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A Modification of Surface Properties and Fabric Coloring Value of Polyester Fabrics with Plasma Wave Radiation

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ABSTRACT

The current study investigates the effect of the tip-cylinder electrode configuration of corona-discharged plasma treatment on coloring in the textile industry. This study aimed to examine the impact of plasma exposure treatment on the fabric surface as seen from the absorption time and the coloring value of the fabric. Corona discharge plasma used in this study was made by a tip-cylinder electrode configuration with a positive plasma type, while the fabric used was a 100% white polyester fabric, and the dyes used were red disperse dyes. The test results were carried out by testing the wet properties of the material, the FTIR test, and the spectrophotometer test. The results showed that this corona-discharged plasma could modify polyester fabric's surface properties and affect the fabric's coloring value. The novelty of this research is that we used plasma radiation for the first time to change the surface properties and fabric coloring of polyester fabric treated with corona plasma.

1. Introduction

One of the important applications of physics in the textile industry is the modification of material surface properties to improve both the functional performance and aesthetic quality of textile products. Surface engineering techniques have become increasingly important because they enable the enhancement of fabric characteristics without significantly altering the bulk mechanical properties of the material. Among various textile quality attributes, color appearance is one of the most influential factors affecting consumer purchasing decisions. In recent years, faded-color textiles have become a prominent fashion trend, particularly among young consumers, leading manufacturers to continuously develop innovative finishing technologies capable of producing controlled fading effects while maintaining fabric quality and production efficiency [1].

To satisfy these market demands, numerous color-fading methods have been investigated for textile materials. Conventional techniques include stone washing, enzyme washing, repeated laundering, sandblasting, and chemical bleaching using oxidizing agents such as sodium hypochlorite or potassium permanganate [2]–[4]. Although these methods are capable of producing desirable faded-color effects, they generally require substantial amounts of water, chemicals, and energy. Furthermore, chemical bleaching processes generate hazardous wastewater containing oxidizing compounds that may contaminate aquatic ecosystems if not properly treated. The increasing environmental concerns associated with textile processing have encouraged researchers and manufacturers to seek cleaner production technologies that minimize the use of hazardous chemicals while maintaining product quality and manufacturing efficiency.

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The implementation of environmentally friendly manufacturing has therefore become one of the major challenges facing the global textile industry. Sustainable textile production not only aims to reduce energy and water consumption but also emphasizes minimizing chemical waste and greenhouse gas emissions throughout the manufacturing process. Several studies have highlighted that environmentally responsible finishing technologies are essential for supporting cleaner production and achieving sustainable industrial development [5]–[11]. Consequently, the development of alternative surface modification methods capable of replacing or reducing conventional chemical treatments has become an active area of research.

Among various environmentally friendly technologies, non-thermal atmospheric plasma has emerged as a promising alternative for textile surface modification. Unlike conventional wet chemical treatments, plasma technology is a dry process that requires little or no additional chemicals and modifies only the outermost surface of the fibers. Consequently, the intrinsic mechanical properties of textile materials remain largely unaffected while significant improvements in surface characteristics can be achieved. Corona discharge plasma, in particular, has attracted considerable attention because of its simple electrode configuration, relatively low operating cost, atmospheric-pressure operation, and ease of integration into existing textile production lines.

Previous studies have demonstrated that corona discharge plasma generates energetic electrons, positive ions, negative ions, ultraviolet radiation, ozone (O_3), hydroxyl radicals (•OH), hydrogen peroxide (H_2O_2), and other reactive oxygen species capable of interacting with polymer surfaces [12]–[18]. These reactive species break weak molecular bonds on the polyester surface and subsequently promote oxidation reactions that introduce oxygen-containing functional groups such as hydroxyl (-OH), carbonyl (-C=O), and carboxyl (-COOH). The formation of these polar functional groups increases the surface free energy of polyester fibers, thereby improving wettability, adhesion, printability, and dye affinity. In addition, plasma-induced oxidation may remove surface contaminants and produce mild bleaching effects that influence the optical appearance of textile materials without requiring aggressive chemical treatments.

Although plasma technology has been widely investigated for textile applications, most previous studies have primarily focused on evaluating individual properties, such as surface wettability, adhesion improvement, or dyeability. Comparatively fewer studies have examined the relationship between plasma-induced chemical modification, water absorbency, and optical color characteristics within a single experimental framework. Moreover, studies investigating atmospheric tip-cylinder corona discharge plasma for polyester fabrics remain relatively limited, particularly those combining surface chemical characterization with quantitative measurements of wettability and color changes. A more comprehensive understanding of these relationships is required to optimize plasma processing parameters for sustainable textile finishing applications.

Unlike previous studies that generally evaluate only a single performance parameter, this study integrates water absorbency testing, FTIR surface chemical analysis, and spectrophotometric color measurements to comprehensively assess the effects of atmospheric tip-cylinder corona discharge plasma on polyester fabrics under identical treatment conditions. This integrated characterization enables a clearer understanding of the relationship between plasma-induced surface chemistry, wettability, and color modification, providing a practical framework for optimizing environmentally friendly textile finishing processes..

Therefore, this study aims to investigate the influence of atmospheric tip-cylinder corona discharge plasma treatment on the surface properties of polyester fabrics by evaluating water absorbency, chemical functional group formation, and color characteristics. The findings are expected to contribute to the development of sustainable textile processing technologies by demonstrating how atmospheric plasma treatment can simultaneously improve the functional and aesthetic properties of polyester fabrics while reducing dependence on conventional chemical finishing methods

2. Research methods

Atmospheric pressure plasma treatment was employed to modify the fabric surface. The non-thermal plasma was generated using a custom-built tip-cylinder electrode configuration, as illustrated in Figure 1. The assembly consisted of a multi-tip anode, where three pointed bolts were affixed to an insulating board at specified intervals, positioned perpendicularly above a solid cylindrical cathode. The anode was connected to a high-voltage source, while the cathode was grounded. A fixed inter-electrode gap of 2.5 cm was maintained between the tip of the anode and the surface of the cylinder. For each treatment, a fabric sample measuring 10 cm × 6 cm was placed on the surface of the cylindrical cathode, ensuring direct exposure to the plasma discharge.

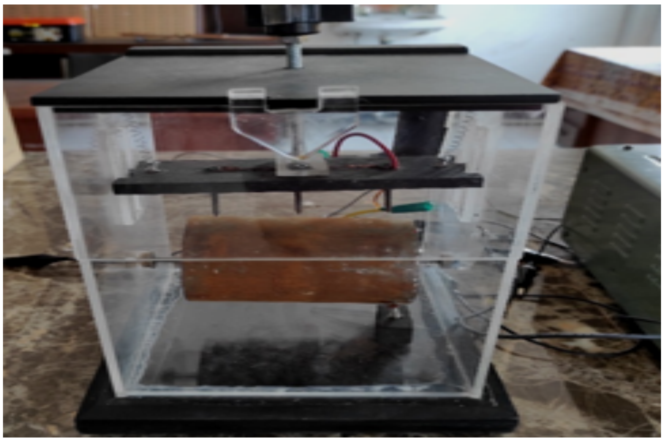


Figure 1 Plasma with Tip-cylinder Electrodes for Modification of The Surface Properties of Polyester Fabrics.

The microstructure analysis of untreated 100% polyester fabric and fabric sample treated by corona discharged plasma process was carried out by Fourier Transform Infrared (FTIR) spectrometer at room temperature and atmospheric pressure according to ASTM E168. We analyzed the color value measurement of the Lab and LCh using a spectrophotometer. Our study used the following procedures: 1) Two pieces of polyester fabric were cut into 10 ×6 cm^2 pieces; 2) One of the fabrics was exposed to plasma waves for six minutes at room temperature and a voltage of 3 kV; 3) FTIR analyzed fabrics; 4) The two fabrics were dyed with 2% dispersion dye at 130 °C in the same dipping bath; 5) Colour results were determined using a spectrophotometer.

2.1 Data Collection Stage

The absorbency test was carried out using a drop test according to the AATCC Test Method, and the testing of the polyester fabric was indicated with the wetting time measurements before and after corona discharge plasma treatment. In this study, the drop test was used to test the wetting properties of the fabrics using a stopwatch, pipette, and pure liquid water. Water from the pipette was dropped from a certain fixed height onto the treated and untreated materials, and then the time required for the water drop to disappear was measured by the stopwatch as the wetting time. In this research, we used textile samples as a preliminary test of the wetting properties of 100% polyester with 60 cm2 (10 cm x 6 cm) by giving the plasma treatment to each surface inside the plasma generator. The experiment was conducted for 2 and 6 minutes of plasma treatment for each test fabric.

3. Results and Discussion

3.1 Result

Based on the absorption test experiment for 100% polyester fabric with plasma radiation exposure for 2 minutes and 6 minutes, the mean absorption time was obtained in Table 1. From Table 1, We showed that the mean absorption time of the fabric was at 6 minutes of exposure to absorb water faster, which was 4 seconds compared to those without plasma exposure of 107 seconds. An FTIR test was also carried out to see the changes in the material properties of the polyester fabric. In the FTIR results, new groups were obtained, especially at the peak around 3348 cm^{-1}, which showed the presence of O-H groups compared to non-plasma polyester fabrics. The results of FTIR can be seen in Figure 2 and Figure 3.

The FTIR test results showed that plasma radiation exposure could graft the OH hydroxyl functional groups and other hydrophilic groups onto the polyester fabric, indicating a change in the fabric's functional groups and mechanical properties. The spectrophotometer results in Table 2 showed that the exposure to the fabric irradiated with plasma waves showed a lighter color from the higher (brighter) L* variable. In addition to the L* value, the h (hue) value also showed that the color direction of the plasma fabric was lighter than the non-plasma polyester fabric.

Table 1
Average Fabric Absorbency Before and After Plasma Radiation Exposure

Exposure times (minutes)	Plasma voltage (kV)	Absorbency times (seconds)
0	0	107 (control)
2	3	14
6	3	4

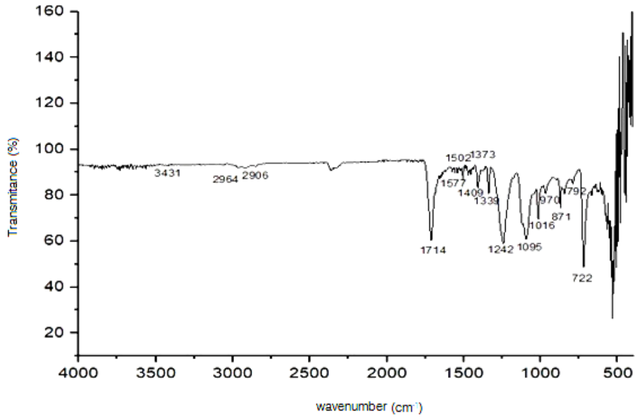


Figure 2 FTIR Test Results for Polyester Fabric without Plasma Treatment

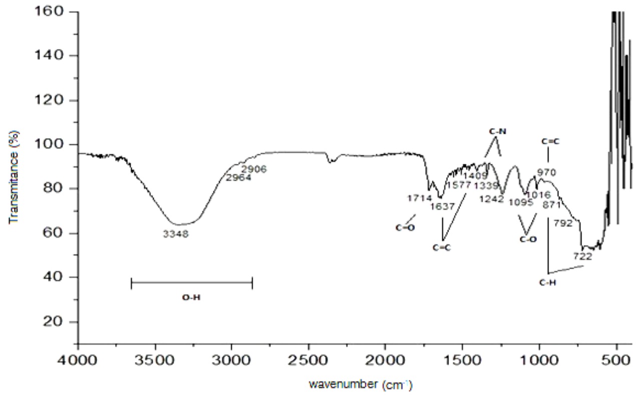
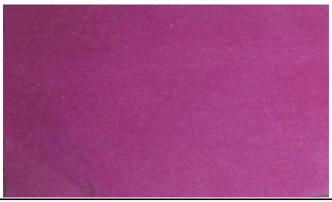
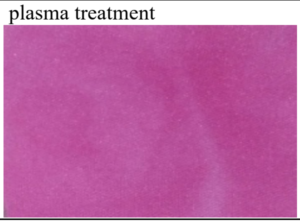


Figure 3 FTIR Test Results for Polyester Fabric With Plasma Treatment

Table 2
Spectrophotometer Results of the Fabrics

Control	plasma treatment
	
L* = 54.77	L* = 59.36
a* = 38.05	a* = 39.84
b* = 122.66	b* = 144.77
C = 128.53	C = 150.15
h = 287.23	h = 285.39

The difference in color between the plasma-treated and untreated fabrics was due to a voltage of 3 kV and an optimal exposure time of 6 minutes. The treatment of exposure to plasma wave radiation on fabrics for too long causes ions and microscopic particles in the air to change to O_3 and H_2O_2, which can be used as compounds to replace fabric bleaching in the textile process. This study needed adequate plasma exposure time to produce a reasonable staining rate.

3.2 Result

The absorption test demonstrated that plasma radiation significantly improved the hydrophilicity of the polyester fabric. As shown in Table 1, untreated polyester required approximately 107 seconds to absorb water, whereas plasma-treated fabrics required only 14 seconds after 2 minutes of exposure and 4 seconds after 6 minutes of exposure. This corresponds to a reduction in water absorption time of approximately 96.3%, indicating that plasma treatment effectively transformed the inherently hydrophobic polyester surface into a more hydrophilic one. The substantial decrease in absorption time suggests that plasma exposure successfully modified only the outermost surface of the fibers without altering the bulk properties of the material.

The improvement in wettability is closely associated with the formation of oxygen-containing polar functional groups generated during plasma exposure. Atmospheric plasma contains energetic electrons, ions, radicals, and reactive oxygen species capable of breaking the weak molecular bonds on the polyester surface. These active species subsequently react with atmospheric oxygen and moisture, resulting in the formation of hydroxyl (-OH), carbonyl (-C=O), and carboxyl (-COOH) functional groups. These newly formed polar groups increase the surface free energy of polyester fibers, thereby reducing the water contact angle and enabling rapid water penetration into the fabric structure.

The FTIR analysis further confirmed these chemical modifications. Compared with untreated polyester (Figure 2), plasma-treated polyester (Figure 3) exhibited a new absorption band centered around 3348 cm^{-1}, corresponding to O–H stretching vibrations. The appearance of this hydroxyl peak provides strong evidence that plasma irradiation introduced hydrophilic functional groups onto the fiber surface through oxidation reactions. Although the primary polyester backbone remained unchanged, the incorporation of oxygen-containing functional groups substantially altered the surface chemistry responsible for liquid absorption behavior. This finding agrees with previous plasma surface modification studies reporting that oxygen plasma treatment enhances polyester wettability primarily through surface oxidation rather than bulk structural degradation.

The relationship between FTIR results and absorbency measurements indicates that the improvement in water absorption was predominantly governed by chemical surface activation instead of physical damage to the fibers. Plasma treatment selectively modifies the outer nanometer-scale layer, preserving the intrinsic mechanical strength of polyester while significantly increasing its affinity toward polar liquids. Therefore, plasma technology provides an environmentally friendly alternative to conventional alkaline or chemical surface treatments that often cause fiber degradation and generate hazardous wastewater.

The spectrophotometer measurements also revealed that plasma treatment affected the optical properties of the polyester fabric. As shown in Table 2, the L* value increased from 54.77 to 59.36, indicating that the plasma-treated fabric became noticeably brighter. Simultaneously, the chroma (C) increased from 128.53 to 150.15, suggesting an increase in color vividness, while the hue angle showed only a slight shift from 287.23° to 285.39°, indicating that the dominant color tone remained relatively unchanged. The increase in brightness may be attributed to the mild oxidative cleaning effect produced during plasma exposure, which removes trace organic contaminants and weakly bound surface impurities, thereby improving light reflectance from the fabric surface.

Another possible mechanism responsible for the brighter appearance involves the generation of ozone (O_3), hydrogen peroxide (H_2O_2), and other reactive oxygen species during plasma discharge. These oxidizing agents possess bleaching characteristics capable of partially degrading colored impurities adsorbed on the fiber surface. Unlike conventional bleaching processes that require high temperatures and chemical reagents, plasma treatment accomplishes this effect under relatively mild conditions with significantly lower environmental impact. However, excessive plasma exposure may eventually lead to over-oxidation, chain scission, or surface etching, potentially reducing mechanical performance. Therefore, optimizing both plasma voltage and exposure time is essential to maximize hydrophilicity while minimizing undesirable surface degradation.

Overall, the results demonstrate a strong correlation among the absorbency test, FTIR spectra, and colorimetric analysis. The introduction of hydroxyl and other oxygen-containing functional groups through plasma-induced oxidation significantly enhanced the wettability of polyester fabrics while simultaneously improving surface brightness. These findings indicate that atmospheric plasma treatment at 3 kV for 6 minutes represents an effective processing condition for modifying polyester surface characteristics without requiring additional chemical finishing agents. Consequently, plasma technology offers considerable potential as a sustainable and environmentally friendly surface modification technique for textile applications requiring improved dyeability, moisture management, coating adhesion, and functional finishing.

3.3 *Implication*

Beyond the physicochemical improvements observed in this study, the results also demonstrate the potential industrial relevance of atmospheric corona discharge plasma for textile finishing applications. Conventional bleaching and surface activation processes generally require multiple wet-processing steps involving large volumes of water, oxidizing chemicals, rinsing, and thermal drying, all of which contribute substantially to energy consumption, production costs, and wastewater generation. In contrast, atmospheric corona discharge plasma is a dry surface modification technique that operates at ambient pressure and requires only electrical energy to generate reactive species. Consequently, the technology has the potential to reduce water consumption, minimize chemical usage, and decrease the energy demand associated with conventional wet finishing processes, thereby supporting cleaner and more sustainable textile manufacturing.

From a production perspective, the significant reduction in water absorbency time from 107 s to 4 s after plasma treatment indicates that the polyester surface can be activated rapidly without prolonged chemical processing. Such rapid surface activation may shorten processing times in subsequent dyeing or finishing operations by improving dye-fiber interaction and facilitating more uniform wetting of the fabric. The observed increase in fabric brightness (L*) together with the introduction of hydrophilic functional groups further suggests that plasma treatment can partially replace or reduce conventional bleaching and chemical surface preparation steps. These improvements may ultimately contribute to lower operating costs through reduced consumption of water, bleaching chemicals, wastewater treatment, and thermal energy.

Another important advantage is the scalability of atmospheric corona discharge plasma technology. Unlike vacuum plasma systems that require expensive vacuum chambers and batch processing, atmospheric corona discharge plasma can be integrated into continuous roll-to-roll textile production lines with relatively simple equipment modifications. This compatibility with existing industrial manufacturing systems makes the technology attractive for large-scale textile production because it minimizes capital investment while increasing production flexibility. Therefore, the combination of improved fabric performance, reduced environmental impact, and compatibility with continuous manufacturing processes highlights the considerable industrial potential of atmospheric corona discharge plasma as an alternative surface treatment technology for sustainable textile finishing.

4. Conclusion

This study investigated the application of tip-cylinder corona discharge plasma as a surface modification technique for polyester fabrics in textile coloration. The results demonstrated that corona discharge plasma significantly altered the surface characteristics of polyester, leading to substantial improvements in fabric wettability and color properties. Plasma radiation treatment reduced the water absorbency time from 107 s for untreated polyester to only 4 s after 6 minutes of exposure at 3 kV, indicating a remarkable enhancement in hydrophilicity. FTIR analysis confirmed the formation of hydroxyl (–OH) and other oxygen-containing functional groups on the fiber surface, demonstrating that plasma treatment successfully introduced polar functional groups without significantly affecting the bulk structure of the material.

In addition to improving hydrophilicity, plasma treatment also influenced the optical properties of the fabric. The increase in the L value indicated a brighter fabric appearance, while the changes in chroma suggested improved color intensity after treatment. These improvements are attributed to plasma-induced oxidation and the generation of reactive oxygen species such as ozone (O_3) and hydrogen peroxide (H_2O_2), which promote surface activation and mild bleaching effects. Consequently, plasma treatment enhances the interaction between polyester fibers and dyes, resulting in better dye uptake and potentially improved color uniformity.

The findings demonstrate that atmospheric corona discharge plasma offers an environmentally friendly alternative to conventional chemical surface modification processes by reducing the need for additional chemicals, water, and energy during textile finishing. Therefore, this technology has significant potential for sustainable textile manufacturing, particularly in improving polyester dyeability and functional finishing while minimizing environmental impact.

Future research should investigate the influence of different plasma operating parameters, including voltage, exposure duration, gas composition, and discharge configurations, on dye fixation, color fastness, mechanical properties, and long-term durability of treated fabrics. Furthermore, microscopic surface characterization using scanning electron microscopy (SEM) and quantitative wettability analysis through contact angle measurements are recommended to provide a more comprehensive understanding of the plasma-induced surface modification mechanisms..

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