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Review on Utilizing Plasma Pretreatment on some Fabrics to Enhance their Printability

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Abstract: Plasma treatment technology has recently gained popularity in the textile industry as it appears to b

e a viable, economically and environmentally sound alternative to traditional wet-chemical processing processes. Plasma surface treatment is a rapid, clean, solvent-free, time-saving, and ecologically friendly. The effectiveness of plasma therapy is determined by several parameters, including the substrate's type and the treatment's operating circumstances. This article provides an overview of plasma's basics and process, as well as the use of various plasma gases on textiles to increase printability, whether printed using silkscreen or inkjet printing.

Keywords: pretreatment; plasma; inkjet; natural dyes; printability; colorants and dyes.

1. Introduction

Chemical modification of textiles was first employed to impart new properties and expand their usefulness for various applications. Physical technology may now be an ecologically friendly method to replace some of these chemical alterations. One of these physical methods is plasma treatment, which is used on practically all synthetic and cellulosic textile fabrics. It alters the fiber surface while leaving the bulk properties the same. It's a rapidly expanding field with some promising applications as an ecologically beneficial method. Compared to chemical treatment, plasma therapy does not entail handling hazardous chemicals; hence, there are no effluent issues [1].

They generally need to be surface treated to change the surface features of polymeric textile materials and increase their adhesion capabilities. The textile industry's traditional liquid chemical processes use a lot of water and harmful chemicals and create many effluents that require expensive purification. Because of their negative environmental impact, the textile industry is compelled to search for alternative dry methods that might provide lower-cost, environmentally friendly production and new product development channels [2-4].

Plasma-based processing may be an appealing option for the textile industry's surface treatment needs because it is a dry, environmentally friendly method that does not require the use of water or chemicals. Furthermore, the treatment duration (sometimes just a few seconds) minimizes energy use. Many experts worldwide have been studying the effects of plasma treatments on various textile materials since the early 1980s, with encouraging findings. [2,5].

In this study, we reviewed the fundamentals and the mechanism of plasma, and the application of different gases of plasma on fabrics to improve its printability when printed with a silkscreen or inkjet printing; we reviewed this in 3 sections:

- Improving the printability of cotton fabric using various types of colorants and dyes.
- Improving the printability of cotton/polyester fabrics using natural dyes.
- Improving the printability of polyester fabric using pigment and natural dyes.

2. Fundamentals of Plasma

Plasma is referred to be “matter's fourth state." Electrically, magnetically, or thermally ionize many gas molecules; nonetheless, electrically conductive plasma is quasi-neutral. Plasma generation uses electric currents, electromagnetic radiation, and microwaves as energy sources [6]. Plasma is formed by a dynamic mixture of ions, electrons, neutrons, excited molecules, free radicals, metastable, and photons after various processes such as ionization, dissociation, and excitation (from ultraviolet to visible electromagnetic radiation). Because of their relatively long life spans, these active species, particularly metastable, are responsible for the surface alteration of substrates [7]. The depth of the treated material's change ranges from 100 to several micrometers, and most of the original material's fabric qualities are preserved. Matter in the plasma state has vastly different physical and chemical characteristics than matter in a neutral state [6,8].

From ambient temperature to >10000 K, plasma possesses a remarkable variety of temperatures and densities. In terms of temperature, two major plasma regimes are identified, notably [5]:

- thermodynamic equilibrium plasma (thermal)
- thermodynamic non-equilibrium plasma (low-temperature).

Thermal and cold plasma are used to modify the surface of various substrates. Low-temperature gas plasma has many energetic electrons, which fits the condition for changing delicate substrate surfaces like textiles [5].

2.1. Low-temperature plasma.

In terms of pressure, low-temperature plasma may be divided into two groups., namely [8,9]:

- low-pressure (vacuum) plasma.
- atmospheric pressure plasma.

Low-pressure (vacuum) plasma offers a wide range of applications in materials processing, particularly in semiconductor device fabrication. High concentrations of reactive species are created under vacuum conditions, allowing for rapid etching and deposition of thin layers. Furthermore, a homogenous glow discharge affects substrate surfaces uniformly. Low-pressure plasma operation, on the other hand, is not without its challenges. Load locks and robotic assemblies are utilized to transfer items in and out to maintain the vacuum system. Low-pressure plasma is operated off-line and in batch mode, except for object size restrictions. High investment costs owing to extensive treatment durations and vacuum maintenance are unfavorable for the mass-production textile sector [8,9].

To avoid such problems, atmospheric pressure plasma has been developed. The ongoing use of plasma therapy without the need for vacuum maintenance saves a lot of money in the long run. In Table 1, the properties of plasma at low and atmospheric pressures are compared [8].

Table 1. Characteristics of low pressure and atmospheric pressure plasma.

Characteristics	Low-pressure (vacuum) plasma	Atmospheric pressure plasma
Operation	batch	Batch/continuous
Capital cost	high	low
Break down voltage	low	high
Gas temperature	low	high

Under atmospheric pressure, a larger voltage is required to break down gas molecules, resulting in the formation of thermal plasma jets and arcs. To prevent arcing and high gas temperatures, a low-density current or short-pulsed feeding power is employed. Pointed electrodes in corona discharges and insulating inserts in dielectric barrier discharges (DBDs) are employed to prevent arcing and excessively high temperatures [10].

When the pressure of plasma ignition rises, the gas temperature rises, and the electron temperature falls. Because inelastic collisions dominate in the vacuum state, electrons are more energetic than gas molecules. When the pressure is more than 101 kPa, the elastic collision is strengthened, the kinetic energy of electrons is efficiently transmitted to the gas, and the gas and electrons have the same temperature [8].

Corona discharge, dielectric barrier discharge (DBD), atmospheric-pressure glow discharge (APGD), and atmospheric-pressure plasma jet are the four primary forms of atmospheric-pressure plasma that may be utilized on textiles [11].

2.2. Mechanism of plasma treatment on textiles.

Textiles can be treated between two electrodes (in the plasma) or near the plasma. Figure 1 shows a schematic of a plasma device with several reactive species [12].

After impinging on the surface, plasma-chemical conversion of the feed gas creates chemically active particles that can change textile surface molecules via chemical reactions. The radicals produced in the plasma area must be allowed to migrate to the reaction site on the textile fiber surface. The distance between single fibers, on the one hand, and the gas density, i.e., the mean distance between gas particles, on the other, restrict the passage of radicals between the regions of generation and reaction. There is a link between the penetration depth of the plasma effect inside the textile structure and process pressure, as well as the textile structure itself, assuming radicals react or recombine after many interactions with gas particles and at surface locations on fibers [12].

The physicochemical interaction between the reactive species and the substrate causes plasma alteration on textile substrates, which may be divided into two categories: ablation and polymer formation. The plasma treatment parameters, such as discharge power, feeding gas, and energy density, determine whether polymer synthesis or ablation takes precedence. Furthermore, the feeding gas significantly impacts the plasma modification processes. Oxygen, for example, is oxidative, whereas hydrogen is reductive. Film deposition, which directly modifies the polymer surface, is favored by polymerizing gases with large concentrations of carbon and hydrogen atoms, such as methane, ethylene, and ethanol. Non-polymerizing gases, on the other hand, such as noble gases, nitrogen, oxygen, hydrogen, and ammonia, alter polymer surfaces by oxidation, ablation, cross-linking, and maybe grafting [8]. Specific chemical processes are aided by the characteristics of reactive gases. The concentration of active plasma species generation is influenced by other operation factors such as frequency, discharge power, exposure period, and feeding gas flow rate.

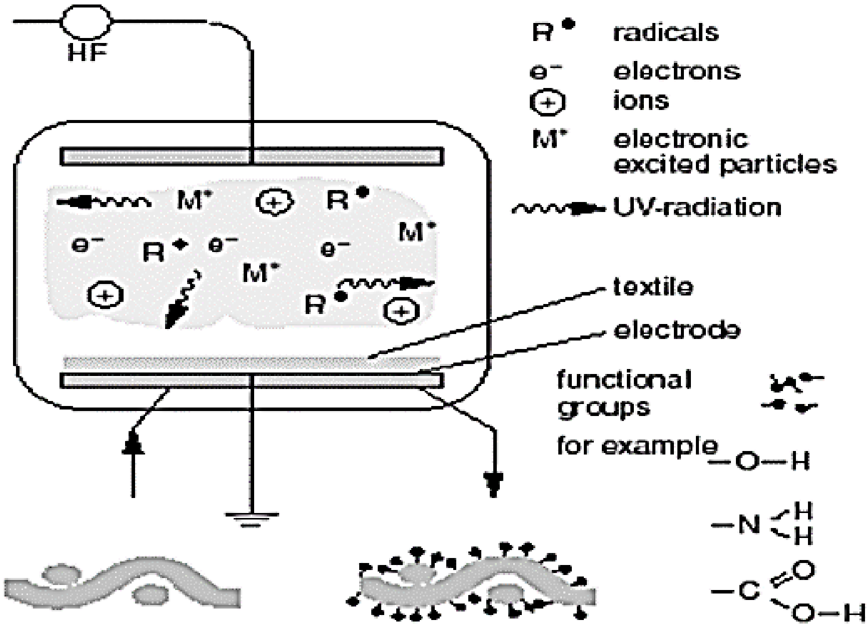


Figure 1. Schematic diagram of plasma constituents in plasma device.

3. Plasma Applications to Textile Processing

Plasma treatments are used in the textile industry for several objectives, including surface energy modification, surface topography modification, adhesion enhancement, and surface cleaning [9]. Plasma dissociates molecules by electron collisions and photochemical reactions, resulting in a high density of free radicals. The chemical bonds in the fiber polymer surface are disrupted, resulting in the creation of new chemical species [13].

When fibers and polymers are treated with plasma, energetic particles and photons produced in the plasma interact intensely with the substrate surface through free-radical chemistry. On average, four significant impacts on surfaces are seen. Each is always present to some degree, but depending on the substrate and gas chemistry, reactor design, and operating settings, one may be preferred. Surface cleaning, ablation or etching, cross-linking of near-surface molecules, and alteration of the surface chemical structure are the four key impacts. The removal of material (impurities or substrate material) from the exposed surface is referred to as plasma cleaning and etching [14].

3.1. Improving the printability of cotton fabric using various types of colorants and dyes.

3.1.1. Inkjet printing of plasma-treated cotton fabric using pigment.

The inkjet printing technology is a well-known and fast-increasing procedure for today's textile printing, with widespread acceptance. The advantages of inkjet printing include outstanding printed pattern quality, less pollution, and a very quick reaction time in terms of fabric fashion. The clarity and color look of inkjet printed graphics is, in essence, an eye-catching selling factor of the finished product. As a result, fabric treatment is required before printing to optimize printing quality, particularly ink absorption. Plasma technology is a common approach widely utilized to change surface qualities among the different environmentally friendly techniques accessible. Plasma treatment mainly affects the surface's thin outer layer, leaving the bulk qualities unchanged and producing no wastewater. On the surface, the treatment generates new functional groups [15,16].

In this investigation, three forms of gas plasma pretreatment, including oxygen (O_2), nitrogen (N_2), and sulfur hexafluoride (SF_6), were used to modify the surface characteristics of cotton fabric to increase ink absorption of water-based pigmented inkjet inks and color reproduction of the treated surfaces. Cotton fabric samples were treated with a radio-frequency inductively coupled plasma (RF-ICP) generator. The textiles were printed with a set of four-color pigmented inkjet inks (cyan, magenta, yellow, and black) after the plasma treatment process. Water-based pigmented inks have a lower spread into the fibers than dye-based inks, resulting in finer-looking text and graphics [12].

X-ray photoelectron spectroscopy (XPS) analysis of the chemical composition of untreated and plasma-treated cotton fabric surfaces revealed. According to Fig. 2, untreated cotton has three functional groups: cellulosic structure, cellulose structure, and lignocellulosic structure (C -C or C- H, C-OH and O-C-O groups). On the surface of the fabric treated with 0.5 Torr of O_2 plasma gas and RF 50W power for 5 minutes, four functional groups can be seen. The number of C-C/C-H bonds on the treated surface reduced dramatically compared to the untreated cloth, whereas the C-O/C-OH and O-C-O rose nearly double. In addition, the plasma treatment resulted in the formation of a novel O-C=O functional group on the surface. When O_2 is subjected to RF radiation, it can be broken down into monatomic oxygen species (O), O+, and $O^{\cdot}$ O_2 plasma is effective for eliminating organics. When the gas was ionized, electrons interacted with polymer surfaces, causing molecular bond cleavages and atom abstraction, resulting in free radicals. As a result, the C-C bonds on the fiber surface were broken, and the reactive oxygen species in the plasma reacted with the radicals on the fabric to produce new functional groups like O=C-O [12].

The following chemical processes on the fiber surface were thought to occur when natural and synthetic fibers were treated by plasma.

RH → R• + H•

R• + O2 → ROO•

ROO• + R1H → ROOH + R1•

R• + O• → RO•

RO• + R1H → R• + R1OH

RO• + H• → ROH

For the fabric treated with N2 plasma at 50W, 0.5 Torr for 5 min, The XPS analysis revealed the core functional group of cotton structure (C-C/C-H), and the N1s signal revealed the development of two additional functional groups by plasma treatment, namely the C-N bond and the O=C-NH. However, as evidenced by XPS, increasing the RF power (100W) resulted in eliminating the O=C-NH and O-C=O functional groups. This might be because a larger input power enhanced the plasma impact on the surface. Higher power plasma produced a greater degree of ion bombardment, resulting in polymer chain scission and some functional group breakdown [12].

For the cotton treated with SF6 plasma, Six functional groups were found on the surface, three of which are the core characteristic functional groups of cotton fabric, while the plasma treatment introduced three novel functional groups (C–F, $C–F_2$, and $C–F_3$). The C–F, $C–F_2$, and $C–F_3$ functions enhanced the fabric's hydrophobicity, resulting in high water contact angles and low surface energy [12].

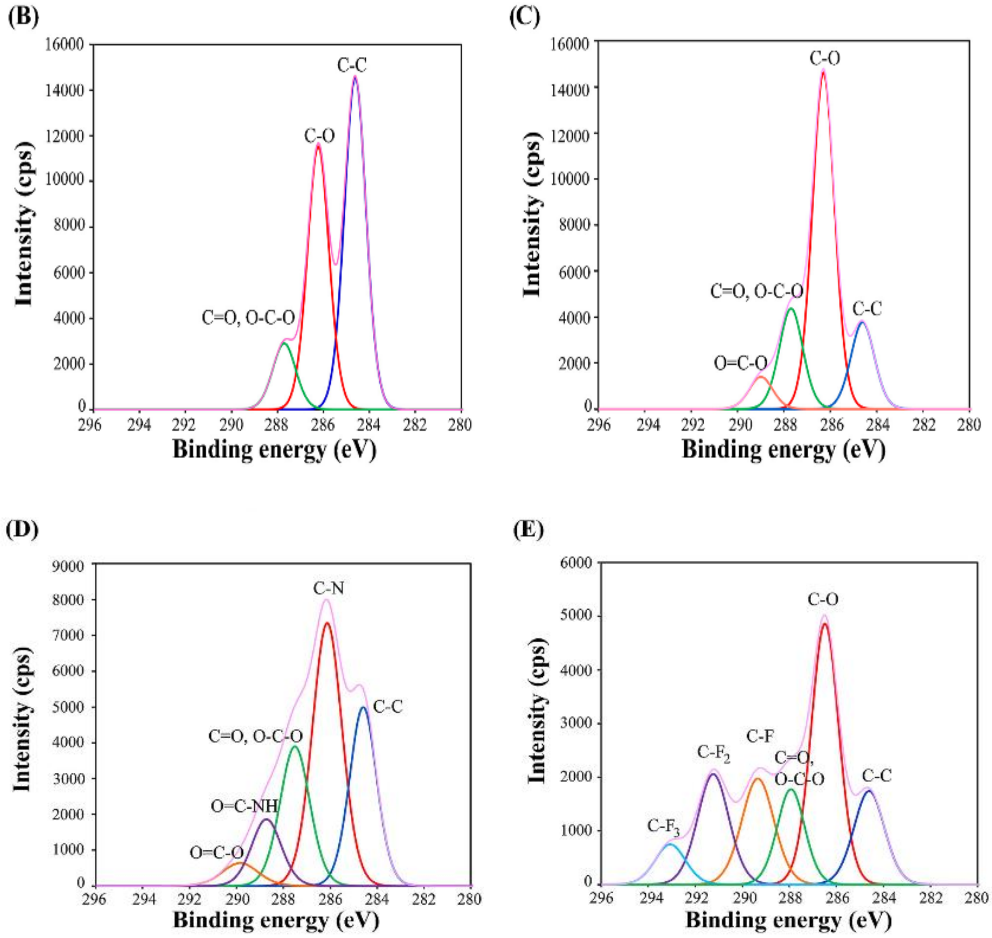


Figure 2. XPS survey spectra of cotton at four conditions, deconvolution of C1s spectra for cotton (B) untreated fabric, (C) treated fabric by oxygen plasma at RF 50W, 0.5 Torr for 5 min, (D) nitrogen plasma at RF 50W, 0.5 Torr for 5 min, (E) SF_6 plasma at RF 50W, 0.5 Torr for 5 min.

Contact angle measurements were used to assess the wettability of the treated cotton cloth surface. The contact angle was evaluated using three independent samples, each of which was tested in three different locations. Untreated fabric contact angles were 77 3 for water as test liquids. The contact angles of the test liquid reduced substantially following O2 and N2 plasma treatments but rose dramatically after SF_6 plasma treatment. Thus, independent of the kind of liquids utilized, plasma treatments have a significant influence on the wettability of cotton materials [17].

As expected, plasma functionalization of the untreated cotton surface with O_2 and N_2 gas enhanced surface hydrophilicity, as evidenced by a decrease in contact angle from 77 3 to spreading phenomena and increased total surface energy. Increases in surface energy caused by plasma treatment are ascribed to the surface being functionalized with more hydrophilic groups, such as carbonyl, carboxyl, hydroxyl, and amine. The level of functionalization is mostly determined by the kind of gas employed and its energy density [12].

The untreated and plasma-treated cotton textiles printed with water-based ink demonstrate that the O_2 plasma treatment obtained the highest total surface energy and maximum color strength. The cloth treated with SF_6 plasma had the highest hydrophobicity and lowest total surface energy, resulting in a low color strength that could not be printed with hydrophilic printing inks. This is because the SF6 plasma-treated cotton surface could not be wetted by the water-based inks, preventing it from absorbing the necessary number of water-based inks. Increases in surface energy caused by plasma treatment are ascribed to surface functionalization with hydrophilic groups such as carbonyl (C-O), carboxyl (COOH), ester (O=C-O), hydroxyl (OH), and amine (-N-). Furthermore, the degree of functionalization is mostly determined by the gas types employed and the energy density. The bigger the extent of total surface energy, the greater the ink absorption and the higher the absorbed ink layer on the surface, resulting in better color strength [12].

Briefly, the oxygen plasma-modified cotton fabric surface allowed more ink absorption and produced a higher color strength (K/S) than the other gases. All of the color intensity values and color gamut of the four process color inks were greatly boosted. The cotton cloth became more hydrophilic after the oxygen plasma treatment, increasing surface wettability. Furthermore, the oxygen plasma has an etching effect due to the bombardment of electrons, ions, and monoatomic species, resulting in a rougher surface. The hydrophilicity and roughness of the fabric surface allowed the ink to penetrate deeper into the fabric, allowing the cloth to catch more ink on the surface.

The color strength of the textiles treated with nitrogen gas plasma was lower than that of the fabrics treated with oxygen plasma. Cotton textiles treated with SF6 plasma had decreased ink absorption and color strength. As a result of the SF_6 plasma treatment, its surface became hydrophobic. Cracks and scratches on the fabric surface of the SF6 plasma treatment were similar to those seen in the oxygen plasma treatment. Thus, hydrophilicity and surface roughness were the primary characteristics that allowed the cotton fabric to absorb more ink and retain greater color strength.

3.1.2. Inkjet printing of plasma-treated cotton fabric using reactive dye.

To improve the final color characteristics of digital inkjet-printed cotton textiles, atmospheric pressure plasma (APP) treatment was used as a pretreatment procedure to promote the deposition of printing paste [18].

Separately, three printing pastes comprising natural polymers were prepared: (1) sodium alginate, (2) chitosan, and (3) sodium alginate-chitosan combination. Stock chitosan solution was made by thoroughly dissolving 5 g of chitosan in 500 ml of 10% acetic acid while constantly stirring. After that, the stock solution was filtered to eliminate any suspended contaminants. The chitosan content of the printing paste was calculated directly from the stock chitosan solution. The printing paste, including chitosan, was made by thoroughly mixing 40 g of stock chitosan, 8 g of sodium bicarbonate, and 10 g of urea with 400 g of deionized water [19]. The combination of sodium alginate and chitosan may improve printing properties and antibacterial action. The printing paste, including sodium alginate and chitosan, was made by thoroughly mixing 150 g stock sodium alginate, 10 g stock chitosan, 8 g sodium bicarbonate, and 10 g urea with 400 g deionized water [18].

Cotton fabric was padded with various printing pastes after plasma treatment before digital inkjet printing. Without additional purification, a commercially available reactive ink of magenta hue with a vinyl sulphone reacting system was employed [18].

The findings of the experiments demonstrated that plasma pretreatment could greatly boost the color yield of the digital inkjet-printed cotton fabric even after washing. In addition, compared to the control cotton fabric printed without plasma pretreatment, additional attributes such as color fastness to rubbing, color fastness to washing, outline sharpness, and antibacterial properties were enhanced. However, the effect of printing paste on the color characteristics of digital inkjet-printed cotton textiles was highly dependent on the printing paste's composition. The scanning electron microscope images demonstrated that the plasma treatment could improve the deposition of printing paste on the cotton fabric surface, as demonstrated qualitatively by contact angle and wetting time measurements and quantitatively by X-ray photoelectron spectroscopy and carboxyl group/nitrogen content analysis [18].

The color yield of the printed cotton fabric samples was determined by calculating the K/S Sum value. The sodium alginate printing paste exhibited the highest color yield with or without plasma preparation. Other color-related features, such as color fastness and outline sharpness, did not favor the sodium alginate printing paste, whereas the sodium alginate-chitosan combination and chitosan printing pastes performed better. Not only did the sodium alginate-chitosan mixture give appropriate color fastness and outline sharpness, but it also produced a color yield comparable to the control fabric. The presence of 100 percent chitosan in the printing paste may give outstanding antibacterial qualities to the digital inkjet printed fabric [18].

On the other hand, sodium alginate alone might inhibit bacterial growth, although the impact was not substantial. When a sodium alginate-chitosan combination was utilized in the printing paste, it had a similar antibacterial impact and superior printing qualities to pure chitosan.

Cracks were produced along the fiber axis and at the fiber surface as a result of plasma treatments, according to SEM photographs. The cracks were filled with printing paste to aid in the dye uptake of the cloth. Plasma pretreatment, on the other hand, may produce hydrophilic groups at the cotton fiber surface, improving printing paste deposition and color yield [18].

3.1.3. Silk screen printing of plasma-treated cotton fabric using reactive dyes.

Under atmospheric pressure, the cotton fabric was subjected to low-temperature plasma [dielectric barrier discharge (DBD)] utilizing air and oxygen (purity 98 percent) [20].
Using a typical silk screen, samples of treated and untreated fabric were printed. The printing paste was made according to the recipe below [20]:

Table 2. The printing paste composition.

Materials	**Amount of materials (g)**
Alginate stock	400-600 g
Urea	50-100 g
Reactive dye	40 g
Sodium carbonate	25-30 g
Water to make up to	1000g

The samples were treated with air and oxygen plasma, demonstrating a gradual change in fiber surface shape with treatment time. The surface of the untreated cotton cloth was generally smooth with occasional grooves. The fabric surface area change might be caused by surface erosion of the cotton fiber during plasma treatment, as well as the etching impact of the plasma treatment on the fiber, which damages the fiber surface. Regardless of the treatment period or the degree of discharge power, etching is highly visible during plasma therapy. Surface fissures or protruding or peeling-off particles on the fiber surface indicate deterioration. Surface damage to the primary wall of cotton fibers and the introduction of additional polar chemical groups might make fibers more hydrophilic and dye-accessible, boosting color strength. Other investigations have found that plasma-treated cotton fibers have physical surface damage, leading to a larger attraction for water or oil. The physical damage generated by plasma treatment appears to improve the wettability of the fiber [20].

Plasma treatment in air or oxygen causes cellulose chain molecules in cotton to oxidize. When cellulosic OH groups are oxidized to carbonyl and carboxyl groups, the hydrogen bonding network inside the fiber is disrupted. This would make cotton fibers more accessible to water molecules, resulting in higher swelling of cotton fibers. According to one study, an increase in the number of COOH groups on cotton causes an increase in the amount of water swelling [20].

Plasma treatment in air and oxygen appears to improve the color strength of the cotton fabric. On the surface etching of cotton, oxygen plasma treatment outperforms air plasma treatment. The discharge power is crucial and has a big impact on the results. The color strength of the printed treated cotton samples improves as the treatment period increases up to about 5 minutes at low powers for both air and oxygen plasma, then it remains virtually constant. We discovered that oxygen plasma treatment is more effective than air plasma treatment [20].

Table 2 revealed that all printed fabric samples are brilliant and that the K/S increases as the treatment time increases. The washing, rubbing, and sweat fastness findings for untreated and treated cotton cloth prints with either air or oxygen plasma. When untreated vs. treated samples are compared, the ratings of sweat (acidic & alkaline) and wash fastness for all samples are essentially the same [20].

Table 3. Color strength and fastness properties of printed untreated and air plasma treated cotton fabric under different conditions of plasma exposure time and discharge power.

Discharge Power (watt)	Treatment time (min)	K/S	Fastness properties							
			Washing fastness		Rubbing fastness		Persperation fastness			
							acid		alkali	
			Alt.	St.	dry	wet	Alt.	St.	Alt.	St.
	0	100	5	5	5	5	5	5	5	5
0.1	1	118.65	5	5	5	5	5	5	5	5
	5	121.72	5	5	4-5	5	5	5	5	5
	10	124.45	5	5	4-5	5	5	5	5	5
	15	125.38	5	5	4-5	5	5	5	5	5
0.3	1	119.4	5	5	4-5	4-5	5	5	5	5
	5	121.87	5	5	5	5	5	5	5	5
	10	124.99	5	5	4-5	4-5	5	5	5	5
	15	125.5	5	5	5	5	5	5	5	5
0.4	1	120.01	5	5	4-5	4-5	5	5	5	5
	5	122.98	5	5	5	5	5	5	5	5
	10	125.68	5	5	4-5	4-5	5	5	5	5
	15	125.54	5	5	5	5	5	5	5	5

3.2. Improving the printability of cotton, cotton/polyester fabrics using natural dyes.

Since ancient times, natural dyes have been recognized for their usage in coloring materials such as wool, silk, cotton, and flax. They come in various colors and may be acquired from many plant sections, including roots, bark, leaves, flowers, and fruit.

The use of ecologically safe ingredients, the most significant of which are natural dyes due to their numerous features, such as biodegradability and environmental friendliness, is a modern trend in textile coloring technology. Natural dyes also include several functional groups, which provide them with antibacterial and UV protective qualities. Even though synthetic dyes are less expensive than natural dyes, small dyer houses and textile exporters choose natural dyes for the reasons stated above [21].

3.2.1. Silk screen printing of plasma-treated cotton and cotton/polyester (60/40) fabric using curcumin dye.

Using the pigment-printing technique, researchers investigated the ability to print various textile fabrics (natural and blends) with natural dyes (which have no affinity for some fibers).

Fabric samples were subjected to atmospheric pressure plasma at low temperatures. The exposure periods (3, 5, 7, and 10 minutes) and plasma discharge strengths (12.5, 24.5, and 41.5W) were varied. Two approaches are used to treat the samples [22]:

- The first technique: Plasma treatment →printing process→ fixation→ washing→ air-drying.
- The second technique: Printing process →fixation by plasma→ washing → air-drying.

For the first technique, the printed samples were fixed using thermal fixation at 180°C for 3 minutes, and plasma was utilized as a fixing tool in the second approach. After being washed twice with cold and hot water, all samples are air dried.

In the second technique, plasma was employed as a treatment and color fixing for cotton and PET/cotton textiles simultaneously.

The fabric was printed using the recipes listed in Table 4 [22]:

Table 4. Printing paste recipe.

Materials	Amount of materials (g)
Synthetic thickener	2 g
Binder	5-20 g
Urea	4 g
Natural Dye	3 g
Water	X g
total	100 g

The results showed that Plasma improved the printability and color strength of all treated materials. With increasing exposure duration and power in the plasma, the K/S values rose. Regardless of the approach, these results hold for the textiles utilized [22].

For cotton fabric at 12.5 watts, the K/S values are 15.17 for 3 and 10 minutes (using the first technique) and 17.04 for the same exposure duration (using the second approach) (using the second technique). The untreated cotton fabric has a color strength of K/S of 12.5. Polyester/cotton textiles had K/S values of 17.01 (first technique) and 18.02 (second technique) for exposure intervals of 3 and 10 minutes, respectively, at the same power (12.5W), whereas untreated PET/cotton has a K/S of 8.93. The rise in K/S may be explained by an increase in the quantity of plasma-created polar groups such as – COOH, – OH, and – CO, as well as an increase in surface roughness caused by etching and other chemical modifications to the surface [22].

The results also showed that employing plasma as a dye treatment and fixing method simultaneously resulted in higher K/S values (second technique). Furthermore, the optimum K/S was found when the two textiles were exposed for 5 minutes at 24.5 watts of discharge power. As the plasma treatment duration or other plasma parameters were increased, the K/S rose marginally or remained virtually constant. Overall, the printability following plasma treatment was satisfactory [22].

Using the second approach, further applications were made on various fabrics (polyester, polyamide, wool, and PE/W) and printed with various natural colors (Curcuma, henna, madder, and pomegranate). The results were excellent, saving time, effort, and energy, and in the second procedure, plasma served a dual purpose, treating and fixing colors on fabric surfaces simultaneously.

Plasma treatment enhanced the binder film strength, which provides greater coupling between binder and fiber related to the rise of polar groups, resulting in good rubbing, washing, sweating, and light fastness of treated textiles [23].

3.2.2. Silk screen printing of plasma-treated cotton and cotton/polyester fabric using Cochineal dye.

The cotton and cotton/polyester materials were subjected to 98 percent pure air plasma and oxygen plasma. Dielectric Barrier Discharge was used to perform the two plasma treatments under atmospheric pressure (DBD).

Table 5 shows the paste used to print the untreated and plasma-treated samples using the classic silk screen printing technique [24]:

Table 5. Printing paste recipe using the classic silk screen printing technique

Stock paste	
Synthetic thickener Alco print DT-CS	955-965 g
water	35-45 g
total	1000 g
Printing paste	
Cochineal dye	40 g
stock paste	X g
water	100g

The samples were dried, thermo-fixed (for 2 minutes at 180°C), and washed after printing according to the following steps:

- Washing with cold water
- Washing with hot water solution (40° C) with 1g/l nonionic detergent
- Washing with hot water (50° C) solution with 1-2g/l sodium hydrosulfate, 1-2g/l sod. hydroxide and 1-2g/l nonionic detergent
- Washing with water at 50°C.
- Washing with cold water, then air dried.

The results showed that The O_2 plasma therapy had a greater impact on cotton and polyester cotton materials than the air plasma treatment. Tables 6 and Table 7 show that O_2 plasma treatment improves the color strength of cotton and PE/cotton textiles. Tables 3 and Table 4 indicate that following plasma treatment, the K/S of cotton and cotton/polyester increases dramatically.

Increasing the plasma exposure period from 3 to 10 minutes and the discharge power from 3 to 15W reduces the wetting time of the treated textiles, resulting in greater wettability. SEM pictures revealed that the surface of untreated cotton and polyester/cotton samples was smoother than that of air plasma and oxygen plasma-treated samples [24].

Table 6. Color strength and fastness properties of printed untreated and air-plasma treated cotton fabrics at discharge power 9W and different intervals of exposure time.

Discharge Power (watt)	Treatment time (min)	K/S	Fastness properties								
			Washing fastness		Rubbing fastness		Persperation fastness				Lightfastness
							acid		alkali		
			Alt.	St.	dry	wet	Alt.	St.	Alt.	St.	
	0	2.15	3-4	3-4	2-3	2-3	3-4	3-4	3-4	3-4	3-4
9 W	5	5.19	4-5	4-5	4	4	4-5	4-5	4-5	4-5	4-5
	7	5.18	4	4	4	4	4	4	4	4	4-5
	10	5.1	4-5	4-5	4	4	4-5	4-5	4-5	4-5	4

Table 7. Color strength and fastness properties of printed untreated and air-plasma treated cotton/polyester fabrics at discharge power 9W and different intervals of exposure time.

Discharge Power (watt)	Treatment time (min)	K/S	Fastness properties								
			Washing fastness		Rubbing fastness		Persperation fastness				Light fastness
							acid		alkali		
			Alt.	St.	dry	wet	Alt.	St.	Alt.	St.	
	0	2.22	3-4	3-4	2-3	2-3	3-4	3-4	3-4	3-4	3-4
9 W	5	5.98	4	4	3-4	3-4	4	4	4	4	4
	7	5.89	4	4	4	4	4	4	4	4	4-5
	10	5.69	4-5	4-5	4	4	4-5	4-5	4-5	4-5	4-5

3.3. Improving the printability of polyester fabric using pigment and natural dyes.

3.3.1. Plasma treatment of poly (ethylene terephthalate) fabric for pigment adhesion enhancement.

PET (polyethylene terephthalate) fabrics have been utilized in the textile industry for a wide range of applications. The surface qualities of PET as a printing material are critical. Due to their smooth morphology and chemical qualities, PET textiles have a poor capacity to hold water and inks without preprocessing. As a result, designs directly printed with pigment inks typically have low color yields. As a result, fabric pretreatment is often necessary before the printing process to get superior inkjet printing results. Surface modification of polyester textiles with atmospheric-pressure air/He plasma was used in this investigation to increase ink absorption of water-based pigmented inkjet inks and color reproduction of the treated surfaces [25].

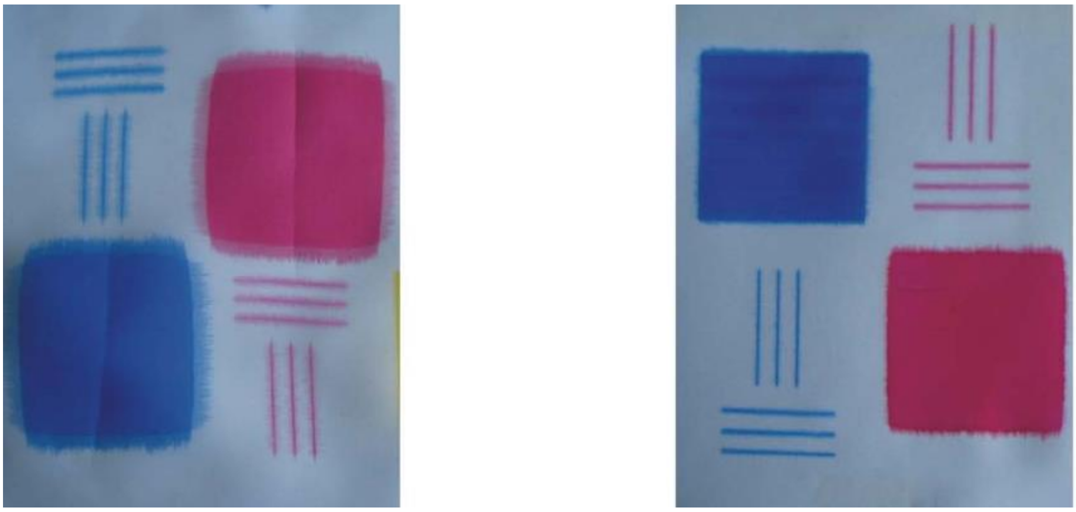
The chemical composition of the polyester surface before and after plasma modification is shown by the surface chemical composition. The oxygen concentration increased by more than 10%, while the carbon content decreased by a comparable proportion. Compared to the control sample, the O/C ratio of the plasma-modified sample rose by 0.16 and 0.21, respectively. When the polyester surface was treated with plasma, it is to be expected that the oxygen-containing polar groups were incorporated [25].

The XPS study shows that the plasma treatment introduced the basic functional groups of the polyester structure C-C/C-H, C-O (and/or C-OH), C=O, and O=C-O (and/or COOH). This finding showed that the plasma treatment shattered numerous C-C bonds on the polyester fiber surface and that the fractured C-C bonds will recombine with oxygen atoms created in plasma, such as C=O, C–OH, and COOH, to form oxygen-containing polar groups [25].

Hydrophilicity was altered by plasma surface modification. The control fabric's contact angle values were 85°. This finding is due not just to the specimen's surface chemical characteristics but also to the fibril structures' surface roughness. However, after plasma processing, the water contact angle was reduced to 29°. The surface alteration considerably increased the fabric's wettability, according to the data. While etching the polyester fiber, the air/He plasma is thought to have added polar groups to the fiber surface [25].

Due to the original chemical characteristics and smooth surface of polyester fibers, pigment particles were difficult to attach to them and moved disordered over the fiber surface, even into gaps between two threads. This finding might explain the bleeding phenomena seen using a video focus-exchanged microscope. An even distribution of pigment particles on the treated fibers, on the other hand, indicated that the hydrophilicity and rough surface of plasma-modified fibers could provide more capacity for the fabric to capture inks and also facilitate the penetration of colorants particles into the polyester fabric [25].

To assess the influence of the plasma modification on printing performance, digital inkjet printing was performed. Color blocks and lines were printed on the substrates with magenta and cyan ink, and photos were recorded with a digital camera. Figure 3 clearly shows this. (a) The bleeding phenomenon is severe at both the weft and warp edge. As expected, the actual printing pattern must be unclear in this situation. In comparison, the edge definition in Fig 3 was found to be substantially more readable. (b). The sample's anti-bleeding property has been significantly enhanced following plasma processing [25].



(A) (B)

Figure 3. Anti-bleeding performance of (a) untreated and (b) air/He plasma treated polyester fabrics.

After plasma treatment, the K/S values increased. The noticeably higher K/S values represent an improvement in the chroma of the plasma-modified materials. The enhancement of the anti-bleeding characteristic is thought to have enhanced the number of ink colorants that remained on per area of the cloth.

3.3.2. Silk screen printing of plasma-treated polyester fabric using Cochineal dye.

The effect of plasma on the printing of polyester textiles with cochineal natural colors was researched and compared in this study. Polyester textiles were treated with O_2/Ar vacuum plasma at 100 W for 15 minutes. For 30 minutes at 80°C, the sample was processed with 5%

copper sulfate as a mordant. Following the plasma process, the fabric was printed with the following paste recipe listed in Table 8 [26]:

Table 8. Printing paste recipe.

Materials	**Amount of materials (g)**
Cochineal dye	50
Sodium alginate	600
Chitosan	100
Sodium carbonate	50
Urea	100
Softener	40
Balance	x
Total	1000

The untreated and plasma-treated samples are printed using the traditional silk screen printing process. After treating the printed fabric, samples were dried at 100° C for 5 minutes and fixed by steaming at 180° C for 5 minutes [26].

Table 9 shows that the color fastness of the treated printed samples has improved. Plasma treatment has increased the printability of textiles, as seen by the K/S values. The wettability of the fabric is increased by plasma treatment, which promotes the penetration of any substance contained in the printing paste. The fastness of prints is an important metric for evaluating natural dyes used in printing [27]. Colorfastness revealed greater values when compared to untreated textiles, which might be attributed to plasma-treated materials' higher K/S values [26].

Table 9. Color strength and color fastness of polyester printed samples with Cochineal dye.

Sample		K/S	Fastness properties								
			Washing fastness		Rubbing fastness		Persperation fastness				Light fastness
							acid		alkali		
			Alt.	St.	dry	wet	Alt.	St.	Alt.	St.	
untreated		0.23	3	3	3-4	3	3	3	3	3	5
Plasma treated and printed treated	15 min plasma, 5 % copper sulphate, 180C fixation	1.54	4	5	5	4-5	4	4	4	4	7
	5 min plasma, 5 % copper sulphate, 180C fixation	0.61	3-4	5	4	4	4	4	4	4	5-6

4. Concolusion

Briefly, plasma treatment might improve the printability of polyester fabric by increasing the adherence and penetration of printing paste to the surface. The air permeability of printed materials has reduced, but the angle of crease recovery has risen. The fastness qualities of printed samples were determined to be adequate to very good.

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Conflicts of Interest

The authors declare no conflict of interest.

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