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Enhancing the Wicking Performance of Nepalese Dhaka Fabric via Dielectric Barrier Discharge Plasma Treatment

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Abstract

This study explores the use of dielectric barrier discharge (DBD) atmospheric air plasma treatment to enhance the wicking properties of Nepalese Dhaka fabric. Plasma treatment significantly improved the fabric's hydrophilicity, leading to a 1.14-fold increase in wicking coefficients compared to untreated fabric. These findings suggest promising applications for the plasma-treated fabric in sectors demanding enhanced moisture management and comfort, such as sportswear and general apparel. Moreover, the improved wicking properties make it suitable for the inner layer of medical garments like gowns and masks, where breathability, moisture management, and comfort are crucial. Understanding the effects of plasma treatment on Dhaka fabric's properties is essential for optimizing its use in various industrial and consumer applications.

Keywords: Dielectric Barrier Discharge (DBD), Textile Properties, Wicking Performance, Water Penetration, Nepalese Dhaka Fabric (NDF)

1. Introduction

Dhaka fabric, a time-honored handwoven cotton textile crafted by the Limbu people of eastern Nepal, is renowned for its vibrant hues and intricate patterns [1], [2]. Beyond its cultural significance in Nepal, Dhaka fabric is gaining global recognition for its aesthetic appeal. However, thoroughly understanding its material properties is essential to assess its suitability for various applications, including personal protective equipment (PPE) [3]. The COVID-19 pandemic highlighted the critical role of effective PPE, such as face masks and medical gowns, in preventing the spread of infectious diseases [4]. Key considerations for PPE fabrics include moisture management and user comfort, especially for the inner layers of medical garments. While natural fibers like cotton, including Dhaka, are widely used in Nepalese handwoven fabrics, their specific properties for PPE applications necessitate detailed characterization [5].

Atmospheric air plasma treatment has emerged as a promising technique for modifying fabric surface properties without compromising the bulk material [6], [7], [8]. This eco-friendly method offers several advantages, including cost-effectiveness, atmospheric pressure operation, and minimal energy consumption. By altering surface characteristics, plasma treatment can enhance fabric functionality across various applications [9].

This study investigates the water resistance of Dhaka fabric and the impact of atmospheric air plasma treatment on its water-wicking properties. Water resistance is crucial for determining the fabric's ability to repel fluids while wicking performance directly influences user comfort and the barrier function of PPE fabrics [10]. By understanding how plasma treatment affects these properties, we aim to optimize Dhaka fabric for potential use in PPE applications and various industrial and consumer contexts.

2. Materials and Methods

Fabric Characterization

The Nepalese Handwoven Dhaka fabric (Figure 1) was obtained from the Dhaka Collection, Asan, Kathmandu (Baghmati Province, Nepal). All fabric samples were placed in an ambient environment before measurements. All measurements, including fabric thickness, weight, grams per square meter (GSM), and density, were performed under controlled conditions with a temperature of 21°C, relative humidity of 52%, and a dew point of 11°C.

Figure 1 Dhaka Fabric

The thickness of the fabric was measured using a digital micrometer screw gauge with a precision of ±0.001 mm. Measurements were taken at five different points on each sample, and the average thickness was calculated.

The GSM was determined by weighing five 10 cm × 10 cm fabric samples using an electronic precision balance with a resolution of 0.0001 g. (Bell Engineering, Model: MG124Ai). The GSM for each sample was calculated using the formula [11]:

$$\text{GSM} = \frac{\text{Weight of Sample (g)}}{\text{Area of sample (m}^2\text{)}}.$$

The density of the fabric is calculated using the formula [12]:

$$\text{Density (kg/m}^3\text{)} = \frac{\text{GSM (g m}^{-2}\text{)}}{\text{Thickness (mm)}}$$

Contact angle measurements were conducted to assess the fabric's wettability using the sessile drop method. A small droplet of distilled water was placed on the fabric surface, and the contact angle between the droplet and the fabric was measured using a goniometer equipped with image analysis software. This method provides accurate and detailed information on the fabric's hydrophilic or hydrophobic nature [13].

Water Impact Penetration Test

To assess the water resistance of Dhaka fabric, a water impact penetration test was conducted following AATCC 42 standards [14]. A custom-built tester (Figure 2), designed by the Technical Training Center (TTC) of Kathmandu University, was employed. This apparatus featured a 27.3 mm-diameter spray head equipped with 19 holes, each of 1.04 mm-diameter, positioned 60 cm from the specimen. A 500 ml water volume was sprayed onto the test sample at a 45-degree angle.

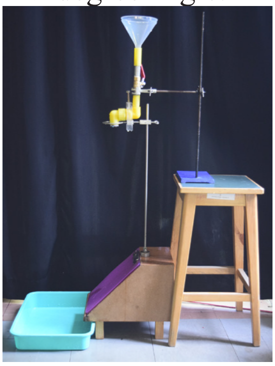

Figure 2 Water Impact Penetration Tester for evaluating Dhaka fabric's water resistance.

The fabric specimen, measuring 28 cm x 22 cm, was placed over a 20 cm x 20 cm standard blotting paper. To assess the fabric's resistance to water penetration under simulated rainfall, the amount of water penetrating the fabric was determined by measuring the weight gain of the blotting paper. This process was repeated five times under consistent conditions, and the average water penetration value was calculated to ensure the reliability of the results. This method effectively evaluates the fabric's initial resistance to water penetration.

The Dhaka fabric, recognized for its unique physical properties, was chosen for the study. We conducted comprehensive measurements to assess its performance and characteristics.

Table 1 summarizes the key metrics.

Parameter	**Value**
Thickness (mm)	0.204 ± 0.012
Weight of 10 cm x 10 cm sample (g)	1.2367 ± 0.0008
GSM (g /m^2)	123.67 ± 0.14
Density (kg /m^3)	606.22 ± 4.60
Water Penetration (g)	8.996 ± 0.414

Atmospheric Air Plasma Treatment

The photograph of the DBD reactor and DBD treatment process on fabric with rectangular copper electrodes are presented in Figures 3 and 4.

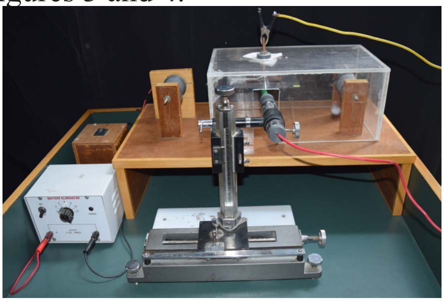

Figure 3 Photograph of a parallel plate Dielectric Barrier Discharge (DBD) reactor

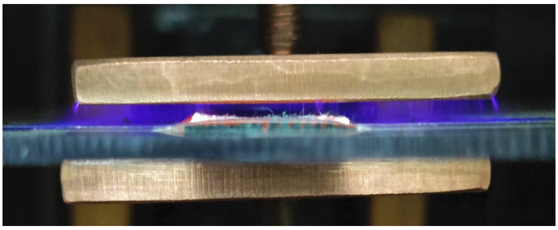

Figure 4 Photograph of DBD treatment process on fabric with rectangular copper electrodes.

The schematic diagram of the experimental setup for atmospheric plasma treatment is shown in Figure 5. Two parallel, rectangular copper electrodes (75.0 mm x 45.0 mm x 4.7 mm) were separated by a 3.5 mm gap with a polycarbonate dielectric barrier of the dimension of 150.0 mm x 120.0 mm x 1.97 mm. An alternating high voltage (16.4 kV peak, 50 Hz) was applied to the electrodes, generating a low-temperature, non-equilibrium air plasma within the reactor for surface treatment of Dhaka fabric. The applied voltage is measured using a high-voltage probe (PINTEK HVP-28HF), while the discharge current is monitored by measuring the voltage across a 10 kΩ shunt resistor with an oscilloscope probe. Current and voltage waveforms are recorded using a digital storage oscilloscope (TDS 2002, Tektronix). Images are captured with a Nikon Digital Camera D3300.

This setup provides a robust and precise method for generating and characterizing plasma discharges, ensuring reproducibility and reliability in the surface modification of fabrics. The detailed measurement and monitoring techniques employed facilitate comprehensive analysis and optimization of the plasma treatment process.

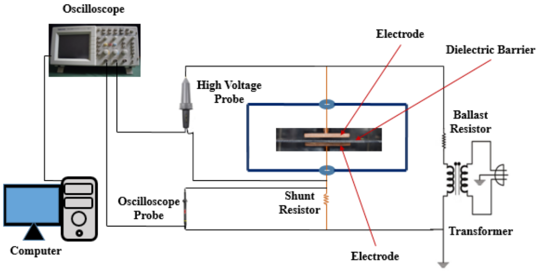

Figure 5 Schematic Diagram of the Experimental Setup for Atmospheric Plasma Treatment.

The energy dissipated per cycle and the power dissipated per cycle can be expressed as follows [15], [16]:

$$E_{av} = \int_{t}^{t+T} V(t)I(t)dt$$

The power dissipated per cycle is given by:

$$P_{av} = f\int_{t}^{t+T} I(t)V(t)dt$$

where f is the frequency of input voltage.

Vertical Wicking Test

The wicking performance of Dhaka fabric was evaluated before and after atmospheric air plasma treatment using a vertical wicking test. Fabric samples (10.0 cm x 1.5 cm) were marked with a 9.0 cm scale using a solvent-resistant pen. A test solution comprising 92 ml of triple-deionized water and 3 ml of fountain pen blue ink was prepared and maintained at 21 °C. The lower 1 cm of each sample was immersed in the solution, ensuring vertical alignment. The time taken for the solution to ascend each centimeter mark was recorded. To minimize temporal effects, three wicking tests were conducted for both untreated and plasma-treated samples within three minutes of treatment. The experiment took place under controlled conditions with a humidity of 52% and a dew point of 11 °C.

Figure 6 depicts a typical setup for the vertical wicking test used to evaluate water wicking in Dhaka fabric.

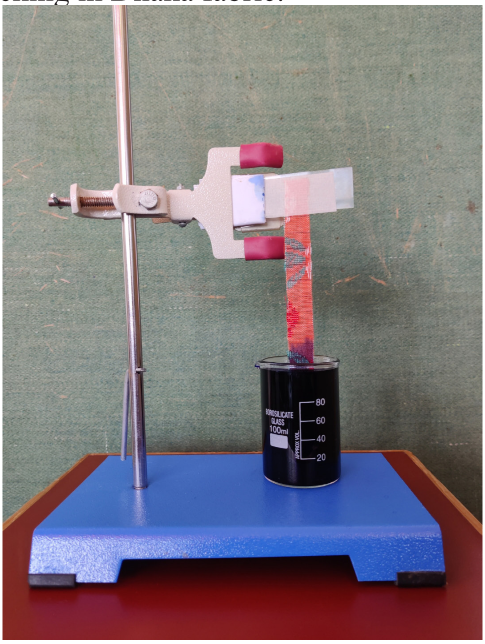

Figure 6 Vertical wicking test setup for Dhaka fabric

Capillary penetration in the fabric is the most important wetting mechanism. This phenomenon can be illustrated by the Lucas-Washburn equation [17], [18]:

$$l = \sqrt{\frac{r\gamma\cos\theta}{2\eta}}\sqrt{t}$$

(1) where l is the length of penetration by the liquid at time t, r is the radius of each of the parallel capillaries of the fabric, θ is the water contact angle of the fabric, γ is the surface tension of the water, η is the viscosity of the water, and t is the time of penetration.

Equation (1) can be written as:

$$t_{sqrt} = \left(W_C^R\right) l$$

(2)

where $t_{sqrt} = \sqrt{t}$, $W_C^R = \frac{1}{W_C}$, and

$$W_C = \sqrt{\frac{r\gamma\cos\theta}{2\eta}}$$

is the wicking coefficient.

The higher the W_c, the better the water absorption ability [19].

3. Results and Discussion:

3.1 Wetting Characteristics and Implications of Fabric Properties

Wetting Characteristics

Figure 7 shows the image of complete wetting with zero contact angle of dhaka fabric.

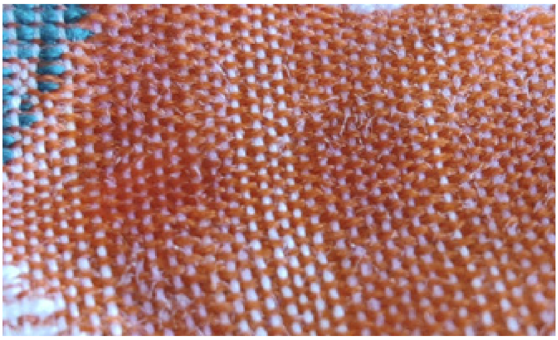

Figure 7 Image of complete wetting on Dhaka fabric

The Dhaka fabric exhibits complete wetting with a zero contact angle. This result indicates a high affinity for water, which is beneficial for moisture management applications. The zero contact angle signifies that water droplets spread entirely over the fabric surface, resulting in significant water absorption.

Implications of Fabric Properties

1. **Hydrophilicity and Water Penetration:** The measured water penetration of 8.996 g ± 0.414 further supports the fabric's hydrophilic nature. The relatively high water penetration value aligns with the observed complete wetting, indicating that the fabric can absorb moisture rapidly, making it suitable for applications where quick moisture management is desired, such as in sportswear.
2. **Physical Characteristics:**
   - **Thickness**: The fabric's thickness of 0.204 mm ± 0.012 suggests a lightweight structure that can contribute to comfort in wear.
   - **Weight and GSM**: The weight of the 10 cm ×10 cm sample is 1.2367 g ± 0.0008 with a GSM of 123.67 g /m^2 ± 0.14, indicating a balance between durability and comfort, critical for apparel applications.
   - **Density**: The fabric's density of 606.22 kg /m^3 ± 4.60 further reflects its lightweight nature, essential for maintaining breathability and comfort.
3. **Limitations for Medical Use: Despite** the favorable properties for moisture management, the complete wetting behavior and the associated high water penetration present limitations for medical applications, such as gowns and masks, where impermeability is crucial for safety and hygiene. The fabric's initial poor water resistance underscores the need for potential modifications to enhance its barrier properties while retaining comfort.

3.2 Energy Dissipation and Power Analysis:

Figure 8 shows the typical current and voltage waveforms, and Figure 9 shows the image of the discharge. From Figure 8, it is evident that the current waveform consists of a large number of discharge pulses corresponding to micro-discharges. The existence of micro-discharges is a characteristic feature of atmospheric pressure DBD [20].

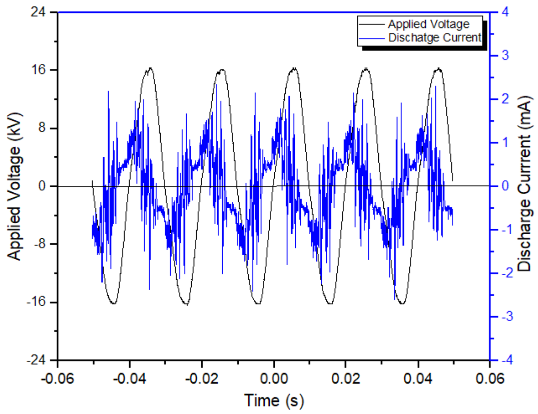

Figure 8 Typical current and voltage waveforms for the discharge

Figure 9 Image of the discharge

The average energy dissipated per cycle during the atmospheric air plasma treatment is a critical parameter for understanding the efficiency of the process.

In this study, the energy dissipated per cycle during the plasma treatment was measured at 3.34 millijoule (mJ), indicating a significant amount of energy used for fabric modification. Additionally, the average power dissipated during the treatment process was calculated to be 167 milliwatts (mW).

These findings demonstrate that the energy and power levels applied during plasma treatment effectively alter the surface properties of Dhaka fabric, resulting in improved wicking performance. The substantial energy dissipation is crucial for enhancing plasma interaction with the fabric's surface, ultimately leading to better moisture management characteristics.

Understanding the relationship between the energy dissipated and the resulting changes in fabric properties is essential for optimizing the plasma treatment process for industrial applications. This knowledge will guide future research aimed at refining treatment parameters to achieve even greater enhancements in fabric performance.

3.4 Wicking Performance

The Dhaka fabric underwent plasma treatment for 10 minutes at a peak voltage of 16.4 kV. By the end of the treatment, the temperature of the fabric reached 21.4°C, increasing just 2.2°C after 10 minutes of treatment. This moderate increase in temperature suggests a minimal thermal impact, making it unlikely to cause any thermal degradation or damage to the fabric. The controlled thermal effect indicates that the plasma treatment was conducted within a safe operational range, ensuring the fabric's integrity remained intact while achieving the desired surface modifications.

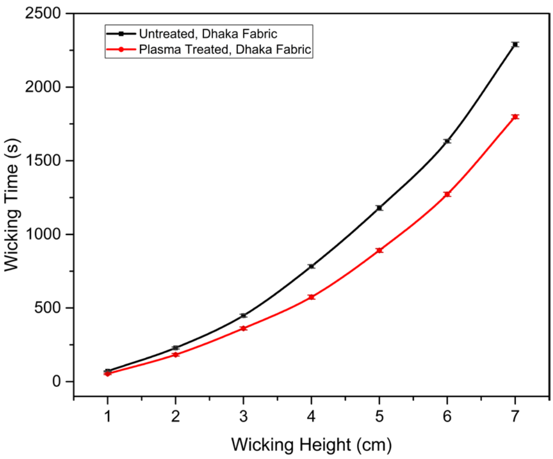

Figure 10 Wicking time comparison between untreated and plasma-treated Dhaka fabric

Figure 10 presents the wicking rates for untreated and plasma-treated Dhaka fabrics, highlighting the enhanced performance post-treatment. The data clearly show the enhanced wicking performance of the plasma-treated fabric compared to the untreated fabric. The untreated Dhaka fabric took 2289 seconds to wick to a height of 7 cm. However, after 10 minutes of plasma treatment, this duration decreased significantly to 1798 seconds. The improved wicking performance of plasma-treated Dhaka fabric is due to several factors. Plasma treatment increases the hydrophilicity of the fibers, which promotes faster water absorption and spreading. It also creates micro- and nanoscale roughness that enhances capillary action, allowing water to move more quickly through the fabric. Additionally, plasma treatment introduces polar groups, such as hydroxyl and carboxyl, on the fabric's surface, which attract water molecules and further enhance wicking. Furthermore, this treatment cleans the fabric surface, revealing its inherent hydrophilic properties.

Figure 11 illustrates the relationship between the square root of the penetration time and the penetration height and a treatment duration of 10 minutes.

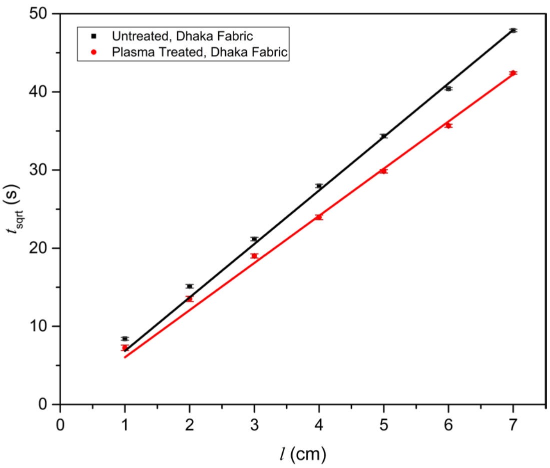

Figure 11 Plot of the square root of penetration time ($\sqrt{t}$) versus penetration length (l) at a constant peak voltage of 16.4 kV and a treatment duration of 10 minutes.

The wicking coefficient (WC) of the untreated Dhaka fabric was 0.146. In contrast, the wicking coefficient for the Dhaka fabric treated with plasma for 10 minutes increased to 0.166. It indicates that the wicking coefficient of the plasma-treated fabric is 1.14 times greater than that of the untreated fabric. As a result, the fabrics treated with plasma demonstrate improved water absorption abilities compared to those untreated fabrics.

4. Conclusions:

This study demonstrates the effectiveness of custom-fabricated DBD plasma treatment in enhancing the wicking performance of traditional Nepalese Dhaka fabric. DBD treatment modifies the fabric's surface without affecting its bulk properties, providing a sustainable and versatile method for enhancing textile performance. The enhanced moisture-wicking properties of plasma-treated Dhaka fabric make it suitable for various applications, including sportswear, general apparel, and medical garments. Future research should prioritize optimizing plasma treatment parameters and evaluating the long-term durability of these modifications to fully realize the potential of this innovative technology for enhancing textile performance.

Data Availability

Upon request, the authors are prepared to provide the figures, data, and supporting articles that validate their findings.

Conflict of Interest

The authors declare no competing interests.

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Author Contributions

G.K.C. contributed to the conceptualization and methodology. G.K.C., A.K.S., and D.P.S. conducted the investigation. G.K.C., A.K.S., and D.S. performed the data analysis. G.K.C wrote the original draft. B.P. and D.P.S. reviewed and edited the manuscript.

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