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RESEARCH ARTICLE

Influence of Electric Potential on Dielectric Barrier Discharge (DBD) Cold Plasma Treatment and Its Effect on the Affinity of Leaf Printing on Cotton Fabric

Weerasak Seerlarat[1,2], Porramain Porjai[3], Sasamol Phasuk[4] and Poonyanuch Nilsang[4,*]

[1]Doctor of Philosophy Program in Science and Innovation for Development, Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Pathum Thani 13180, Thailand
[2]Food and Beverage Innovation for Health, Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Pathum Thani 13180, Thailand
[3]Division of Physics, Faculty of Science and Technology, Rajamangala University of Technology Thanyaburi, Pathum Thani 12110, Thailand
[4]Science and Innovation for Development Program, Faculty of Science and Technology, Valaya Alongkorn Rajabhat University under the Royal Patronage, Pathum Thani 13180, Thailand

([*]Corresponding author's e-mail: poonyanuch@vru.ac.th)

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Abstract

This research aimed to develop a fabric printing process that utilizes natural dyes in combination with dielectric barrier discharge (DBD) plasma treatment. The study focused on determining the optimal electric potential for plasma treatment of cotton fabric and implementing eco-printing by transferring leaf pigments onto the fabric through heat transfer. Four types of leaves used for cotton fabric printing include Teak leaves (*Tectona grandis* Linn. f.), Indian trumpet flower leaves (*Oroxylum indicum* L. Kurz), Castor Bean leaves (*Ricinus communis* L.), and Bellyache bush leaves (*Jatropha gossypifolia* L.). Cotton fabric was subjected to DBD cold plasma treatment at 500, 1,000, 1,500, and 2,000 V, respectively, prior to leaf printing. The highest absorption coefficient and scattering coefficient (K/S) values were obtained from each printed leaf. The results revealed that high-voltage plasma treatment leads to a high K/S. These findings confirm that cold plasma has altered the physical structure of the cotton fibers, facilitating improved dye penetration into the fabric. Scanning Electron Microscope (SEM) images showed that untreated cotton fibers appeared smooth, round, and undamaged, while plasma-treated fibers exhibited rough, flattened, and fractured surfaces. However, the results concerning color fastness properties, including rub, light, and wash fastness, indicated that the color tends to fade and wash out easily. The optimal electrical potential for plasma treatment was 1,000 V, resulting in the cotton fibers absorbing the highest color intensity. This voltage also maintained favorable mechanical characteristics, with warp and weft tensile strengths of 500 and 360 N, respectively, and elongation values of 15.4 and 17.6%.

Keywords: Cold plasma treatment, Leaf printing, Natural dyes, Fabric printing, Dielectric Barrier Discharge (DBD)

Introduction

Fabric printing is a traditional technique used for textile decoration and is considered a long-established creative art. Traditional knowledge has been passed down through generations [1] using natural dyes to dye natural fibers, such as silk and cotton. Due to their diversity, natural dyes possess distinctive characteristics, including soft and beautiful hues. They can be classified based on their chemical structure into 7 main groups: Chlorophylls, carotenoids, flavonoids, anthocyanins, quinonoids, indigoids, and betalains [2-

4]. The traditional process using natural dyes tends to fade easily, leading to increased use of synthetic dyes. However, it has been found that most synthetic dyes contain harmful chemicals that may cause allergic reactions, and many of them are carcinogenic. Moreover, the unstable synthetic dyes from the printing process are often washed out and released into the environment, significantly contributing to water pollution in the textile industry. Growing awareness of the toxic and harmful effects of synthetic dyes [5] has led to a preference for natural alternatives. Currently, fabrics printed with natural dyes are gaining popularity due to their properties, such as durability and environmental friendliness. These attributes enhance the competitiveness of natural dye-based products in the textile printing industry. Additionally, fabric printing adds vibrancy to textiles and can be performed manually or with machinery [6]. Furthermore, these products are continuously being developed to meet the evolving trends of the fashion industry and the growing demand for eco-friendly goods [7]. Fabric printing requires a binding agent between the dye and the fabric fibers, commonly known as a mordant. Mordants are compounds widely used in dyeing or printing with natural dyes to enhance effectiveness. They can create color variations and alter the shades of natural dyes [8,9]. Natural dyes require mordants for better adhesion to fabric fibers than synthetic dyes. However, natural dyes have several limitations, particularly lightfastness and wash fastness. Additionally, while natural dyes offer a range of shades, even with various mordants, they still cannot achieve the same level of color diversity as synthetic dyes [10]. “Leaf printing”, “Botanical printing”, “Eco-dyeing”, or “Eco-printing”, there are several terms for a technique where plants, leaves, flowers, and other floral elements leave their shapes, colors, and marks on fabric. Eco-dyed or printed fabric is created by wrapping plant materials with cloth, binding them, and applying heat via steaming. This process allows the color from the plants to infuse into the fabric [11-13]. At present, the concept of eco-printing aims to provide alternatives to eco-friendly initiatives that reduce negative impacts on the environment and preserve it [14].

Cold plasma is a unique state of matter composed of ions, electrons, or free radicals [15]. Factors influencing plasma treatment efficiency include the voltage source’s flow rate and the gas composition [16]. Cold plasma technology has been widely applied in various fields such as agriculture and food processing [17-21]. Cold plasma is distinct from solid, liquid, and gas. It can be generated through electrical discharge in a medium, which may be a gas or a vaporized liquid, forming particles or radicals. These radicals can diffuse through the medium and undergo. Chemical reactions, such as oxidation or reduction, effectively replace traditional chemical agents. For practical production and applications, cold plasma radicals are typically generated through 3 primary methods: Discharge over a liquid surface, discharge in liquid, and discharge in vaporized liquid [22,23]. Plasma technology has gained increasing attention in the textile industry due to its ability to reduce the emission of harmful chemicals, making it a sustainable process. This technology can enhance specific surface properties of textiles within a short processing time without affecting the fundamental characteristics of the treated materials [24]. However, the adoption of plasma processes in the textile industry remains limited. Implementing plasma technology in textiles requires careful consideration of fabric properties such as structure, composition, and fiber surface purity. Additionally, selecting appropriate plasma processing parameters is crucial to achieving optimal results. Plasma technology is a valuable tool for textile advancements, providing a more cost-effective and environmentally friendly alternative to conventional chemical processing. The process is simple, solvent-free, reduces production time, and has minimal environmental impact. Moreover, applying plasma technology does not alter the essential properties of fabrics while enhancing surface characteristics. Despite its high potential, this technology has yet to be fully utilized for all textile materials [24]. Electric potential difference plays a crucial role in initiating cold plasma formation. The appropriate voltage accelerates electrons within the gas, causing collisions with gas molecules and generating ions, radicals, and high-energy particles interacting with material surfaces. This process enhances fabric dyeability by improving dye absorption, cleans fibers by removing surface contaminants, and modifies water repellency or hydrophilicity as required. Therefore, electric potential difference is a key element in controlling the efficiency of cold plasma, effectively enhancing textile properties in an environmentally friendly manner [25].

This research aims to create a fabric printing process utilizing natural dyes from leaves along with dielectric barrier discharge (DBD) cold plasma treatment. Currently, eco-printing using leaf patterns has gained popularity in Thailand, particularly among handicraft communities, local textile producers, and environmentally conscious design sectors. However, this process still faces several significant challenges that affect the quality of the printed textiles, such as poor color adhesion, low color intensity, uneven pattern definition, and a lack of standardized process control suitable for industrial production. Therefore, to address this issue, cold plasma treatment is implemented to improve the surface characteristics of cotton fabric, enhancing the clarity of the printed designs and the color's durability on the fibers. This method fosters local weaving skills, supports community economic development, and enhances the commercial value of traditional knowledge. Furthermore, it seeks to establish a distinctive identity for Thai textiles in the international market while promoting environmental sustainability.

Materials and methods

Cotton fabric

The natural fiber fabric used in the experiment was made from cellulose fibers derived from the cotton plant. It was a handwoven cotton fabric, traditionally crafted with warp and weft threads, sourced from the Pak Kham Phu community in the Na Nai Subdistrict of Phanna Nikhom District, Sakon Nakhon Province, Thailand. The handwoven cotton fabric used in the experiment measured 50×50 cm^2, including the warp and weft threads. It was washed with laundry detergent, rinsed with clean water, and boiled at 70 °C for 30 min. Afterward, the fabric was gently wrung out and air-dried until completely dry.

Leaves

Four types of leaves used for fabric printing were selected from a community in Khlong Luang District, Pathum Thani Province, Thailand. These include Teak leaves (*Tectona grandis* Linn. f.), chosen from young leaves at the tips of branches, characterized by a reddish-brown color, with a width of not less than 8 cm and a length of not less than 10 cm. Indian trumpet flower leaves (*Oroxylum indicum* L. Kurz) were selected from mature leaves with a dark green color, a width of no less than 5 cm, and a length of no less than 8 cm. Castor Bean leaves (*Ricinus communis* L.) were chosen from fully matured leaves that are dark green, with 8 lobes and a diameter of no less than 8 cm. Bellyache bush leaves (*Jatropha gossypifolia* L.) were selected from young leaves with a width of no less than 8 cm and a length of no less than 8 cm.

Cold plasma treatment

A dielectric barrier discharge (DBD) plasma device, developed in-house, was employed for this experiment, as illustrated in **Figure 1**. The DBD system consisted of 2 copper plates functioning as electrodes which the dimensions of electrode were 0.2 cm thick, 10 cm width, and 120 cm long. The electrode gap was maintained at approximately 5 mm. The lower electrode was insulated with a 0.2 mm-thick acrylic sheet. Plasma was generated within the inter-electrode space by applying high voltage through an AC power supply (Electrostatic Ionization, Model 200E, China), with voltage settings adjustable between 500, 1,000, 1,500, and 2,000 V and the frequency of 1,500 Hz. The discharge voltage signal, V(t), was acquired through the 1^{st} channel of a digital oscilloscope using a voltage divider. The discharge current, I(t), was monitored with a Pearson current transformer (Model 6585, PMC; bandwidth up to 250 MHz) and recorded on the oscilloscope's 2^{nd} channel. The methodology for determining the discharge voltage via the voltage divider has been detailed in our previous work [24]. The voltage and current waveforms were captured using a digital oscilloscope (TDS2014B; Tektronix, Inc., USA). The average discharge power and electric field of were calculated using Eqs. (1) - (2) [26]. Normal cotton fabrics were treated with cold plasma at various voltages for 5 s before leaf printing. The room temperature and humidity were set at 25 ± 2 °C and 60 ± 5 %RH.

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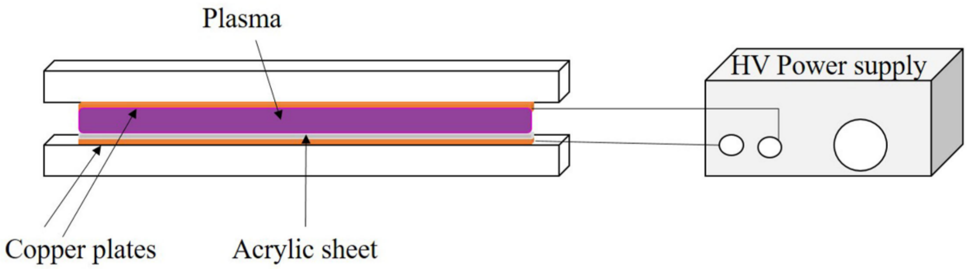

Figure 1 A schematic of the DBD plasma system.

$$P(W) = \frac{1}{T}\int_0^T V(t)I(t)dt \quad (1)$$

$$E = \frac{V_{p\,max}}{(d_1 + \frac{d_2}{\varepsilon_r})} \quad (2)$$

where P, V(t), and I(t) represent power, discharge voltage and current, respectively. The d_1 is gap between electrodes (5 mm), d_2 is barrier thickness (2 mm), and ε_r is permittivity of acrylic (3.5). The optical emission spectrum (OES) of the plasma plume was recorded using a broadband CCD spectrometer (Exemplar LS; BWTEK Inc., USA). The instrument was equipped with a 600 grooves/mm grating and a 25 µm slit, allowing spectral measurements within the 200 - 850 nm range.

Mordants

Preparation of Mordant solution used in this experiment according to Laowangsa [27] as follows: 200 g of ammonium aluminum sulfate ($(NH_4)Al(SO_4)_2 \cdot 12H_2O$) and 1 g of ferrous sulfate ($FeSO_4$) were added to 1 L of 5% acetic acid. Mix thoroughly until all components are fully dissolved into a homogeneous solution. Soak the prepared fabric in the mordant solution and knead it gently for 5 min to ensure even absorption. Hang the fabric in the shade to dry completely. Once dry, rinse the fabric with clean water and proceed to the fabric printing process in the next step.

Printing process

To determine the suitable voltage for using cold plasma in fabric printing from leaves, the experiment was organized into 6 groups: 1) Standard handwoven cotton fabric (Original cotton fabric), 2) Cotton fabric printed with leaves without plasma treatment (Control), and 3 - 6) Cotton fabric subjected to cold plasma at 500, 1,000, 1,500, and 2,000 V, respectively, prior to leaf printing. In the leaf printing process, the control group's cotton fabric was soaked in a mordant solution before leaf printing, while the fabrics from groups 3 - 6 were exposed to cold plasma at various electric voltages before being soaked in the mordant solution. Afterward, 4 types of leaves were placed on each piece of cloth, covered with a plastic sheet, tightly tied, and steamed at 70 °C for 120 min. Each treatment was conducted in 5 replicates. After steaming, the fabric was carefully removed, and the leaves were taken off. The fabric was washed with detergent and hung to dry.

Analysis

Color measurement

Subsequently, the color adhesion properties of the cotton fabric were evaluated using spectroscopy techniques to measure color in the L*, a*, b*, (K/S) system and the reflectance (R) at its lowest point. The obtained R values were then used to calculate the color strength (K/S) according to Eq. (3) [25], where K/S represents color strength and R represents reflectance. To ensure adequate color adhesion, intensity, and pattern sharpness, the data from the color adhesion tests of the printed fabric were analyzed to assess their suitability for different fabric samples, which were then further examined in the subsequent process.

$$K/S = (1-R)^2/2R \quad (3)$$

Light fastness test

The light fastness of plasma-treated cotton yarn was tested using an Atlas Xenon Arc Weather-Ometer Model Ci 3000+, which is equipped with a watercooled xenon arc lamp, following the test standard ISO 105-B02:2004 (E) Exposure Cycle A2 [28].

Wash fastness test

Testing the wash fastness of plasma-treated and leaf-printed cotton yarn is performed using a laundering device according to ISO 105-C06:2010 (E) [28]. The printed yarn is sewn between 2 adjacent test fabrics (wool and cotton). The sample is washed in the laundering device with a non-ionic detergent at a concentration of 4 g/L, at 50 °C for 45 min. The color change and staining on the adjacent test fabrics are then evaluated.

Rub fastness test

According to ISO 105-X12:2016 (E) [28], leaf-printed cotton yarn's dry and wet rub fastness is tested using a rectangular rubbing device (crock block) with a top edge size of 19×25.4 mm^2. The fabric sample is mounted on a test panel, and the yarn is rubbed 10 times for dry and wet tests. The staining on the adjacent white test fabrics (cotton and wool) is then evaluated.

Tensile strength test

The tensile strength test was conducted according to ISO 13934-1:2013 [28] using a universal testing machine. The fabric samples were cut into strips measuring 50×250 mm^2 at a relative humidity of 65%, and clamped in the machine with a gauge length of 75 mm. The test speed was set at 50 mm/min.

Scanning electron microscope (SEM)

The surface structure of cotton fabric, treated with cold plasma and the untreated, was examined using a Quanta 400 scanning electron microscope (SEM) from FEI, USA. This microscope was used to inspect the external structure or surface of the samples. For SEM imaging, test specimens were prepared by cutting 0.2 cm pieces from the cotton fabric in the warp and weft directions. The sample fibers were extracted using tweezers, then gold-coated for 2 min in 2 cycles, and mounted on a stub, resulting in 3-dimensional images. The surface resolution is approximately 1 - 2 nm, with a magnification range of 100 to 10,000 times. The cotton fabric samples used for analysis were in sheet form, measuring 1×1×1 cm^3. The analysis was performed using a JSM-5410LV SEM at an operating voltage of 20 kV, with magnifications ranging from 1,000 to 5,000 times, and the particle size was analyzed using SemAfore 5.2 software.

Statistical analyses

The results are expressed as the mean ± standard deviation (SD). Experimental data were analyzed using one-way analysis of variance (ANOVA) and Duncan's multiple range test ($p < 0.05$) with SPSS software version 26.0 (SPSS, Chicago, IL, USA).

Results and discussion

DBD plasma characteristics

Figure 2 shows the discharge voltage and current characteristics for generating an DBD plasma with different input voltage. The waveforms of the voltage and the current discharges were pulse-modulated with a frequency of 1500 Hz. The maximum peak discharge values were 3.30, 2.05, 3.50, and 3.30 kV for 500, 1,000, 1,500, and 2,000 V, respectively. Correspondingly, the peak discharge current values were 0.25, 0.50, 0.575, and 0.615 A. Analysis of the system's energetics indicated that the power dissipated per pulse scaled with increasing input voltage, yielding values of 2.48, 3.50, 8.14, and 8.37 W, respectively.

Notably, the calculated electric field strengths for these conditions were 0.592, 0.368, 0.628, and 0.592 kV/mm. These findings unequivocally demonstrate that the electric field generated in this air DBD plasma system operates at a level substantially below the typical 3 kV/mm breakdown threshold for air. Our observations are consistent with Ruangwong *et al*. [26] who also achieved air DBD plasma with electric fields around ~1 kV/mm. This behavior is likely explained by the presence of highly localized, non-uniform electric fields within the setup. Such fields generate a significant fringe field that exerts considerable electrical stress on the entire dielectric. This stress causes the air at the tip edges to lose its dielectric strength and break down, manifesting as an electron discharge (corona discharge).

To verify the performance of the air-based atmospheric pressure plasma jet (APPJ) system, a representative optical emission spectroscopy (OES) spectrum is shown in **Figure 3**. The OES profile of the air plasma operated under ambient conditions exhibited multiple emission lines corresponding to various transitions. The intensity of OES spectra increased with the input voltage. Notably, the nitrogen 2nd positive system ($C\prod_u \rightarrow B\prod_g$, 268 – 546 nm) and the 1st negative system ($B\Sigma_u^+ \rightarrow X\Sigma_g^+$, 286 – 587 nm) were clearly identified. The presence of ˙OH emission bands at 306.6 and 309.4 nm. The formation of ˙OH radicals in ambient air, which involves water vapor, may occur through primary electron impact dissociation, ion neutralization processes, or dissociation via reactive radicals and metastable species. The atomic emission line of hydrogen (H_α) was identified in the OES spectrum at 656.8 nm. Additionally, the dissociation of molecular oxygen resulted in the appearance of atomic oxygen, with a characteristic emission detected at 777.7 nm. The generation mechanisms of these nitrogen systems and reactive species have been previously detailed in our earlier publication [29,30]. Our results agree with the previously research that the high power dissipated could generate high intensity of reactive species [31].

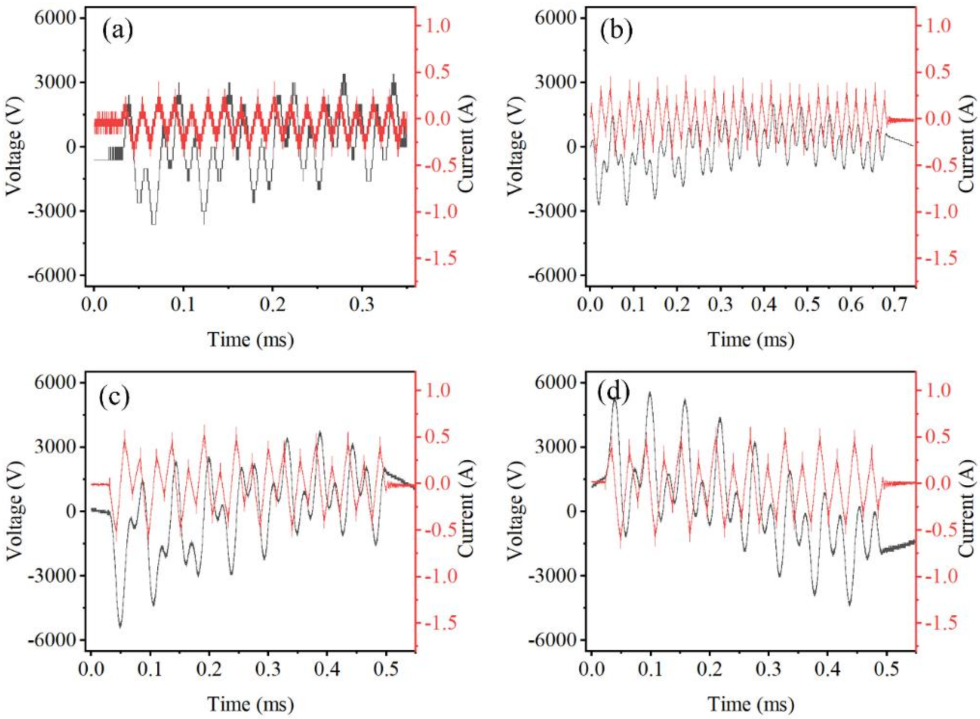

Figure 2 Discharge voltage and current of the DBD plasma (a) 500, (b) 1,000, (c) 1,500, and (d) 2,000 V.

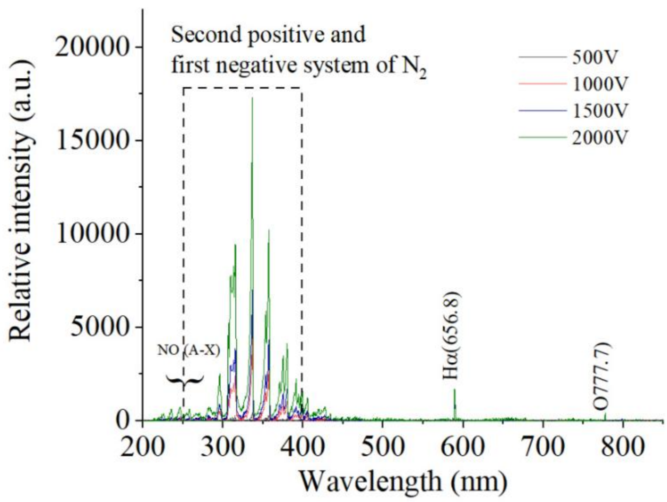

Figure 3 Optical emission spectra of the air DBD plasma with different input voltages.

Printing color measurement

The color measurement of different kinds of leaves, comparing plasma treatments at various electric potential levels applied to printing cotton fabric, ranges from low to high voltage levels (500, 1,000, 1,500, and 2,000 V) as shown in **Table 1**. The results reveal that cotton fabric treated with plasma at different levels resulted in a decrease in lightness (L*). The color lightness of each leaf type decreased, indicating that the leaf shades became darker after plasma treatment before printing the fabric. Compared to untreated fabric, the values of a* and b*, the data differ across leaf types due to the leaves producing different yellow, green, and red tones. Regarding color strength (K/S), higher color strengths were observed in the shades obtained from higher plasma treatments. From the K/S value graph in **Table 1**, an increase in color intensity was observed, potentially due to the plasma treatment combined with mordant use, which intensified the color of each type of leaf. This aligns with Ding and Freeman [32], who stated that metal-based mordants can form insoluble compounds with dye molecules. Therefore, the cause may be attributed to the formation of complexes between metal ions and alizarin dye (present in the leaf extracts) in the dye bath, without directly attaching to the fabric fibers.

Table 1 presents data showing that applying different electric potentials (500, 1,000, 1,500, and 2,000 V) to cotton fabric printed with various leaf patterns (teak leaves, castor leaves, bellyache bush leaves, and Indian trumpet leaves) resulted in increased (K/S) values of the leaf-printed fabric compared to samples not treated with cold plasma. When the electric potential increased from without plasma treatment (control) to 500 V, the (K/S) value also rose, indicating enhanced absorption of the leaf-derived dye for all 4 types of leaves. This data suggests that a heat transfer process occurred, facilitating dye transfer from the leaves to the cotton fabric. This process led to an interaction between the leaf dye and the mordant on the fabric fibers. Metal-based mordants can form insoluble compounds with dye molecules. Therefore, the cause may be attributed to the formation of complexes between metal ions and alizarin dye (present in the leaf extracts) in the dye bath, without directly attaching to the fabric fibers [33]. It can thus be concluded that, in this case, plasma treatment at an electric potential of 1,000 V is the most effective. Pairing it with an appropriate mordant yield the highest color intensity, as shown in **Figure 4**. The characteristics of the leaves treated with plasma at an electrical potential of 1,000 V (**Figure 4(d)**) show clear leaf edges and a deep leaf color, with no color bleeding at the edges of the leaves. The veins of the leaves are clearly defined.

Table 1 Comparative study of cold plasma treatment to determine the electric potential difference on leaf-printed fabric.

Leaves	**Color value**				**Color fastness (K/S)**
	Plasma treatment	**L***	**a***	**b***	
Teak leaves	Original fabric	83.14 ± 0.54	1.08 ± 0.01	12.92 ± 0.51	0.41 ± 0.05
	Control	35.13 ± 0.00^{c}	18.33 ± 0.00^{a}	12.54 ± 0.00^{b}	9.73 ± 0.00^{b}
	DBD 500 V	54.48 ± 6.75^{a}	8.49 ± 2.01^{b}	33.10 ± 5.71^{a}	24.64 ± 6.58^{a}
	DBD 1,000 V	55.02 ± 8.41^{a}	6.03 ± 5.64^{b}	32.05 ± 7.25^{a}	21.41 ± 2.65^{a}
	DBD 1,500 V	54.74 ± 4.01^{a}	6.50 ± 3.91^{b}	31.21 ± 7.03^{a}	20.57 ± 2.59^{a}
	DBD 2,000 V	46.39 ± 4.20^{b}	11.29 ± 5.22^{b}	29.92 ± 8.52^{a}	23.70 ± 4.03^{a}
Indian trumpet flower leaves	Control	75.37 ± 0.00^{f}	0.13 ± 0.00^{g}	33.41 ± 0.00^{h}	3.61 ± 0.00^{h}
	DBD 500 V	62.96 ± 5.99^{g}	6.12 ± 1.69^{f}	40.85 ± 2.55^{g}	12.38 ± 2.58^{g}
	DBD 1,000 V	63.06 ± 5.47^{g}	5.72 ± 1.60^{f}	44.41 ± 1.36^{f}	13.38 ± 1.18^{fg}
	DBD 1,500 V	61.66 ± 5.78^{g}	6.18 ± 1.81^{f}	41.23 ± 2.71^{g}	14.78 ± 3.04^{fg}
	DBD 2,000 V	65.67 ± 5.61^{g}	5.75 ± 2.62^{f}	42.20 ± 2.66^{fg}	16.18 ± 2.30^{f}

Leaves	Color value				Color fastness (K/S)
	Plasma treatment	**L***	**a***	**b***	
Castor Bean leaves	Control	73.16 ± 0.00	–0.89 ± 0.00^{m}	43.51 ± 0.00^{k}	4.49 ± 0.00^{n}
	DBD 500 V	66.56 ± 6.07	0.39 ± 1.28^{km}	35.37 ± 5.10^{n}	11.85 ± 2.03^{m}
	DBD 1,000 V	65.35 ± 7.89	1.09 ± 2.06^{k}	30.06 ± 4.59^{m}	14.85 ± 2.03^{km}
	DBD 1,500 V	68.46 ± 6.12	–0.59 ± 0.90^{m}	38.45 ± 1.95^{mn}	16.36 ± 1.60^{km}
	DBD 2,000 V	65.66 ± 5.24	0.10 ± 0.42^{km}	41.56 ± 2.71^{km}	19.64 ± 7.89^{k}
Bellyache bush leaves	Control	68.66 ± 0.00	–3.55 ± 0.00	33.61 ± 0.00^{r}	5.45 ± 0.00^{r}
	DBD 500 V	68.48 ± 6.29	–4.36 ± 1.73	38.58 ± 1.00^{q}	8.50 ± 0.74^{s}
	DBD 1,000 V	64.52 ± 8.64	–4.33 ± 3.32	34.50 ± 3.71^{r}	12.60 ± 2.74^{r}
	DBD 1,500 V	66.11 ± 9.17	–3.64 ± 2.16	35.93 ± 1.07^{qr}	14.44 ± 1.63^{qr}
	DBD 2,000 V	69.63 ± 7.04	–3.32 ± 3.03	36.95 ± 4.25^{qr}	15.70 ± 2.06^{q}

Note: The values are mean ± standard deviation (n = 5). Different superscript letters in the same column indicate that the samples significantly differ according to the DMRT test at $p \leq 0.05$.

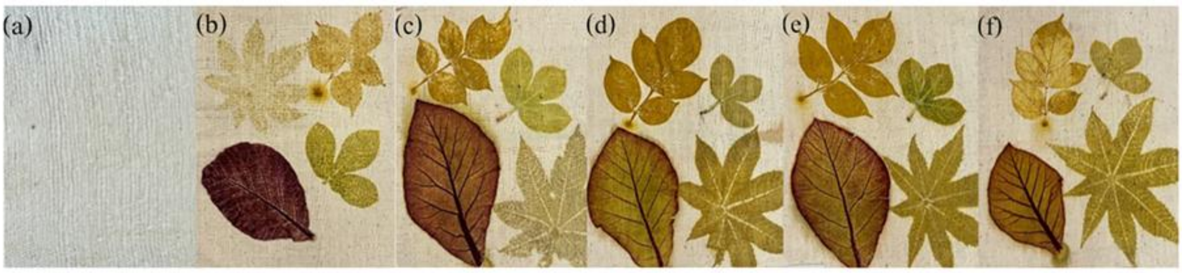

Figure 4 Fabrics Printed with Leaf Patterns Subjected to Cold Plasma Treatment at Different Electric Potentials: (a) Original cotton fabric (b) control (c) 500 V (d) 1,000 V (e) 1,500 V, and (f) 2,000 V.

Color fastness properties

Light fastness properties

The color-printed cotton fabric treated with cold plasma was tested for performance according to the International Organization for Standardization (ISO) standards, the Color Fastness to Artificial Light: Xenon Arc Fading Lamp Test. The test results are presented in **Table 2**. The xenon arc light fastness test results revealed that printed fabrics using leaf-based natural dyes without plasma treatment had a color change fastness rating of 2 - 3, which falls between "poor" and "fair". This indicates that natural dyes derived from leaves generally exhibit low light fastness due to the minimal presence of ferrous sulfate, contributing to lower color stability under light exposure. Fabrics treated with plasma at various voltages before printing showed a color change fastness rating of 1 ("very poor"), leading to poor abrasion resistance of the colors. Cold Plasma Treatment is a process that uses energy from high-energy particles such as electrons, ions, and moving particles to alter the chemical and physical properties of the cotton fabric surface. Specifically, it leads to the formation of new functional groups, such as oxygen functional groups, or the creation of unstable chemical bonds, which may weaken the adhesion of color to the fabric surface. This can result in color fading when exposed to UV light. These changes can affect the light fastness of the color and cause the fading of the leaf print color [34] .

Table 2 Light fastness properties of Fabric printing at various voltages of DBD.

Plasma treatment	Color staining value
Control	2 - 3
DBD 500 V	1
DBD 1,000 V	1
DBD 1,500 V	1
DBD 2,000 V	1

Note: The ratings are interpreted as follows: Level 8 - Excellent, Level 7 - Outstanding, Level 6 - Very Good, Level 5 - Good, Level 4 - Fairly Good, Level 3 - Fair, Level 2 - Poor and Level 1 - Very Poor, with a maximum score of 8.

Wash fastness properties

The test used the ISO 105-C06:2010 (E) method: Textiles - Tests for Color Fastness - Part C06: Color Fastness to Washing with Soap or Soap and Soda. The results of the color fastness to washing test are shown in **Table 3**. The findings revealed that the color fastness to color change of leaf-printed fabric without plasma treatment was rated at levels 2 - 3 (poor to fair). The use of cold plasma at different electrical potentials can have varying effects on dye adhesion and the durability of color after washing. Applying a lower electrical potential helps slightly roughen the surface. It improves the adhesion of the dye to a good level, while higher electrical potentials may lead to more profound structural changes in the cotton fibers, resulting in stronger dye adhesion. Cold plasma also enhances dye absorption by modifying the surface structure of the fibers, allowing for increased dye uptake. When the fibers absorb more dye, they adhere better to the color. Without the use of a dye-fixing agent after printing or treating fabric with nanoparticles, the color's fastness to washing will decrease, causing the color to fade easily [35].

Table 3 Wash fastness properties of Fabric printing at various voltages of DBD.

Plasma treatment	Color change values	Color staining values					
		Acetate	Cotton	Nylon	Polyester	Acrylic	Wool
Control	2 - 3	4 - 5	4	4 - 5	4 - 5	4 - 5	4 - 5
DBD 500 V	1	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5
DBD 1,000 V	1	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5
DBD 1,500 V	1	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5
DBD 2,000 V	1	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5	4 - 5

Note: The rating scale is as follows: Level 5 - Excellent, Level 4 - Good, Level 3 - Fair, Level 2 - Poor and Level 1 - Very Poor, with a maximum score of 5.

Rub fastness properties

Test for Color Fastness to Rubbing: The test was conducted according to ISO 105-X12: 2016 (E). "Textiles - Tests for Color Fastness - Part X12: Color Fastness to Rubbing". The results of the color fastness to rubbing test are shown in **Table 4**. The color fastness to abrasion of the leaf-printed fabric without plasma treatment in the dry condition is rated at level 4 (good), and in the wet condition, it is rated at levels 2 - 3 (poor to fair). Plasma treatment before printing at electrical potentials ranging from 500 to 2,000 V has dry condition ratings of 2 - 3 (poor to fair), and in the wet condition, it is rated at levels 1 - 2 (poor to very poor). Cold plasma treatment decreases the color fastness of the leaf-printed fabric by altering the surface characteristics of the fabric and affecting the adhesion of the dye printed on the fabric. These changes include surface roughening, where the fibers become rougher, temporarily improving the fabric's ability to absorb dye. However, over time, the rougher surface may weaken the adhesion of the dye to the fibers, making it easier for the color to peel off when the fabric is abraded or exposed to friction. Chemical changes on the fabric's surface can also cause the chemical bonds between the dye and the fabric fibers to loosen, leading to weaker adhesion. Introducing functional groups that interact with the dye may create weaker bonds, making the dye peel off more easily when subjected to friction or abrasion. Cold plasma treatment creates unstable chemical bonds between the dye and the fabric fibers, leading to insufficient strength in the adhesion to withstand abrasion. This weak adhesion causes the color to come off easily when exposed to friction or wear from real-world use [36].

Table 4 Rub fastness properties of Fabric printing at various voltages of DBD.

Plasma treatment	Color staining values	
	Dry (5 levels)	Wet (5 levels)
Control	4	2 - 3
DBD 500 V	2 - 3	1 - 2
DBD 1,000 V	2 - 3	1 - 2
DBD 1,500 V	2 - 3	1 - 2
DBD 2,000 V	2 - 3	1 - 2

Note: The rating scale is as follows: Level 5 - Excellent, Level 4 - Good, Level 3 - Fair, Level 2 - Poor and Level 1 - Very Poor, with a maximum score of 5.

Fabric strength properties

The tensile strength and elongation characteristics of fabrics treated with dielectric barrier discharge (DBD) plasma at various voltages, as detailed in **Table 5**, offer crucial insights into the mechanical implications of plasma-based textile surface modification. Both warp and weft directions exhibited measurable changes in maximum force and apparent elongation, reflecting the impact of plasma-induced surface and structural changes. In the warp direction, the untreated fabric demonstrated a tensile strength of 270 N and an elongation of 14.4%. The control sample, potentially subjected to non-plasma thermal or mechanical preconditioning, exhibited a significant increase in warp strength (520 N) and elongation (20.8%). Cold plasma treatment at 500 to 2,000 V resulted in a general reduction in tensile strength (ranging from 450 to 500 N), while the elongation increased, reaching a maximum of 18.1% at 2,000 V. This trend indicates that while DBD treatment may slightly reduce structural integrity, it enhances flexibility, likely due to surface etching, polymer chain scission, and increased molecular mobility. These phenomena are consistent with the findings of Shishoo [37] and Morshed *et al*. [38], who reported similar mechanical effects from plasma processing on textile substrates. In contrast, weft direction showed higher initial tensile strength (430 N) in the untreated sample but demonstrated a consistent decline in strength with increasing DBD voltage. Notably, the lowest values (290 N) were observed at 1,500 and 2,000 V. Apparent elongations also decreased from 20.3 to 14.8% over this voltage range, suggesting that high-voltage plasma exposure leads to embrittlement and microstructural degradation. These results echo the observations of Morent *et al*. [39] where high-voltage plasma treatments caused significant surface erosion and deterioration in mechanical properties. Interestingly, the sample treated at 1,000 V maintained favorable mechanical characteristics, combining relatively high warp strength (500 N) with moderate elongation (15.4%) and balanced weft properties (360 N, 17.6%). This suggests that 1,000 V may serve as an optimal voltage threshold, balancing the benefits of surface activation with the preservation of fabric integrity.

The findings indicate that the printing process affects cotton fabric's fiber structure by reducing the tensile strength of weft yarns. Cold Plasma Treatment affects the physical properties of textile fibers, such as increasing the tensile strength of the warp yarn and reducing the tensile strength of the weft yarn. This process alters the surface and chemical properties of the fibers, leading to changes in the surface of the fabric by increasing the surface roughness. This roughening increases the surface area of the fibers, which strengthens the alignment of the warp yarn by improving the adhesion between fibers, resulting in higher tensile strength of the warp yarn. In contrast, the weft yarn may be affected differently, as plasma treatment can make the surface of the weft yarn rougher, which may reduce its elasticity and tensile strength. Cold plasma treatment also reduces apparent elongation due to the increased surface roughness of the fibers, enhanced resistance to elongation, and improved chemical bonding between the fibers and functional groups. These factors contribute to the fibers' inability to stretch as much when subjected to tensile force [40].

Table 5 Tensile strength of Fabric printing at various voltages of DBD.

Plasma treatment	Warp		Weft	
	Maximum force, N	Apparent Elongation, %	Maximum force, N	Apparent Elongation, %
Original cotton fabric	270	14.4	430	20.3
Control	520	20.8	380	19.5
DBD 500 V	450	17.3	310	15.1
DBD 1,000 V	500	15.4	360	17.6
DBD 1,500 V	450	15.1	290	15.5
DBD 2,000 V	450	18.1	290	14.8

Scanning electron micrograph of printing fabric

Figure 5 shows the study of photographic images of the surface structure on cotton fabric that underwent cold plasma treatment and untreated samples. The experiment revealed that scanning electron microscope (SEM) images showed that untreated cotton fibers exhibited a smooth surface and a round cross-sectional appearance, as shown in **Figure 3(a)**. Plasma-treated cotton fibers had flattened surfaces and exhibited damage, characterized by fractures and rough textures, as illustrated in **Figures 3(b) - 3(f)**. Plasma treatments at different voltages, including 500, 1,000, 1,500, and 2,000 V, showed apparent damage to the fibers compared to untreated ones. It can be inferred that the residual hydroxyl groups in graphene oxide form hydrogen bonds with ferrous sulfate particles and with the polar groups generated by plasma treatment on the cotton surface. This interaction positively affects the adhesion of dyes and fixing agents. SEM images of untreated and plasma-treated cotton revealed significant agglomerations of fixing agent particles and notable changes in morphology due to the electrical potential differences resulting from cold plasma treatment (DBD). These changes were particularly evident under SEM analysis due to the penetration of active particles onto the cotton surface (ranging from 500 to 2,000 V) [24,41], Cotton surfaces treated with plasma (500, 1,000, 1,500, 2,000 V) displayed similar characteristics, with organic coating media distributed across the fabric surface. The largest particle agglomerations were observed on surfaces treated at 500, 1,000, 1,500, and 2,000 V, indicating that the particles were not uniformly distributed at the nanometric scale. No obvious plasma effects were observed on the leather surfaces [42,43]. However, as previously reported, plasma treatment causes an etching effect on the cotton surface, modifying the micro-pores and enhancing the penetration or adhesion of coating formulations. Consequently, these micro-pores may be partially or fully covered [24]. Bhat *et al.*

[44] also reported that the use of cold plasma could improve the surface properties of cotton fabric, such as increasing polar functional groups and enhancing the adhesion of printed dyes, aims to improve the quality of fabric printing. Cold plasma generated by electrical discharge produces radicals and high-energy species, such as atomic oxygen (O), ozone (O_3), and ions, which react with the cotton fabric surface. This interaction increases the surface hydrophilicity by reducing the water contact angle and increases surface roughness, thereby expanding the effective surface area and improving the adhesion of dyes or fixing agents.

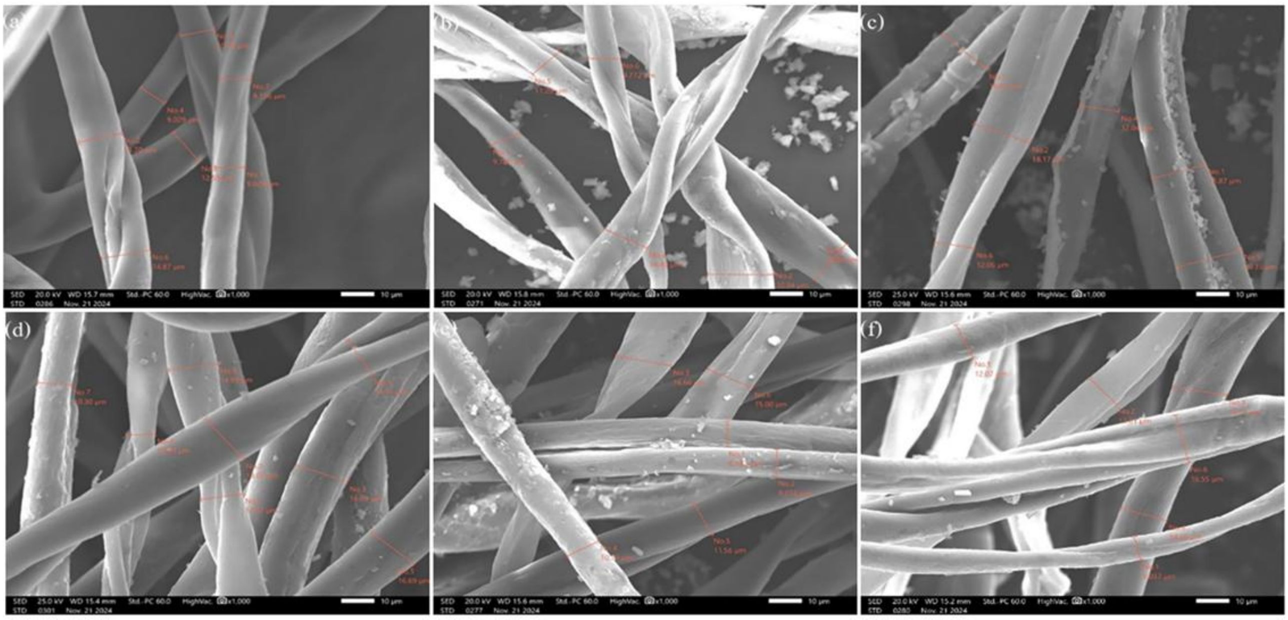

Figure 5 SEM micrographs of cotton fiber: (a) Original cotton fabric (b) control (c) 500 V (d) 1,000 V (e) 1,500 V (f) 2,000 V.

Conclusions

This research studied the fabric printing process using leaf dye or eco-printing fabric combined with cold plasma (DBD) at different electrical potential levels, ranging from low to high voltage (500 - 2,000 V). The findings revealed that cotton fabric treated with cold plasma before printing with leaf exhibited the best color adhesion. The optimal electrical potential for plasma treatment was 1,000 V, which resulted in the highest color intensity absorbed into the cotton fibers. This voltage also maintains favorable mechanical characteristics with 500 N warp and 360 N weft tensile strengths and elongation values of 15.4 and 17.6%, respectively, representing a well-balanced textile. These properties present several advantages in textile applications, particularly where a balance between strength and flexibility is essential. The moderate elongation and high tensile strength are ideal for scenarios requiring mechanical durability without excessive stiffness, such as in functional apparel, upholstery, or industrial applications textiles. However, the color fastness properties, including rub, light, and wash fastness, show ratings ranging from fair to very poor. This indicates that the color tends to fade, transfer, or wash out easily. Over time, the longevity and visual quality of the fabric are compromised, and its resistance to physical and environmental stresses such as rubbing, sunlight, or laundering is low. Enhancing color fastness in eco-printed cotton fabrics requires a synergistic combination of pre-treatment, mordanting, fixation, and post-treatment steps that should be considered in further experiments.

In summary, a promising and sustainable application for cold plasma-treated cotton fabrics is in eco-printing, a dyeing method using natural plant-based pigments and mordants. Treatment with cold plasma significantly improves the surface energy and wettability of cotton fibers, leading to better dye uptake and fixation of natural colorants without the use of synthetic chemicals [45]. Moreover, cold plasma pretreatment can lessen the need for harsh mordants, facilitating cleaner production practices that align with eco-textile standards [46]. By utilizing DBD plasma-treated cotton fabrics in eco-printing, manufacturers can achieve high-quality coloration while reducing environmental impact, water usage, and chemical waste. This technology represents a crucial advancement in promoting green textile innovations.

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Declaration of generative AI in scientific writing

The authors used a generative AI tool (Grammarly) solely for English grammar and language improvement. The scientific content, data interpretation, and conclusions were entirely developed by the authors.

CRediT Author Statement

Weerasak Seerlarat: Methodology, Data curation, Formal analysis, Writing-original draft

Porramain Porjai: Methodology, Validation, Supervision, Reviewing and Editing.

Sasamol Phasuk: Methodology, Conceptualization

Poonyanuch Nilsang: Conceptualization, Methodology, Supervision, Writing-Reviewing and Editing, Project administration

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