American Journal of Polymer Science & Engineering
http://www.ivyunion.org/index.php/ajpse/

Research Article

Effect of Dielectric Barrier Discharge Parameters on Certain Properties of Natural Polymeric Material (Cotton) Fiber

Rahul G. Navik[1, 2], Ajit G. Dalvi[2], Shivraj B. Karande[1, 2] and Yingjie Cai[1*]

[1]Engineering Research Centre for Clean Production of Textile Dyeing and Printing, Ministry Of Education, Wuhan Textile University, Wuhan 430073, China

[2]DKTE'S Textile and Engineering Institute, Ichalkaranji, Kolhapur, Maharastra, 416115, India

Abstract

Dielectric Barrier Discharge (DBD) plasma reactor, operated at atmospheric pressure was used for modifying the properties of bleached plain woven cotton fabrics. Cotton fabric was treated at 3.0, 3.5 and 4.0 kV electrode current for 2.5, 5.0, and 7.5 min in the presence of air plasma, in order to establish the chemical effect on cotton fiber. Some properties such as wick-ability, absorbency, tensile strength, tear strength, dye-ability; FT-IR analysis and surface morphology analysis were carried-out as well. The outcomes revealed that, plasma treatment resulted in surface etching, generation of carboxylic and carbonyl group contents in cotton fiber. The increased carbonyl and carboxylic group content resulted in enhancement of fiber wettability and rate of fabric vertical wicking. The reactive dyes uptake of treated samples were increased almost linearly but decreased with increased treatment time and intensity of voltage across the electrodes. A slight increase in tensile and tear strength was found in air plasma treated fabrics. Yellowness of the fabric was increased after plasma treatment. The SEM micrographs confirmed the atmospheric plasma could modify the fiber surface outwardly.

Keywords: Cotton; Dielectric Barrier discharge; Wicking height; Colour yield; FT-IR; SEM

Academic Editor: Taihong Shi, PhD, Sun Yat-sen University, China

Received: July 27, 2015; **Accepted**: September 1, 2015; **Published**: October 8, 2015

Competing Interests: The authors have declared that no competing interests exist.

***Correspondence to**: Cai Yinjgjie, Engineering Research Centre for Clean Production Of Textile Dyeing and Printing, Ministry Of Education, Wuhan Textile University, Wuhan 430073, China

E-mail: yingjiecai@wtu.edu.cn

1. Introduction

Cotton is one of the most important textile fiber in the world due to their excellent properties, such as breathability, moisture, heat conduction, softness, hypoallergenic and antistatic properties [1-5]. It is a unique biological object; because of it is gigantic biological cell of micro-molecule of microscopic linear dimensions [6]. However, it contains several unwanted impurities and removal of impurities is obvious to make raw fabric white and absorbent to prepare them for dyeing, printing or chemical finishing [7, 8]. In recent years, plasma related techniques have been increasingly used in the etching, deposition, or other modifications of textile materials to improve their surface properties [9, 10]. Because, plasma treatment modifies or removes the fibers hydrophobic outer layer, improving dye-fiber interaction and increasing the flux of dye molecule through the fiber surface into the fiber bulk [11]. During the treatment bombardment of active species causes surface atoms ejection when, transferred energy is greater than atom binding energy. A large number of cracks and grooves are generated on fiber surface by etching which, modifies surface properties physically. Furthermore, during the treatment or immediately after plasma treatment on exposure to the atmosphere free radicals insert new hydrophilic carboxylic and hydroxyl derivatives (e.g. –C=O, -C-O, -COOH, -OH) on fiber surface [12, 13]. Polymer chains are partially decomposed during the plasma treatment and new functional are formed and these newly formed polar groups act as reactive centers for subsequent chemical modification or as an anchor for the other agents [14]. Dielectric barrier discharge plasma reactors, operate at elevated pressure and glow discharges at low pressure in a vacuum system, are used to modify the fibers and textiles as some existing chemical processes. They can modify the surface nature of hydrophobic polymers without remarkable deterioration to their bulk properties by etching and polarization [1]. The different types of gas or mixture of gases that can be used for plasma treatment of textile such as argon, carbon dioxide, sulphur dioxide, water and tetra-flouro-methane, and oxygen. Oxygen and oxygen containing plasma are most frequently and are very effective in increasing the surface energy of textiles [15]. Nitrogen and nitrogen containing plasmas are used to produce nitrogen functionality such as amino groups of polymer of polymer surface [16]. Fluorine and fluorine containing plasma are used to decrease the surface energy and to increase the hydrophobicity of polymer surface. Each gas produces a unique modified surface [17]. In oxygen plasma two processes occurs simultaneously; etching, of polymer and textile surface through the reaction of atomic oxygen with the carbon atoms, giving volatile reaction products, and the formation of oxygen functional groups at the textile and polymer surface through the reaction between active species from the plasma and the surface atoms. The balance of these two processes depends on the operation parameters such as the nature of textile substrate, the temperature of the substrate, electrode materials, pressure, power level, and gas flow rate [18].

In the present work an attempt has been made to enhance the function properties of cotton fiber with the use of least expensive air as a plasma gas, in a DBD reactor. Optimum treatment parameters such as treatment time and voltage across the electrodes on properties of cotton fiber such as whiteness, yellowness, tensile and tear strength, wicking height and colour yield of reactive dyes were well reported in this paper.

2. Experimental detail

2.1 Materials

Commercially available plain woven, scoured, bleached, 100% cotton fabric (warp count - 40 Ne and weft count - 40 Ne) with average weight (130 g/m^2), supplied by Piyush Syndicate (Mumbai, India) was used in this study. Before the plasma treatment, to minimize the chance of contamination, samples were washed with 0.5 % non-ionic detergent (Enkamole LFS supplied by Yogeshwar Chemical Ltd.) solution at 80 ^{o}C for 30 min, then rinsed with plain water for another 15 min, and dried at ambient temperature before plasma treatment.

2.2 Plasma treatment

Cotton fabric was treated in a DBD plasma reactor designed by, Facilation Center for Industrial Plasma Technologies (India) was used. The main components of the reactor includes, an Al_2O_3 ceramic electrode with active area 40 × 50 cm and a high power supply unit (500 W). The gap between the electrodes could be adjusted in the range of 0.5 – 2.5 mm. However, the distance between the electrodes was 2 mm during the treatment and air was used as reactive gas and system was worked at atmospheric pressure. Cotton fabric samples with an average thickness of 0.3 mm passed between the electrodes continuously, and both sides of the fabric were exposed to the plasma treatment. The cotton fabric was treated with 3.0, 3.5 and 4.0 kV electrode current, for 2.5, 5.0 and 7.5 min. After LTP treatment, the fabrics were conditioned in 65% RH (Relative humidity) at 27±2 ^{o}C before being used.

2.3 Dyeing

Dyeing of untreated and DBD treated cotton samples was carried out by classical exhaustion method in a laboratory Rota dyer equipment. Samples were dyed with Reactive Red 195 and Reactive blue 171, supplied by the Coloutex Industries Ltd, (India). The dye solutions were prepared by dissolving the 1gm of dye powder in 100 ml hot distilled water and then samples were dyed in 1.5 % o.w.f. (on weight of fabric) shade with liquor ratio of 1:30. The dyeing was started at 40 ^{o}C and temperature was raised to 80 ^{o}C at the rate of 3 ^{o}C per min. The samples were allowed to remain in that condition for 45 min, and then rinsed with distilled water and air dried.

3. Testing and Analysis

3.1 Absorbency

To explore the effect of DBD treatment at different electrode voltage for different duration on absorbency behavior of cotton fabric, the wettability of cotton fabrics was evaluated according to the AATCC test methods: 79:2007.

3.2 Wicking Height

The wicking behaviour of plasma treated and untreated cotton fabrics were measured according to the German standard method DIN 53924.

3.3 Whiteness and Yellowness

The whiteness and yellowness indexes of untreated and DBD treated cotton fabric at different parameters were measured by Macbeth colorage ® 3000 spectrophotometer with 10^o observer under the D_{65} light source and calculated according to the CIE, ASTMD1925 and TAPPI 452/ISO2470 equations.

3.4 Tensile Strength

Tensile properties of untreated and plasma treated cotton fabric was determined according to the ASTM D5035 (1995), with Instron tester after conditioning the fabric samples at 65±2 % RH and 27±2 ^oC temperature for 24 hours.

3.5 Tear Strength

Tear strength of untreated and DBD treated cotton fabric was measured with Elmatear tear strength tester (James and Heal Co. UK) according to the IS 6489 -1971 test method.

3.6 Colour Yield (K/S)

The colour yield of untreated and DBD treated cotton samples was determined by Macbeth colorage® 3000 spectrophotometer with colour lab software. The fabric was folded two times before measurement for ensuring opacity and measured twice, i.e. measured on both the warp and weft directions to obtain average results. The colour yield expressed as a K/S value ranging from the wavelength of 400 to 700 nm with 20 nm interval within the visible spectrum. The K/S values were summed up according to equation (1).

$$K/S = \frac{(1-R)^2}{2R} \quad (1)$$

Where, K= Absorption coefficient depending upon the concentration of colorants, S= Scattering coefficient caused by the dyed substrate, and R= Reflectance of coloured sample.

3.7 FT - IR Analysis:

In order to determine the surface functional group changes caused by air plasma treatment, Fourier transform infrared spectroscopy (FTIR) assessment were carried out using Necolet Avatar 8400 FTIR model, with 4

cm^{-1} resolution. An average of 15 scans was recorded in the ATR mode.

3.8 Surface Morphology

The change in surface morphology of plasma treated cotton fabric was investigated using scanning electron microscope (SEM 5400, Japan). Samples were observed 5000 to 10,000 times of magnifications.

4. Results and Discussion

4.1 Absorbency

Absorbency measurement of air plasma treated fabric in DBD reactor was conducted immediately after treatment and compared with untreated sample and, results represented in Table 1. From the table it is clear that, the wettability of air plasma treated cotton was improved. The absorbency time of treated cotton decreased from 4 sec to less than 2 sec. However, the treatment voltage and exposure duration showed the significant differences in absorbency behavior i.e. when the treatment voltage was 3.0 kV the improvement in absorbency was observed at 5.0 to 7.5 min exposure duration whereas, identical effect was found with 3.5 and 4.0 kV for 2.5 min exposure duration. The decreased absorbency duration attributed to the surface ablation and formation of new polar groups. The enhanced surface roughness resulted in decreased barrier between water drop and surface caused by the vapor formed between the fiber and water drop. Water vapor traps at the bottom of the grooves of enough depth and water comes in direct contact with raised areas of groove and penetrates inside the fiber interstices immediately [19].

Table 1 Absorbency behavior of cotton before and after DBD treatment.

Voltage across electrodes (kV)	Plasma treatment time (min)	Absorbency time (sec)
Untreated Cotton	----	4
3.0	2.5	3
	5.0	2
	7.5	2
3.5	2.5	2
	5.0	3
	7.5	3
4.0	2.5	2
	5.0	3
	7.5	3

DBD generates an active gas plasma consisting of free electrons, positive ions, and other chemical species. These active species can be used to modify the material surface physically and chemically. The enhanced wettability might be due to the etching effect of DBD emission on the cuticles of cotton fibers [20]. This results in partial degradation and removal of hydrophobic non-cellulosic. In addition the surface of cotton fiber would be oxidised by oxygen radicals in the plasmas and produces more oxygen-containing groups, this might also contribute to the improvement of wettability of treated cotton samples [1]. However, excessive treatment did not remarkably improve the wettability.

4.2 Wicking Height

The increased wicking of untreated and DBD treated cotton is represented in figure 1. Compared to the untreated fabric, the rate of wicking was very rapid initially and the same speed was maintained up to a height of 12.8 cm at 3.0 kV for 2.5 min in warp direction, and in weft direction was 12.3 cm at 4.0 kV for 2.5 min on the cotton stripe. However, no significant impact of electrode voltage and treatment duration on wicking height of cotton fabric was observed in both warp and weft directions.

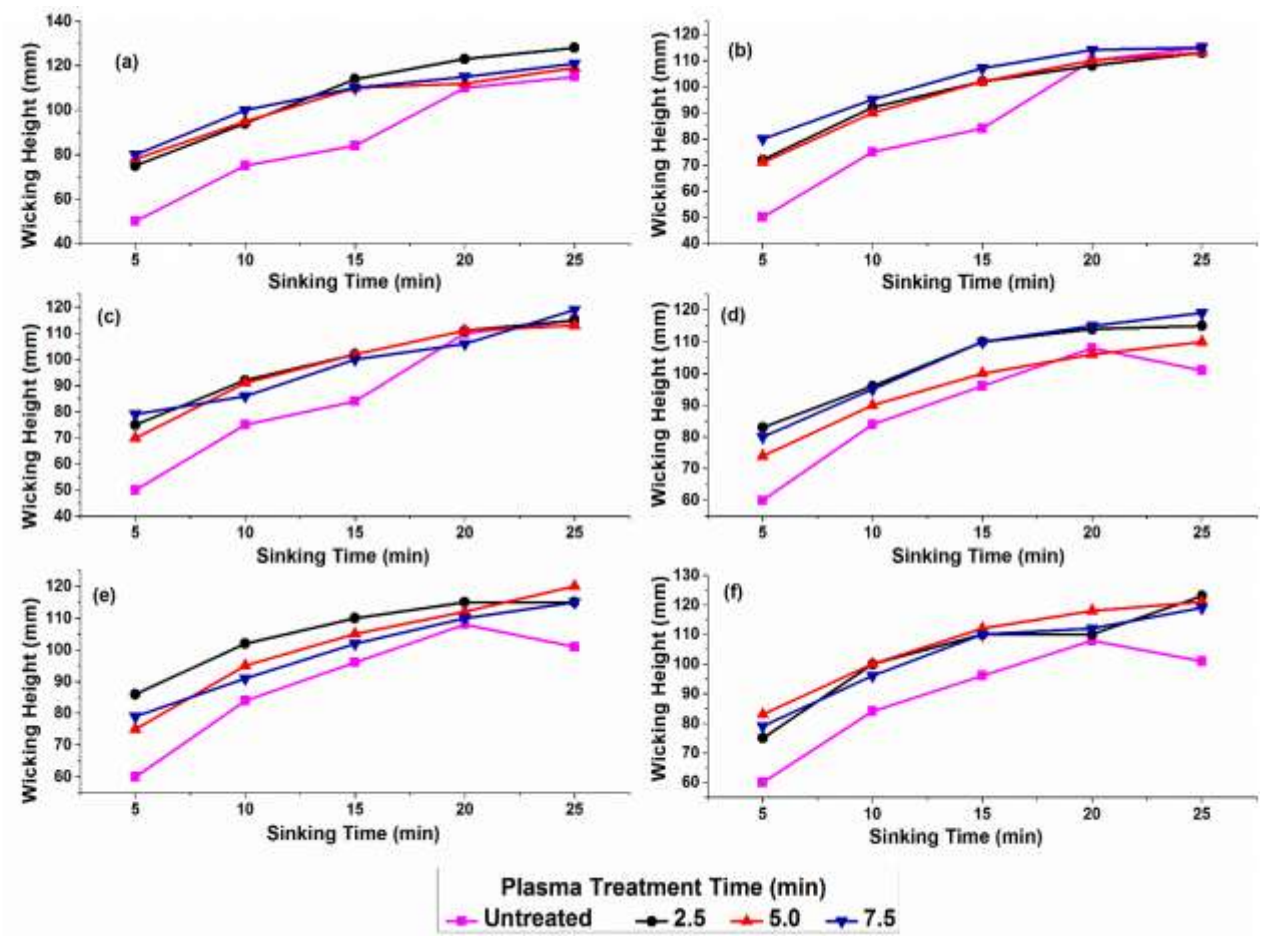


Figure 1 Wicking height in warp direction of untreated and air plasma treated cotton fabric with 3.0 kV (a), 3.5 kV (b), and 4.0 kV (c), and wicking height in weft direction of untreated and air plasma treated cotton fabric with 3.0 kV (d), 3.5 kV (e), and 4.0 kV (f), in warp direction (a) and weft direction (b) at different parameters.

This observation suggests that with increasing voltage across the electrodes, the cellulosic fibers may become slightly more hydrophilic since wettability is a perquisite for wicking; a liquid that does not wet fibers cannot wick into a fabric. Moreover, due to plasma etching effect the effective pore size present cotton fibers may increase and adversely reduce the capillary pressure thus increasing the wicking ability [21, 22]. This can be explained by the facts that increasing the discharge power result in an increase of the amount of reactive plasma species. The presence of more plasma species can leads to increased fiber wettability and/or an increased wicking ability due to a more intense bombardment on the fiber surface [23]. Both this aspects will be further explored by performing SEM and FTIR measurements in order to determine the chemical and physical properties of the plasma treated cellulosic fibers.

4.3 Whiteness and Yellowness

The dependence of whiteness and yellowness on the electrode voltage and treatment time with air plasma is shown in figure 2. It is clear that, dielectric barrier discharge emission caused a slight yellowing compared with the untreated cotton fabric. When the exposure time of DBD treatment was prolonged, the degree of yellowness increased and whiteness decreased accordingly. This might result from pyrolysis and oxidation of the surface components [20]. The untreated fabric sample had the lowest yellowness, while the fabric sample treated by LTP treatment for 7.5 min at 4.0 kV electrode voltage got the highest yellowness index values. However, the overall changes in yellowness and whiteness were not so obvious when the parameters of DBD treatment were changed from 3.0 to 4.0 kV electrode voltage and time from 2.5 to 7.5 min.

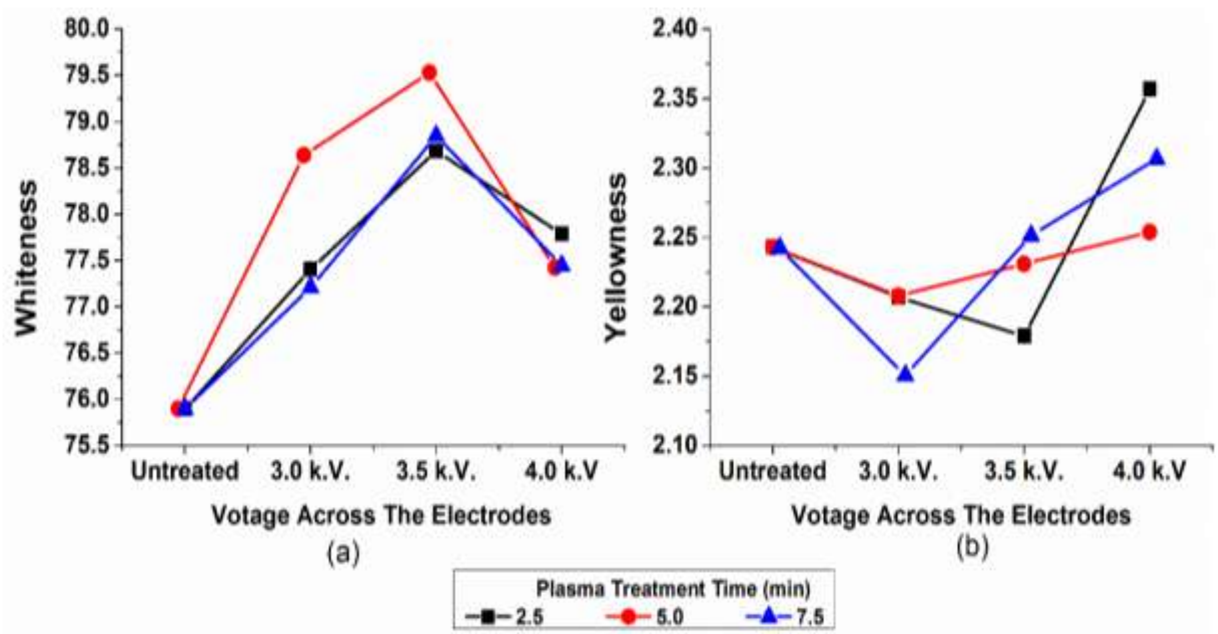


Figure 2 Effect of air plasma treatment on whiteness (a), and yellowing property (b) of cotton treated in dielectric barrier discharge plasma reactor.

DBD treatment it seemed that the oxygen (present in air) damage on the fabric surface after a certain period of time. The longer the LTP exposure time, the greater damage of fiber surface. Since, whiteness of textile substrate dependents upon the surface smoothness i.e. more smooth surface leads to the reflection of incident light whereas rougher surface leads to the diffuse reflection of incident light and cause yellowness of the fibers. Treatment at higher electrode current for longer duration leads to the serious etching of the fiber surface and hence overall yellowness was increased when the electrode current was 4.0 kV for 5.0 to 7.5 min. As a result of the degree of yellowness and whiteness was dependent on the plasma treatment conditions such as treatment time, plasma gas and voltage across the electrodes [24]

4.4 Tensile Strength

Tensile strength is one of the important properties in assessing the quality of treated fabric. Hence, the tensile strength of plasma treated fabric was compared with that of the untreated fabric. It is observed that on several occasions the tensile strength of plasma treated sample is higher than that of the control sample. Figure 3 represents the effect of parameters on tensile strength. It is evident from the figure, with increase in electrode voltage from 3.0 to 4.0 kV for 2.5 to 5.0 min exposure time, tensile strength was increased up to 4 % but longer exposure time for 7.5 min at higher voltage from 3.5 to 4.0 kV is found to be decreased up to 2.2 %. From SEM micrographs it is evidenced that, air plasma treatment leads to the ablation of fiber surface and micro cracks was formed. The newly formed micro cracks might be the root cause for the increased inter fiber cohesion and thus prevents the sliding action on application of force.

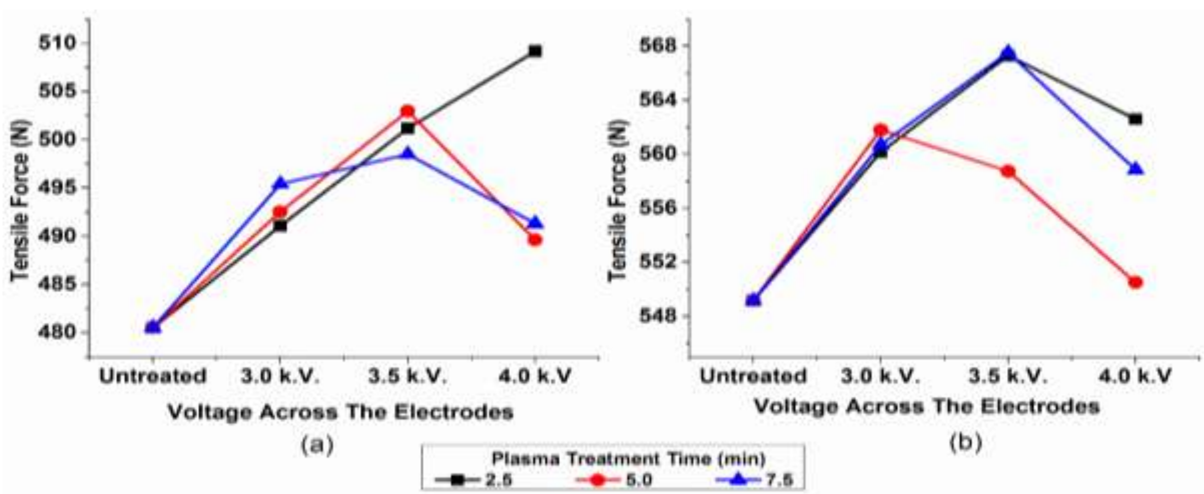


Figure 3 Tensile strength of cotton before and after air plasma treatment in warp direction (a), and weft direction (b) in dielectric barrier discharge plasma reactor.

Apart from change in surface topography air plasma leads to the formation of polar groups by the action of plasma in the cuticle of fibers; these newly formed polar groups are responsible for an increase in inter-fiber cohesion and leads to the better mechanical properties. However, at higher intensity of electrode current leads to the damage of cuticle and cellulose degradation due to serious bombardment of active plasma species and leads to the reduction in tensile strength [25, 26].

4.5 Tear Strength

The tear strength of untreated and DBD treated cotton fabric under different conditions are represented in figure 4. The outcome revealed that the tear strength of cotton fabric was increased 0.25 to 0.45 % both warp and weft directions, when compared to untreated samples. The maximum strength was observed when duration of treatment was 2.5 to 5.0 min for 3.0, 3.5 and 4.0 kV respectively. This may be attributed to the increased inter yarn and inter-fiber friction because of the surface modification by the plasma treatment, restrict the sliding action of yarn during tearing and thereby increases the fabric's tearing strength [27].

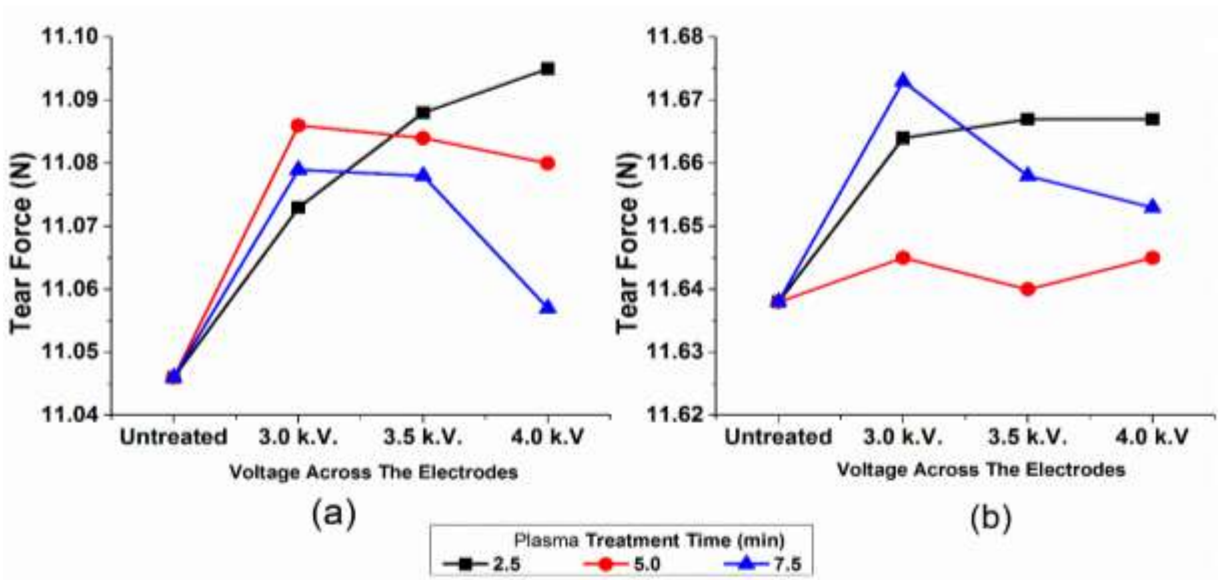


Figure 4 Tear strength of untreated and air plasma treated cotton fabric in warp direction (a), and weft direction (b) in dielectric barrier discharge plasma reactor.

For many instance it was observed that, treatment for longer duration resulted in a considerable decrease in tear strength due to the serious oxidation fiber surface. A slight reduction in tear strength was observed when cotton samples were treated at 3.5 and 4.0 kV for 7.5 min. treatment at higher voltage for longer duration cause serious damage to the surface as well as loss of some polar groups of cotton fiber therefore, reduction in tear strength [26]

4.6 Colour Yield (K/S)

Effect of exposure time to the air plasma at different discharge currents on the colour yield of reactive dyes (Reactive Red 195 and Reactive Blue 171) on untreated and air plasma treated cotton fabric dyed in 1.5 % shade illustrated in figure 5. It is observed that, the colour yield of cotton fabric was improved after DBD treatment. The enhanced colour yield increase by plasma treatment may be explained by, the higher hydrophilicity of the fiber surface, which produces a faster adsorption and diffusion of the dyestuff from the dye bath to the core of the fiber structure and increased number of hydrophilic groups which may allow a higher number of molecules to bind the dye molecules in the fiber. [24, 28]. The treatment time and electrode voltage have a greater impact on the colour yield of reactive dyes on DBD treated cotton fabric. It was increased with increasing treatment voltage but, decreased when treated for longer duration up-to 7.5 min at high voltage (i.e. 3.5 kV and 4.0 kV) The decreased colour yield might be attributed to the loss of polar groups for the dye molecules were might be lost and hence the dye-ability of treated cotton fabric was decreased. The maximum colour yield was obtained when the discharge current was in the range of 3.0 – 3.5 kV electrode. Hence, these voltage was considered as optimum discharge current in accordance to the dye ability of cotton fibre.

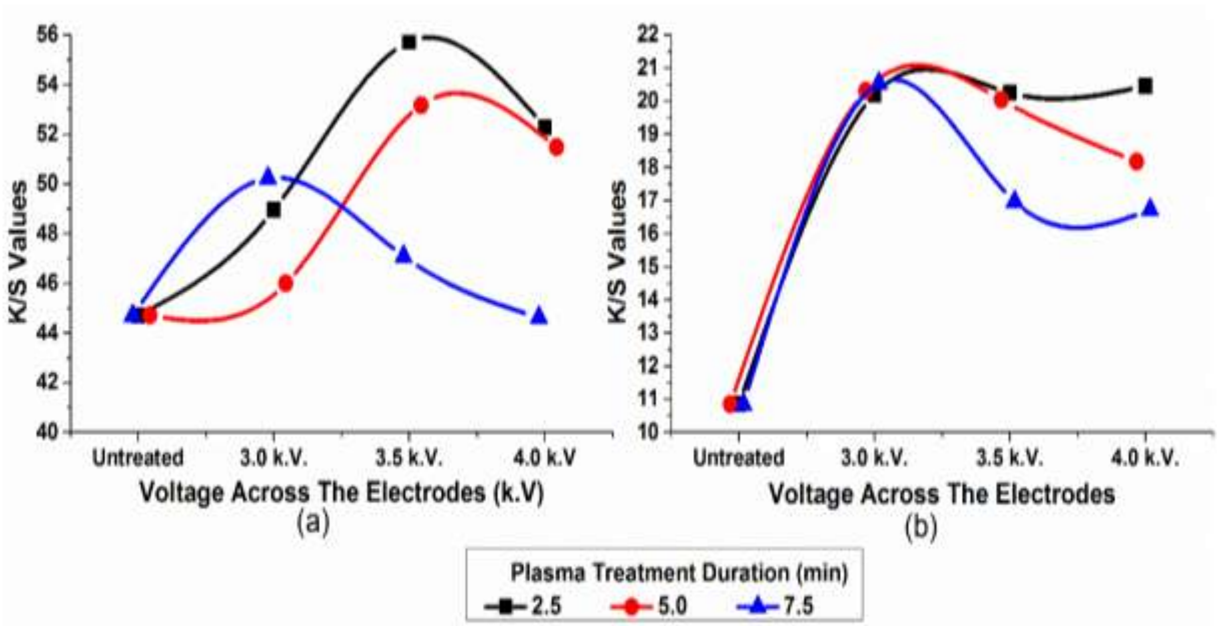
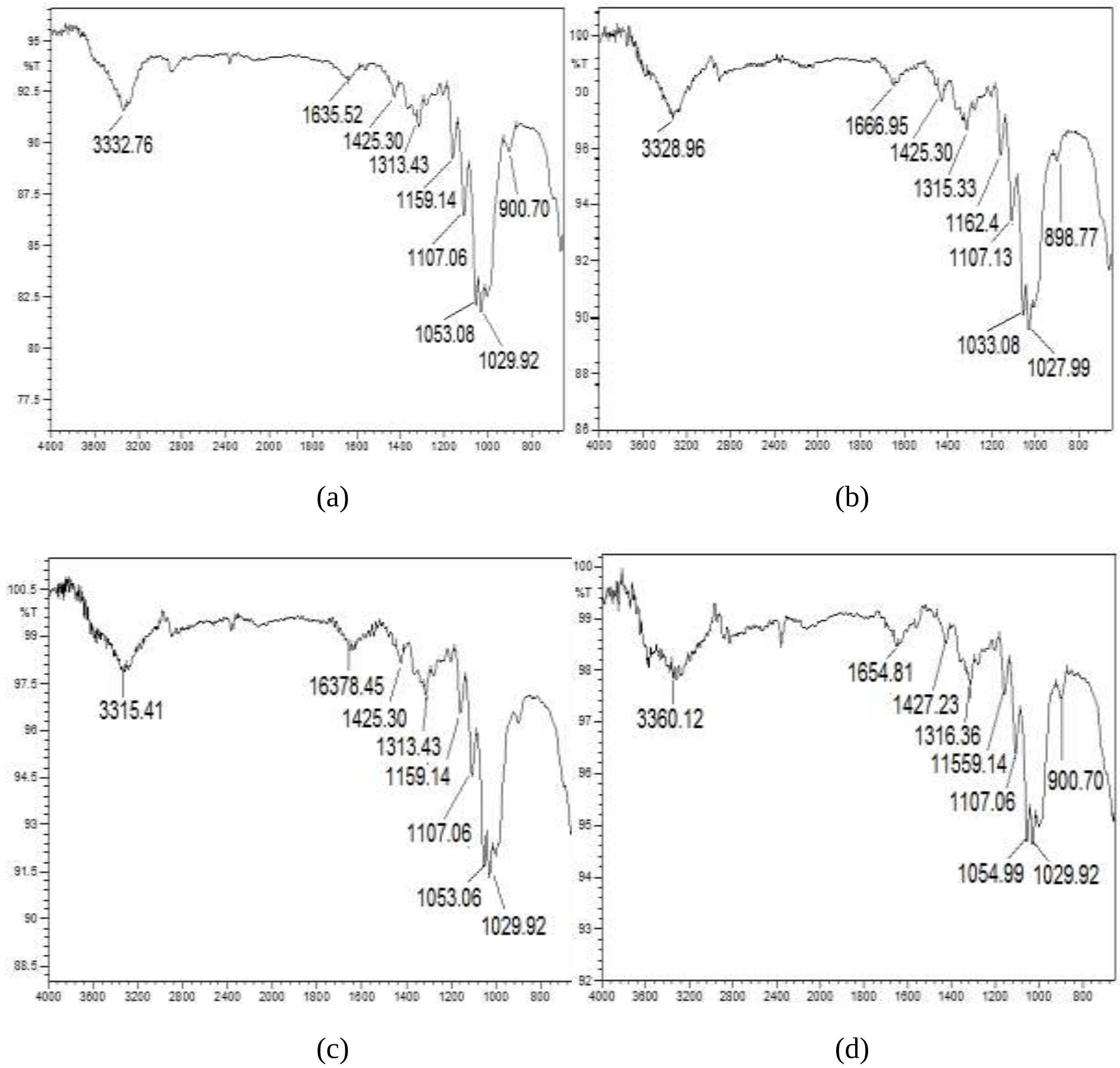


Figure 5 Colour yield of untreated and air plasma treated cotton fabrics with Reactive Blue171 (a), and Reactive Red 195.

4.7 FT - IR Analysis

FTIR analyses were performed on untreated and DBD treated cotton samples with different parameters (electrode voltage and treatment time), and their corresponding spectra are shown in figure 6. The spectrum obtained from untreated and plasma treated cotton species are very similar, but the spectrum for DBD treated cotton showed some difference in peaks of 1635 and 3332 cm^{-1} corresponding to the C=O vibrations groups in the carbonyl structure and O-H stretching vibrations, respectively [29]. Bombardment of plasma on cotton fabric enables the initiations of chemical reaction and leads to alteration of chemical composition of the cotton fabric i.e. increase of hydrophilic groups such as –OH, -C=O, and $-COO^-$ that can improve hydrophilicity of the fabric [30, 31]. Besides, transmittance intensity of plasma treated fabric was lower than of the untreated fabric. This mainly attributed to the number of polar groups formed and bonded on the fabric polymer in which transmittance is inversely proportional to concentration of the corresponding groups [32].

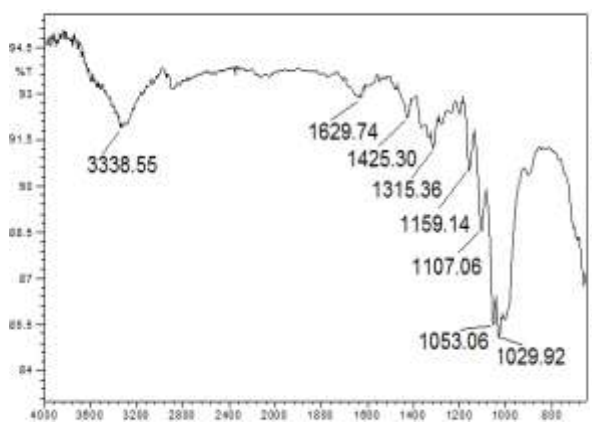


(e)

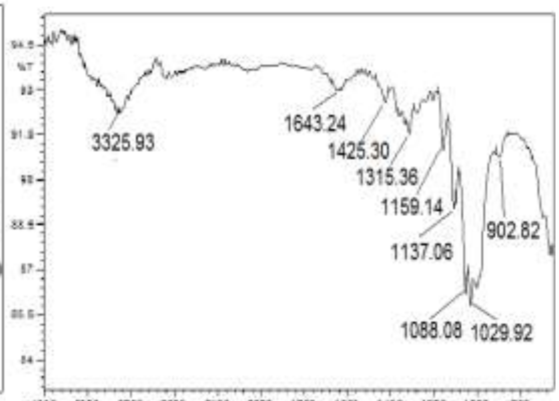
(f)

(f)

(g)



(h)



(i)

Figure 6 FT - IR spectrum of untreated cotton (a), air plasma treated cotton at 3.0 kV electrode voltage for 2.5 min (b), 3.0 kV for 5.0 min (c), 3.0 kV for 7.5 min (d), 3.5 kV for 2.5 min (e), 3.5 kV for 5.0 min (f), 3.5 kV for 7.5 min (g), 4.0 kV for 2.5 min (h), 4.0 kV for 5.0 min (i), and 4.0 kV for 7.5 min (j).

4.8 Surface Morphology (SEM)

As 3.0 kV for 7.5 min of DBD treatment time showed improvement in overall properties of cotton fabric (e.g. tear and tensile strength, dye ability, wick ability, and absorbency) in this study. Thus the SEM image of air plasma treated cotton fabric in dielectric barrier discharge reactor with 3.0 kV for 7.5 min treatment time was selected for study and their corresponding micrographs were shown in Figure 7. When compared, it was observed that the untreated cotton fiber surface had a smooth surface while the air plasma treated cotton fiber surface became wrinkled and roughened.

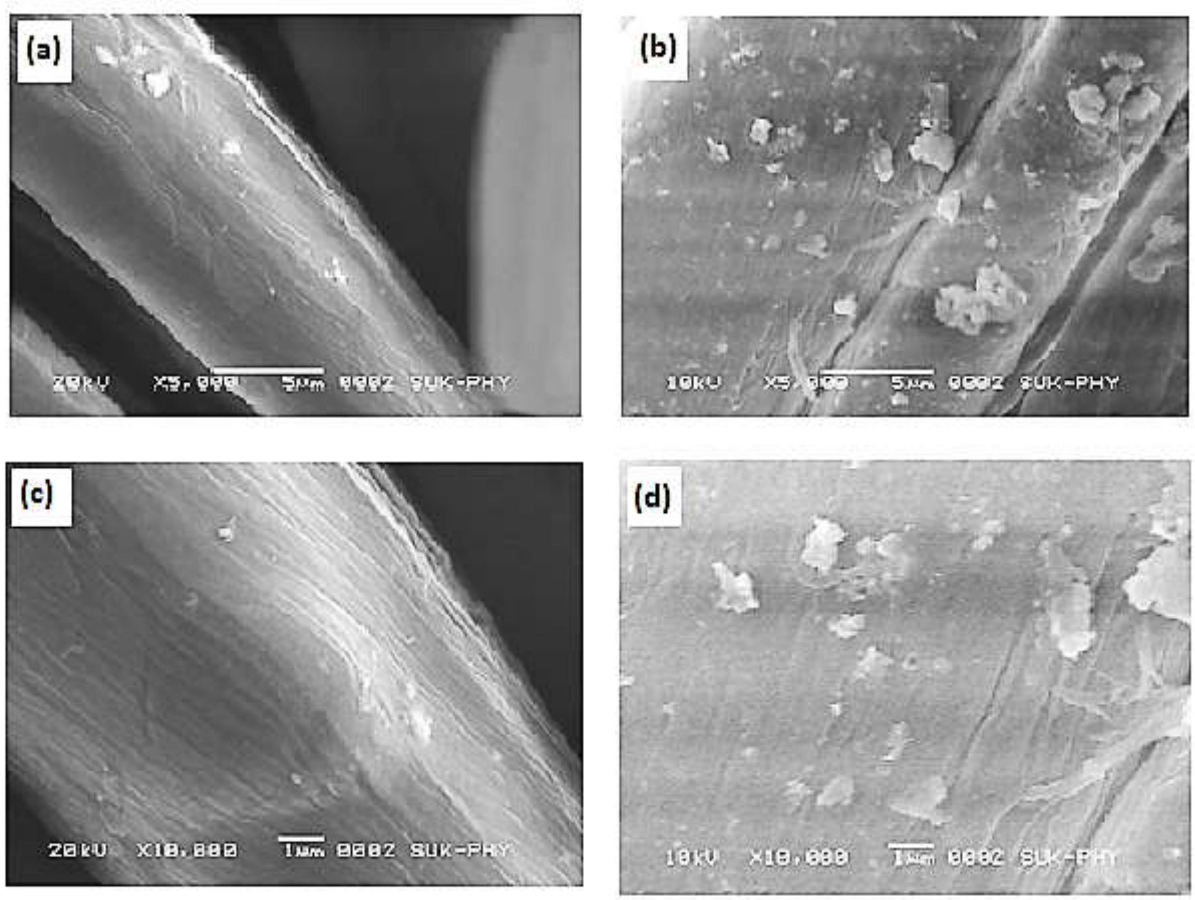


Figure 7 SEM micrograph of untreated cotton at X 5000 (a), and X10, 000 times (c), air plasma treated cotton fibre with 3.0 kV for 7.5 min at X 5000 (b), and X 10,000 times (d).

The change in the cotton fiber surface appearance might be due to the pyrolysis and localized ablation of the surface layer causing a surface damage due to active species in air plasma [33, 34]. During air plasma treatment ablation, the fiber surface was subjected to certain degree of etching. Presence of micro-pores on the fiber surface indicated this predominant effect of the interaction of air plasma (chemical etching) with the fiber surface. The differential etching of crystalline and amorphous regions might be the origin of the roughness. This process, lead to almost complete breakdown of relatively small number of molecules on the fiber surface into a very low molecular component, which would eventually vaporize into the low pressure system along the fibers axis [24].

Conclusions

The effect of air plasma treatment on physiochemical properties of cotton fabric have been studied with respect to the treatment time and plasma power. As expected air plasma treatment generates greater change in the fiber and fabric properties under the experimental condition used. The plasma treatment leads to surface erosion of the cotton fibers, which generates an increase in tensile and tearing strength in certain degree and decreased slightly when, the voltage across the electrodes increased, the highest physical strength was obtained at 2.5 to 5.0 min DBD treatment when, treated with different voltages across the electrodes. The FT-IR spectrum clearly showed that, oxygen containing groups such as C–O, C=O, O–C–O and O–C=O was enhanced in DBD treated cotton fiber, which, might be the root cause for improvement in wetting and wicking properties. It was found that, the air plasma treated cotton fabric surface turned yellow due to pyrolysis of fiber surface when, compared with the untreated cotton fabric. The colour intensity of the reactive dyes on air plasma treated cotton fabric was increased with 3.0 – 3.5 kV electrode current. This is well explained by the fictionalization of the surface with oxygenated moieties, without any significant alteration in the surface topography of the fibers. SEM outcomes suggested that, atmospheric plasma treatment made the surface structure into a rougher state because of the etching effect. In other words, air plasma generated in DBD reactor have the potential of influencing not only the chemical properties but also the physical properties of the cotton fiber.

Acknowledgements

Authors are grateful to "Institute of Chemical Technology, (India), for providing FTIR facility and "Wool Research Association" (India) for providing "Dielectric Barrier Discharge" plasma reactor.

References

1. Marcandalli B, Riccardi C. Plasma treatments of fibres and textiles. In: Shisoo R, ed. Plasma Technologies for textiles. Cambridge:Woodhead Publishing; 2007:286
2. Lam YL, Kan CW, Yuen CWM. Physical and chemical analysis of plasma treated cotton fabric subjected to wrinkle resistance finishing. **Cellulose.** 2011, 18:493-503
3. Ab. Shusa MH, El-Husamy MB, Hashem Am, El-Nagar AH. A leatching type antibaterial agent in the easy care finishing of knitted cotton fabric. **J Indus Text.** 2007, 37:55-77
4. Kan CW, Lam YL. Low stress mechanical properties of plasma-treated cotton fabric subjected to zinc oxide-anti-microbial treatment. **Materials.** 2013, 6:314-333
5. Kolarova K, Vosmanska V, Rimpelova S, Svorcik V. Effect of plasma treatment on cellulose fiber. **Cellulose.** 2013, 20:953-961
6. Karkhmalev V A, Paiziev A A. Spiral structure of cotton fibres. **Cellulose.** 2006, 13:45-52
7. Karmarkar SR. Pre-treatment of textiles under plasma conditions. In: Karmarkar SR, ed. Chemical technology in pretreatment process of textiles. Newyork:Elsevier; 1999:395-414
8. Karahan HA, Ozdogan E. Improvement of surface functionality of cotton fibres by atmospheric plasma treatment. **Fibers and Polymers.** 2008, 9:21-26
9. Lou S., Wim J, Ooij V. Surface modification of textile fibers for improvement of adhesion to polymeric matrices: a review. **J Adhes Sci Tech.** 2002, 16:1715-1735
10. Kang JY, Sarmadi M. Textile plasma treatment review-natural polymer based textiles. **Amer Asso Text**

Chemi Col. 2004, 4:4

11. Morrent R, De-Geyter N, Verschuren J, De-Clerck K. Non-thermal plasma treatment of textiles. **Surf Coat Tech.** 2008, 202:3427-3449
12. Lerourex F, Compagne C, Perwuelz A, Gengembre L. Fluorocarbon nano-coating of polyester fabrics by atmospheric air plasma with aerosol. **Appl Surf Sci.** 2008, 254:3902-3908
13. Cai Z, Qiu Y. The mechanism of air/oxygen/helium atmospheric plasma action on PVA **J Appl Polym Sci.** 2006, 99:2233-2237
14. Calvimontes A, Mauersberger P, Nitschke M, Dutschk V, Simon F. Effects of oxygen plasma on cellulose surface. **Cellulose.** 2011, 18:803-809
15. Kan CW, Man WS, Ng SP. A study of pigment application on atmospheric pressure plasma treated cotton. **Fibers and Polymers.** 2014, 15:2313-2318
16. Kale K H, Desai A N. Atmospheric plasma treatment of textiles using non-polymerising gases. **Indian J Fibr Text Res.** 2011, 36:289-299
17. Prasath A, Sivaram SS, Anand Vijay VD. Desizing of starch containig cotton fabrics using near atmospheric pressure, cold DC plasma treatment. **J Instit Engine (India): Series E.** 2013, 94:1-5
18. Shahidi S, Ghoranneviss M, Moazzenchi B. New advances in plasma technologies for textile. **J Fus Energ.** 2014, 33:97-102
19. Zhong W. Surface Tension, Wetting and Wicking. In: ed. North America:Woodhead Publishing Limited,; 2006:136-153
20. Wang Q, Fang X R, Wang L P, Wu J, Chen J. Plasma aided cotton bioscouring: Dielctric barrier discharge versus low pressure oxygen plasma. **Plasma Chem Plasma Proc.** 2009, 19:399-409
21. Sun D, Styllus G K. Effect of low temperature plasma treatment on the scouring and dyeing of natural fabrics **Text Res J.** 2004, 74:49-56
22. Wong K K, Tao X M, Yuen C W M, Yueng K W. Low temperature plasma treatment of linen. **Text Res J.** 1999, 69:846-855
23. Indubarkar S, Morent R, Geyter N D, Desmet T, Anukaliani A, Dubruel P, Leys C. Chemical and physical analysis of cotton fabrics plasma treated with a low pressure DC glow discharge. **Cellulose.** 2010, 17:417-426
24. Yuen C W M, Kan C W. Influence of low temperature plasma treatment on the properties of ink-jet printed cotton fabric. **Fibers and Polymers.** 2007, 8:168-173
25. Prabaharan M, Carneiro N. Effect of low temperature plasma on cotton fabric and it's application to bleaching and dyeing. **Indian J Fibr Text Res.** 2005, 30:68-74
26. Pibo M A, Huang J, Cao G, Xu W. Influence of temperature on corona discharge treatment of cotton fibres. **Fibers and Polymers.** 2010, 11:941-945
27. Lam Y L, Kan C W, Yuen C W M. Effect of oxygen plasma pretreatment and Titanium dioxide overlay coating on flame retardant finished cotton fabrics. **Bioresources.** 2011, 6:1454-1474
28. Patino A, Cristina C, Cristina R, Caballera G, Navrro A, Canal J M. Surface and bulk cotton fabric modifications plasma and cationisation: influence on dyeing with reactive dye. **Cellulose.** 2011, 18:1073-1083
29. Alessio Mezzi Daniela Caschera, Luciona Corri and Tilde de Caro. Effects of plasma treatments for improving extreme wettability behavior of cotton fabrics. **Cellulose.** 2014, 21:741-756
30. Zhong Z.Z Zang H.J, Guo F, and Liu W.M. The influence of plasma treatment on the tribological properties of hybrid PTFE/cotton fabric/phenolic composites. **Polymer Compos.** 2008, 30:1523-1531
31. Bujanda A Ppas D, Demree J.D, Hirvaneh J.K. Kosik W, Jenson R, and M.C. Knight S. Surface modification of polyamide fibers and films using atmospheric plasmas. **Surf Coat Tech.** 2006, 201:4384-4388
32. C.W. Kan Y.L. Lam, C.W.M. Yuen. Fabric Objective Measurement of the Plasma-treated Cotton Fabric Subjected to Wrinkle-resistant Finishing with BTCA and TiO2 System. **Cellulose.** 2011, 18:493-503
33. Vander L C, Ostenson M, Gatenholm P, Rajauskas A J. Surface modification of cellulose fibre using dielectric barrier discharge **Carbohy Polym.** 2006, 65:179
34. Ysuda T, Gazicai M, Yasuda M. Plasma polymerisation and plasma treatment. **Appl Polym Sci.** 1984, 38:201