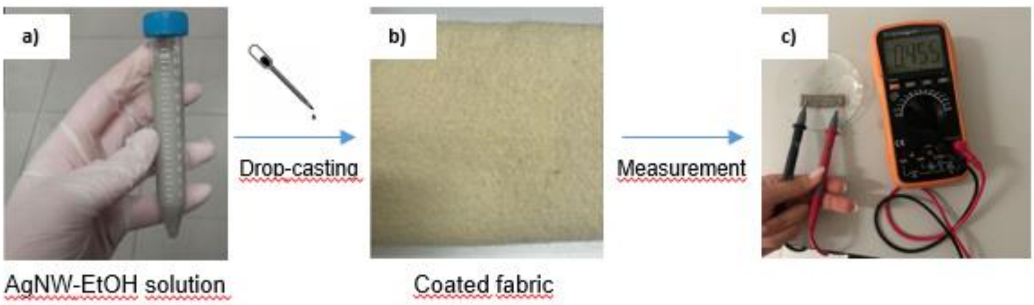

Figure 2 Schematic illustration of coating poplar/ PET blended nonwoven fabric with AgNWs and conductivity measurement

2.4 Scanning Electron Microscope

Scanning electron microscope (SEM) images of the nonwoven fabric, before and after AgNW coating process, was captured using the TESCAN VEGA3 Scanning Electron Microscope. The microscope featured an 2 to 7 mm working distance and operated at a speedup voltage of 10 kV. Prior to SEM scans, the specimens were subjected to conductive coating with Au/Pd applied under vacuum conditions for 3 minutes using a Quorum SC7620 Sputter Coater.

2.5 ECG Measurement

In this research, highly conductive nonwoven fabric based wearable electrode system integrated into a t-shirt. The three electrodes were positioned at three locations, as depicted in **Figure 3(a)**: two active electrodes were situated on the right arm (RA) and left arm (LA) regions of the human body, while the reference electrode was positioned on the right leg (RL) area. An elastical bandage was sewn onto the t-shirt to ensure optimal contact between the electrode and the skin and also to keep the electrodes from sliding. Also, a medium-thickness spacer fabric was incorporated between each electrode and the t-shirt to enhance the contact between the electrodes and the skin. Additionally, a highly conductive yarn was employed for the circuitry connecting the electrodes to the microprocessor.

The designed ECG system (**Figure 3b**) provides the signal measurement via the AD8232 ECG Sensor. This sensor amplifies and filters the raw ECG signal from the textile based electrode. Beetle BEE is responsible for collecting and transmitting data in the system. With its wireless technology, it can transfer data directly to the computer. The energy of the system is provided by the battery placed in the case, including Beetle BEE and ECG sensor.

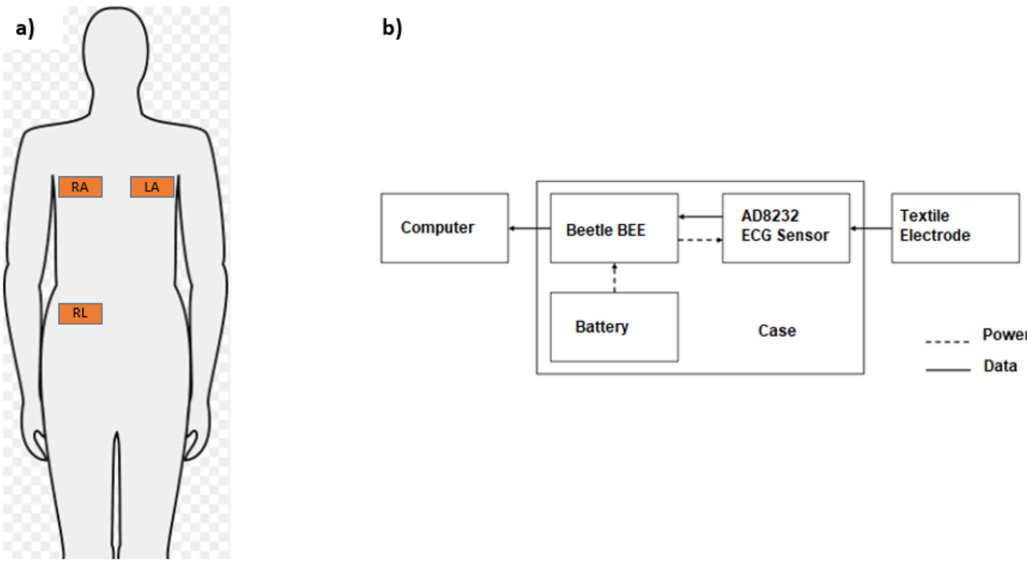

Figure 3 ECG electrode locations (a) and the designed system (b)

3. RESULTS AND DISCUSSION

Silver nanowires (AgNWs) offer the advantage of being applicable onto textile surfaces through environmentally friendly methods. Besides, AgNWs exhibit higher conductivity and lower production costs when compared to other materials. Considering all these, in this study, AgNWs were chosen to transform the nonwoven fabric into a conductive state.

Among the numerous techniques used to made traditional textile materials conductive, drop-casting is considered as the simplest, due to application of the solution onto the textile surface using a Pasteur pipette. This method was conducted to produce conductive poplar/ PET nonwoven fabric.

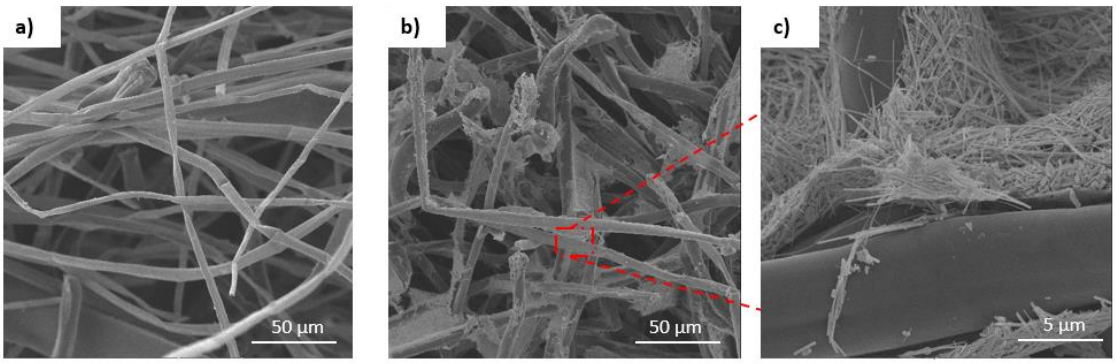

Figure 4 SEM images of nonwoven fabric before coating at 500x magnification (a) and after coating with AgNWs under 500x (b) and 5kx (c) magnifications

SEM analysis was conducted on the fabric sample both before and after the AgNW coating process. **Figure 3** display images of untreated nonwoven fabric (**Figure 4a**), treated with a AgNW at 500x (**Figure 4b**) and 5kx magnifications (**Figure 4c**). The SEM images clearly reveal the deposition of silver nanowires on the samples uniformly and well-distributed across the entire surface, indicating the success of methodology.

The measurement results demonstrated that nonwoven poplar/ PET blended fabric sample exhibited favorable conductivity values with 5.20 ± 1.8 Ω/cm of electrical resistivity. Also this value is well-suited for ECG applications in electronic textiles.

Raw ECG signals were measured in order to evaluate the performance of poplar/ PET nonwoven fabric-based electrode, and the results are depicted in **Figure 5**.

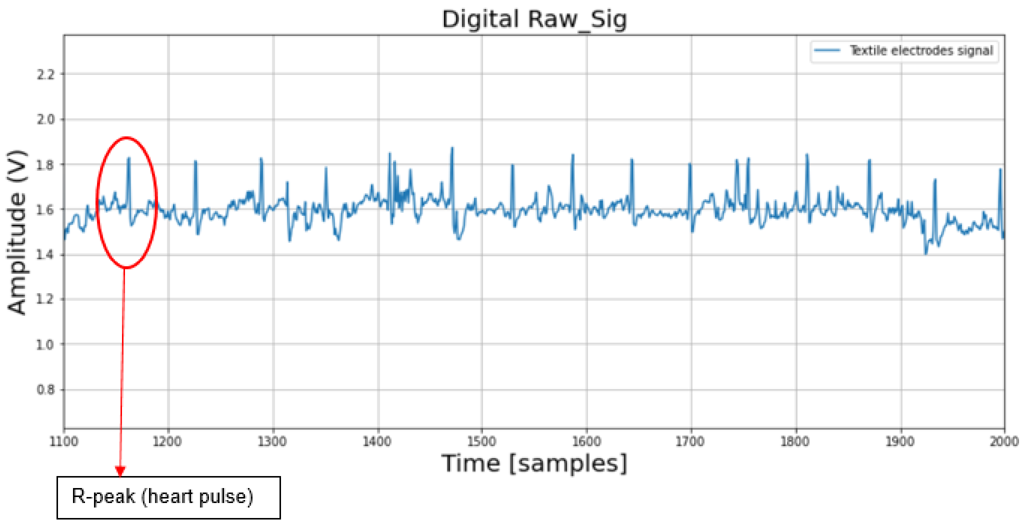

Figure 5 ECG signal measurement of poplar/ PET nonwoven fabric- based ECG electrode

The results demonstrate that ECG signals collected by textile electrode exhibit the continuous recording and display R-peaks with no missing peaks, affirming the acceptability of the waveforms. The average signal amplitude of the R-wave for the textile electrode was slightly lower. However, it has been observed that the textile- based electrode and the proposed measurement system provide successful results by providing a wireless communication technology and noise reduction.

4. CONCLUSION

In this study, bio-waste poplar fibers were transformed into a nonwoven fabric by needle-punching to be used as a valuable resource in the field of wearable electronics. Nonwoven poplar/ PET blended fabrics were coated with AgNWs and made conductive. Flexibility, excellent electrical conductivity, cost-effectiveness are the main qualities of the obtained conductive poplar/ PET fabric. Besides, utilizing poplar fibers in this way provides significant environmental and industrial benefits as it increases the biodegradability of the product.

The conductivity properties of the nonwoven fabric were measured by a multimeter. The results of the study indicated that AgNW coated poplar/ PET nonwoven fabric has electrical resistance of 5.20 ± 1.8 Ω/cm which is very reasonable for ECG electrode applications.

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