Surface treated cotton fabric with stain repellent property for the use in aircraft upholstery

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Abstract
Nanotechnology modifications play a major role in textile industry due to extraordinary properties exhibit in fabrics due to nanomaterials. It offers different functionalities namely self-cleaning, wrinkle resistance, flame retardancy, protection from UV radiations or antibacterial property. Further, it is important to maintain cleanliness in aircraft upholstery always but the airlines have to bear a considerable amount of money to clean up the aircraft upholstery. Interestingly, nanotechnology can provide stain repellence property for fabrics in aircraft upholstery. This study covers a method of developing a stain repellent fabric which was stable even after 25 standard laundering conditions. In this study nanotechnology was used to modify a cotton fabric with stain repellent property. After nanotechnology modification, the surface wettability of the treated fabrics was characterized by static water contact angle measurements before and after 25 washes carried out under standard laundering conditions. Similar testings were carried out for the untreated fabric samples. The static water contact angle for the treated fabric was 161° with the recovery of 97.5% after 25 washing cycles. SEM and AFM micrographs were used to analyze the coatings. Further, the stability of hydrophobicity in the modified cotton fabric after 25 washes was also tested for tea, coffee, and water solutions which are vulnerable stain types in aircraft upholstery. It clearly proved that the modified cotton fabric even after 25 washes showed hydrophobicity for tea, coffee, and water. Therefore, it could be concluded that the developed modified cotton fabric can consider to be used as an aircraft upholstery.

Keywords
Aircraft, cotton fabric, self-clean, stain resistance, surface treated, textile

Introduction
Researchers have been working to mimic the biological surfaces such as lotus leaves, butterfly wings, mosquito eyes, moth eyes, red rose petals, gecko feet, desert beetle, and spider silks which exhibit excellent hydrophobicity.1–5

The surfaces with hydrophobic and/or super hydrophobic properties have received a great scientific and industrial attention because of their wide range of applications.4,6 Hydrophobic or super hydrophobic surfaces can be made by chemically treated methods to manufacture products in various domains, namely in automotive, aerospace, marine applications, and textiles. Super hydrophobic surfaces bring in tremendous enhancement in the functional performances compare with their conventional counterparts.6

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The existence of contamination often affects the efficiency and safety of transportation. Therefore, self-cleaning is an important and interesting property in transportation sector. Hydrophobic fabrics have also self-cleaning properties which can be used in upholstery, usual cloths, mattresses, and also in sport cloths.

As per the statistics released in 2018 by the International Air Transport Association (IATA) the estimate air passenger numbers could hit 8.2 billion per year by 2037. Increased demand for capacity means, there should be more aircraft and necessary improvements to the ecosystem to keep those aircraft flying safely. However, corrosion is a constant threat to the structural integrity of aircraft occurred mainly due to saltwater air. Meanwhile, inside the cabin, spills of coffee and soft drinks can damage to the interior of the aircraft. In order to maintain the proper standards of the aircraft it must undergo regular inspections which airlines have to spend a huge sum for maintenance. There are several research articles published related to super hydrophobic nanomaterials on aircraft surfaces, air conditioner, and refrigerator tubes which lead to have a freeze less surface when in touch with moisture. In addition, the literature highlighted the super hydrophobicity in aircraft paints and varnishes, pipe coating, and fabric. However, there wasn’t any published literature related to the hydrophobic properties of aircraft upholstery fabric materials which is found in the carpeting, wall fabric, and seat covers on an aircraft.

The two main requirements to create an excellent super hydrophobic surface are surface roughness and low surface energy. Several technologies such as E-beam lithographic, etching, stretching, spin coating, plasma deposition can be used to develop hydrophobic surfaces. In addition, electrospinning can also be used to manufacture nanofibers with coatings from a charged solution. Furthermore, nano-technologies also can be used to produce super hydrophobic or hydrophobic surfaces.

Sol-gel technique has been applied to the fabrication of superhydrophobic surfaces on fabrics, but fabrics are vulnerable to have stains of tea, coffee, and wine. In sol-gel method, hydrolysis reaction of the precursor material is carried out to form a nano-colloidal solution in order to provide preferable durability of stain repellency for the fabric which was treated by TiO2 sol. The precursors are often based on metal organic compounds such as titanium (IV) isopropoxide Ti(O\(_2\)C\(_3\)H\(_7\))\(_4\). Introducing of crosslinking groups are advantageous in order to improve the binding sites. This will reduce washing cleaning cycles as durability of such highly hydrophobic fabrics. This will lead to reduce cost for cleaning and as well as the cost for labor. The binding group can be reacted with cellulose which is available on fabric surface. The application of fluorocarbon finishes on fabrics to impart stain repellency has shown considerable growth during last decade. However, the use of fluorocarbon on fabric is also a major environmental concern as there are many adverse effects of it on environment. There are plenty of evidences concerning possible persistence, bioaccumulation, and/or toxicity of these types of fluorocarbon chemicals in the environment.

In contrast to the extensive studies on fabricating superhydrophobic cellulose fabrics, only very few research mentioned about the performance of repellent property even after cleaning. Polycarboxylic acids (PA) are one of the multi-functional organic molecules with chemical and thermal stability. It could make ester linkage with hydroxyl groups of cellulose at an elevated temperature on fabric. It is known that carboxylic acids could be esterified with cellulose –OH, and also could co-condense with Ti-OH groups in the nano sol solution which leads to the formation of interfacial ester bonds.

In this method non-toxic 1,2,3,4, butane tetracarboxylic acid (BTCA) was used to bind both Ti-OH and cellulose –OH to offer an alternative approach in improving durability of hydrophobicity in fabric finished by sol-gel method (Scheme 1). To lower the surface energy further stearic acid was also used as it has 18-carbon chain. Stain repellency of the modified aircraft fabric was evaluated by static water contact angle measurement. The objective of this study was to modify cotton fabric with superhydrophobic properties which provide protection for the fabric upon spillage of variety of beverages. In addition, introduction of superhydrophobic fabric in cotton fabric will lead to provide self-cleaning property which save huge amount of cost for regular cleaning and also the cost to purchase new fabrics.

**Methodology**

A piece of fabric was considered as a control sample and other three fabrics were treated with the binder as explained in section 2.2. After the treatment with the binder only two fabric pieces were treated with TiO2 sol as discussed in section 2.3. The left behind fabric piece was characterized to verify the formation of esteric bonds. After treating with TiO2 sol, only one fabric piece was further modified with stearic acid in order to further improve the hydrophobicity as explained in section 2.4. All the experiments were repeated twice.

**Materials**

Four fabric pieces which are being used as cotton fabrics having the dimensions of 5cm × 5cm were used for the experiments. These fabrics were obtained after scouring and bleaching process. These fabrics had 1 × 1 rib structure with a weight of 196 g/m². Titanium isopropoxide (AR grade purity > 99.9%, from Sigma-Aldrich Co, USA), ethanol (AR grade purity > 99.9% from Heyman UK), acetic acid (AR grade purity > 99.7% from Sigma-Aldrich Co, USA), 1,2,3,4-butanetetra carboxylic acid (BTCA) (1% w/w) (assay 99%, Sigma Aldrich Co, USA), sodium.
hypophosphite monohydrate (NaH$_2$PO$_2$) (0.6% w/w) (Sigma Aldrich Co, USA), stearic acid ( Sigma-Aldrich Co, Germany), and acetone (AR grade purity $>99.5\%$, Sigma-Aldrich Co, USA) were used without further purification. Deionized water was used for all the experiments.

**Esterification of cellulose fabric with BTCA as the binder**

Two cotton fabric pieces were immersed in aqueous solution of 1,2,3,4-butane tetra carboxylic acid (BTCA) (1%, w/w) with NaH$_2$PO$_2$ as catalyst (0.6%, w/w) for 10 min at room temperature and then padded with a wet pickup of 70%-80%. The sample was dried at 80°C for 5 min in an oven followed by curing at 170°C for 2 min in an oven.

**Preparation and grafting of TiO$_2$ sol**

Titanium-IV tetraisopropoxide Ti(O-iPr)$_4$ (TIP), ethanol, and acetic acid were maintained in a molar ratio of 1:100:0.05 respectively. Ti(O-iPr)$_4$ was hydrolyzed using acetic acid at room temperature. To the prepared solution, the required amount of ethanol was added drop by drop under vigorous stirring for 2 h and the stirring was continued until a clear solution of TiO$_2$ nano-crystals were formed.$^{26,27}$ BTCA treated two fabric pieces were washed once using water to remove excess BTCA followed by immersed in the TiO$_2$ sol solution for 10 min and then padded with a wet pickup of 70%-80%. The samples were dried at 90°C for 3 min and cured at 120°C for 1 h.$^{24}$ TiO$_2$ sol was coated on the remaining fabric piece to compare the hydrophobic property with the fabric which were treated by both BTCA and TiO$_2$ sol.

**Surface energy lowering of the treated fabric with stearic acid**

To lower the surface energy of the fabric, stearic acid was used individually. One of the fabric pieces which was treated by BTCA and TiO$_2$ sol was immersed in a stearic
acid (0.5%, w/w) solution of acetone for 10 min, then padded, and cured at 110°C for 1 h.28

**Characterization**

*Characterization for the synthesized TiO$_2$ sol.* The nano particles were characterized using the following technique:

Particle Size Analyzer (PSA) – Particle sizes of the titania sols prepared were measured using three samples with the particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd, UK).

*Characterization for untreated and treated cotton fabrics.* Fourier Transform Spectroscopy (FTIR) – An untreated and treated cotton fabrics were analyzed using a FTIR (Vertex model 80, Bruker). The diffuse reflectance mode was used and the transmittance spectra were recorded over the range 4000–600 cm$^{-1}$. The resolution was 4 cm$^{-1}$ and the number of scans was 64 for each spectrum.

Scanning Electron Microscopy (SEM) – A small piece of untreated and treated cotton fabrics before and after 25 washes were viewed at high magnification using SEM (Hitachi SU 6600, Japan). Applied voltage was 5.0 kV and used secondary electron mode for the analysis.

Atomic Force Microscopy (AFM) – An untreated and treated cotton fabrics before and after 25 washes were characterized using Atomic Force Microscope (AFM), Park system. Images were obtained using an XE-100 microscope. The measurements were taken in air at room temperature using non-contact mode, with Si tips of the 1650-00 type scanning at frequencies 0.5 Hz.

*Evaluation of hydrophobicity for the modified cotton fabric.* The wettability of fabric samples is mostly characterized by static water contact angle (θ) with the fabric. At room temperature, a 10 µl droplet of deionized water was placed in to five different positions on the modified cotton fabric surface using a micro pipette. The polynomial line fitted on the water bubble and tangent line plotted at the intersection point to calculate the static water contact angle (θ) as shown in Figure 1. The average static contact angle value was calculated based on the average of five measurements.

*Evaluation of retainability of hydrophobicity during washing in the modified cotton fabric.* The modified cotton fabric pieces were washed separately under standard laundering conditions.29 The samples were cut in to a specific size (4 inch × 4 inch) and put into a beaker. Four hundred milliliters of distilled water was added with 2 g of detergent into the beaker. The samples were subjected to stirring at 40°C for 30 min. Each test specimen was rinsed three times in beaker using water for 1 min by hand squeezing. The specimens were dried in an oven at 70°C and then fabrics were conditioned at standard humidity and temperature for at least 1 h before the evaluation of properties. Washing was done 25 times for each fabric piece as per the standards for cotton fabric materials.30

**Results and discussion**

*Characterization of TiO$_2$ sol*  

The TiO$_2$ nano sol particle size distributions have been determined using three samples from the particle size analyzer. The Z-average values of the samples are found to be 0.3444 and 33.43 nm respectively as shown in Figure 2.

*Characterization of untreated and treated cotton fabrics*  

The structure of untreated cotton fabric (control) and treated cotton fabrics were confirmed by FTIR analysis. The FTIR analysis was done for the fabric after treating with BTCA. BTCA treated fabric was washed once in order to remove excess BTCA, which were deposited on fabric. The carboxylic groups in BTCA and the hydroxyl groups of the fabric surface results in ester bonds. The free carboxylic acid groups available in BTCA, attached with TiO$_2$ sol after treating with TiO$_2$ sol. The untreated cotton fabric was compared with modified cotton fabric.
The transmittance spectrum (Figure 3(a)) of untreated fabric exhibit O-H stretching at around 3434 cm\(^{-1}\). After modification with BTCA according to Figure 3(b), the transmittance spectrum exhibit O-H stretching absorption at around 3412 cm\(^{-1}\) and C-H stretching vibration at 2903 cm\(^{-1}\).

The method of determination of ester binded fabric, employing infrared spectroscopy FTIR, was developed by Yang.\(^{31}\) Carbonyl groups on cotton fabric treated with polycarboxylic acids are retained in three forms: ester, carboxyl acid, and carboxylate anion. If the polycarboxylic acid contains three or more carboxyl groups all the three forms could be appear in a single molecule.\(^{32}\) The ester carbonyl and carboxyl carbonyl bands overlap in the spectra of the BTCA treated fabric and the both peaks occurs in the range between 1690 and 1760 cm\(^{-1}\). In Figure 3(b), band at 1719 cm\(^{-1}\) represent both ester carbonyl and carboxyl carbonyl bands. The standard procedure is to treat the cotton fabric with 0.1 M NaOH solution, to convert all the free carboxyl groups in the fabric to carboxylate.\(^{33}\) After treating with 0.1 M NaOH as shown in Figure 3(c), the band at 1718 cm\(^{-1}\) represents the carbonyl of ester, while the band at 1576 cm\(^{-1}\) represents the carbonyl of carboxylate, the basic form of the free carboxylic acid. According to the literature, after treating with 0.1 M NaOH two carbonyl bands at 1725 and 1552 cm\(^{-1}\) appear in the spectrum.

According to the Figure 3(c), 0.1 M NaOH treated cotton fabric shows a band at 1576 cm\(^{-1}\) which represents the carbonyl of carboxylate which is basic form of the free carboxylic acid available in the coated BTCA of the fabric. The fabric which was treated by 0.1 M NaOH again retreated with 1 M HCl, the carbonyl of carboxylate groups converted to carboxylic acid groups and the peak at 1576 cm\(^{-1}\) disappear and only the peak at 1733 cm\(^{-1}\) appears as shown in Figure 3(d).

Scheme 1 illustrates the estimated chemical binding mechanism of modified cotton fabric which was drawn by ChemDraw software version 15. Even though TiO\(_2\) sol bind to BTCA as shown in Scheme 1, there is no band can be clearly associated to the Ti-OH group in FTIR spectra.\(^{38}\)

As illustrates in Scheme 1, untreated aircraft upholstery cotton fabric contains O-H bonds which has bonding capability with BTCA,\(^{39}\) in the presence of NaH\(_2\)PO\(_2\) as shown in step 1. In step 2, nano sol solution of TiO\(_2\) was introduced and it was reacted with OH groups in the carboxyl acid,\(^{40}\) which substitute by BTCA to the cotton fabric. In step 3, stearic acid was dissolved in acetone and it was allowed to react with the product from step 2, which consist with untreated OH groups available in TiO\(_2\) sol solution.\(^{41}\) As stearic acid consists with many hydrocarbon groups it assists to improve the hydrophobicity of the cotton fabric, which indicates as the end product of step 3 in the Scheme 1.

**Surface wettability of treated and untreated cotton fabric**

Surface wettability was examined by measuring the static contact angle. The untreated fabric absorbs water droplets quickly (within approximately 2s) due to hydrophilicity and the capillary effect of the fabric. Therefore, the untreated fabric completely wetted with water, which is common and well known for cotton fabric.\(^{28}\) The fabric treated only with TiO\(_2\) sol showed poor water repellency, while the cotton fabric treated with BTCA, TiO\(_2\) sol, and stearic acid showed super hydrophobicity even for 25 washes. Five measurements were taken for each fabric and average value was determined for static contact angle.

According to the data shown in Table 1, BTCA, TiO\(_2\) sol, and stearic acid coated fabric showed highest static contact angle without washing and even after 25 washes this modified fabric showed highest static contact angle. Untreated fabric and only BTCA coated fabric showed hydrophilicity all the time, while only stearic acid and only TiO\(_2\) sol treated fabrics showed hydrophobicity without washing and completely hydrophilicity after 25 washes. This may be due to wash off of coated TiO\(_2\) sol and stearic acid. In the system having both BTCA and TiO\(_2\) sol showed hydrophobicity without washing and even after 25 washes hydrophobicity was observed. In the presence of BTCA binder TiO\(_2\) sol cotton fabric showed super hydrophobicity even after 25 washes.
Effect of BTCA and stearic acid on washing durability of cotton fabric

It is clearly seen from the results that the static water contact angles were significantly discrepancies of hydrophobicity between the ester-bridged fabric and TiO\(_2\) sol treated fabric. Free carboxylic acid groups on BTCA and stearic acid were proposed to have strengthened the stability of TiO\(_2\) sol coating, and ultimately the durability of the hydrophobicity provided by esterification. 1,2,3,4-Butane tetracarboxylic acid (BTCA) attracted most attention for washing durability. BTCA and stearic acid treated fabric particularly exhibited a high static contact angle of 161° with the recovery of 97.5% even after washing, presenting quite promising durability. Further, it is clear that when there are more interaction sites on the surface in TiO\(_2\) sol treated cotton fabric, the more carboxylic acid groups in polycarboxylic acid molecules can be blinded. Therefore, when there are more interaction sites it is more difficult to break the ester-bridge on the surface of the modified fabric which helps to withstand for better laundering ability.

Morphology of untreated and treated cotton fabrics

Typical longitudinal fibril structure with natural veins, which was clearly observed on untreated fabric (Figure 4(a)), disappeared after coated with TiO\(_2\) sol as shown in Figure 4(b). The vanished characteristic parallel ridges and grooves could be due to the weakly cross-linked condensation layer formed by TiO\(_2\) sol hydrolyzed under acidic conditions.\(^{42}\) Also, there is no depositions could observe in Figure 4(b), which showed the absence of formation of TiO\(_2\) nano particles. After 25 washes a cluster of broken fragments could be clearly observed on fibers (Figure 4(c)), which implied that the TiO\(_2\) sol coating was cracked after washing as there was no BTCA binder. As seen from Figure 4(c), the thickness of the TiO\(_2\) sol coating is approximately 1 µm.
In the BTCA, TiO$_2$ sol and stearic acid treated fabric showed no depositions on the cotton fabric surface after 25 washes as shown in Figure 4(e), while there were several depositions observed on the fabric surface before washing as shown in Figure 4(d).

Nevertheless, the SEM cannot provide clear explanation about why the BTCA, TiO$_2$ sol, and stearic acid treated fabric is stable upon water interactions. AFM analysis were conducted to the fabric samples to correlate the super hydrophobic behavior of the fabric samples with the surface roughness. Similar study was found in the literature, as well.

AFM analysis were conducted to the fabric samples to correlate the super hydrophobic behavior of the fabric samples with the surface roughness. Similar study was found in the literature, as well.

According to the 3D image shown in Figure 5(a), riggers were clearly visible in untreated cotton fabric, where as in Figure 5(b) shown depositions of TiO$_2$ sol and stearic acid which were responsible for hydrophobicity. The Figure 5(c) shows after 25 washes the degree of depositions were reduced but still deposition could be observed on the surface of the fabric. This leads to give further, hydrophobicity on the cotton fabric by reducing surface energy.

Based on the AFM results shown in Figure 5, it can be observed that the surface porosity is also improved in the wetting properties of the surface.

**Evaluate the stain repellency of the modified cotton fabric**

Generally, tea, coffee, and water can be identified as main water based drinks found in aircraft during a flight. Hence, aircraft upholstery is highly vulnerable for tea, coffee, and water stains. Figure 6, illustrates tea, coffee, and water liquid drops setting on the modified cotton fabric after 25 washes. Further as per literature, there are evidences that cotton has been used in aircraft applications.

A tea bag contained 5.00 g of powdered tea was added to 5 ml of boiled hot water in a beaker. Five gram of coffee powder was also added to a separate beaker consist of 5 ml...
of boiled hot water. In addition, 5 ml of boiled hot water was added to another beaker as a control solution. All the solutions were allowed to cool and when the temperature reached to the room temperature, all the solutions were filtered. Ten microliter of droplet from each solution was placed on three modified cotton fabric having the dimension of 10 cm × 10 cm using a micro pipette. Five droplets were placed at a time from the same solution on a modified cotton fabric piece. The rest two fabrics were also added with the five droplets from each solution respectively. Static water contact angles were measured and calculate the average static water angle for each solution. The results are given in Table 2.

As shown in Figure 6 and based on the average static water contact angle values given in Table 2, it is evident that the modified cotton fabric after 25 washes showed hydrophobicity for tea, coffee, and water which are vulnerable stain types in an aircraft upholstery. The stability of hydrophobicity can be confirmed as this experiment was carried out 25 washes.

### Conclusions

In this work, BTCA was used as the binder to improve the washing durability of cotton fabric which was achieved hydrophobicity by sol-gel technology combining TiO₂ sol and stearic acid. The results showed that the BTCA binder and stearic acid treated cotton fabric could effectively improve the washing durability of cotton fabric, while TiO₂ sol only and stearic acid only coated cotton fabrics showed weak hydrophobicity without washing and complete hydrophilicity after 25 washes. Untreated cotton and only BTCA coated cotton fabrics showed no hydrophobicity at all. The BTCA and TiO₂ sol coated cotton fabric showed hydrophobicity without washing and hydrophilicity after 25 washes. The BTCA, TiO₂ sol and stearic acid treated cotton fabric was durable for laundering at a recovery percentage of static contact angle of 97.5%. This study demonstrated that the surface treatment using BTCA and stearic acid to TiO₂ sol is a promising alternative for achieving durable hydrophobic in cotton fabrics. The stability of hydrophobicity in the modified cotton fabric after 25 washes was also tested with tea, coffee, and water solutions which are vulnerable stain types in aircraft upholstery. It clearly proved that the modified cotton fabric even after 25 washes showed hydrophobicity for tea, coffee, and water. Therefore, it can be concluded the developed modified cotton fabric can consider to be used as an aircraft upholstery.

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### References

1. Wagner T, Neinhuis C and Barthlott W. Wettability and contaminability of insect wings as a function of their surface sculptures. *Acta Zool* 1996; 77(3): 213–225.
2. Parker AR and Lawrence CR. Water capture by a desert beetle. *Nature* 2001; 414(6859): 33–34.
3. Gao X and Jiang L. Biophysics: water-repellent legs of water striders. *Nature* 2004; 432(7013): 36.
4. Byun D, Hong J, Saputra KO, et al. Wetting characteristics of insect wing surfaces. *J Bionic Eng* 2009; 6(1): 63–70.
5. Koch K, Bhushan B and Barthlott W. Diversity of structure, morphology and wetting of plant surfaces. *Soft Matter* 2008; 4: 1943–1963.
6. Manoharan K and Bhattacharya S. Superhydrophobic surfaces review: functional application. fabrication techniques and limitations. *J Micromanuf* 2019; 2(1): 59–78.
7. Jin M, Xing Q and Chen Z. A review: natural superhydrophobic surfaces and applications. *J Biomater Nanobiotechnol* 2020; 11: 110–149.
8. Picoloa N, Moraesb VT, Lebrãob GW, et al. Sol-gel processed superhydrophobic plastic surfaces modified with perfluorooctyltriethoxysilane (POTS). *Mater Res* 2019; 22(Suppl. 1): e20190488.
9. IATA. IATA forecast predicts 8.2 billion air travelers in 2037. 2018, https://www.iata.org/en/pressroom/pr/2018-10-24-02/(accessed 24 October 2018).
10. Zhang L, Xue C-H, Cao M, et al. Highly transparent fluoroine-free superhydrophobic silica nanotube coatings. *Chem Eng J* 2017; 320: 244–252.
11. Drelich J and Marmur A. Physics and applications of superhydrophobic and superhydrophilic surfaces and coatings. *Surf Innov* 2014; 2(4): 211–227.
12. Rose BR. *Advances in mechanical engineering*. 1st ed. Chennai, India: Springer, 2020, pp.1663–1674.

| Stain type | Average static water contact angle, degree (after 25 washes) |
|------------|---------------------------------------------------------------|
| Tea        | 119 ± 1                                                       |
| Coffee     | 120 ± 1                                                       |
| Water      | 152 ± 1                                                       |
13. Piscitelli F, Chiariello A, Dabkowski D, et al. Superhydrophobic coatings as anti-icing systems for small aircraft. *Aerospace* 2020; 7(1): 2.

14. Moghadam A and Tafreshi HV. On liquid bridge adhesion to fibrous surfaces under normal and shear forces. *Colloids Surf A* 2020; 589: 124473.

15. Esmaeili AR, Mir N and Mohammadi R. A facile, fast, and low-cost method for fabrication of micro/nano-textured superhydrophobic surfaces. *J Colloid Interface Sci* 2020; 573: 317–327.

16. Holme I. Innovative technologies for high performance textiles. *Color Technol* 2007; 123(2): 59–73.

17. Przybylak M, Maciejewski H, Dukiewicz A, et al. Fabrication of superhydrophobic and antibacterial surface on cotton fabric by doped silica-based sols with nanoparticles of copper. *Nanoscale Res Lett* 2011; 6: 594.

18. Prusty A, Gogoi N, Jassal M, et al. Synthesis and characterization of non-fluorinated copolymer emulsion for hydrophobic finishing of cotton textiles. *Indian J Fibre Text Res* 2010; 35: 264–271.

19. Nakamichi H. *Polymeric materials encyclopedia*. In: Salamone JC (ed.). Boca Raton, FL: CRC Press, 1996, p.1536.

20. Jiang WC, Huang Y, Gu GT, et al. A novel waterborne polyurethane containing short fluorooalkyl chains: synthesis, characterization and its application on cotton fabrics surface. *Appl Surf Sci* 2006; 253(4): 2304–2309.

21. Huang W, Xing Y, Yu Y, et al. Enhanced washing durability of hydrophobic coating on cellulose fabric using polycarboxylic acids. *Appl Surf Sci* 2011; 257: 4443–4448.

22. Hernández-Padrón G, Rojas F and Castaño VM. Ordered SiO$_2$-(phenolic-formaldehyde resin) in situ nanocomposites. *Nanotechnology* 2003; 15: 98–103.

23. Daoud WA and Xin HJ. Low temperature sol-gel processed photocatalytic titania coating. *J Sol-Gel Sci Technol* 2004; 29(1): 25–29.

24. Gulrajani ML. Self-cleaning technology in fabric: A review. *Indian J Fibre Text Res* 2006; 31: 187.

25. Xue CH, Jia ST, Chen HZ, et al. Superhydrophobic cotton fabrics prepared by sol–gel coating of TiO$_2$ and surface hydrophobization. *Sci Technol Adv Mater* 2008; 9(3): 035001.

26. Borisova A and Reihmane S. Hydrophobic treatment of blended fabric’s surface. *Mater Sci Tech* 2013; 19(2): 169–173.

27. Airframe handbook, Aircraft fabric covering. Federal Aviation Administration, United States of America, chapter 3, vol. 2. Federal Aviation Administration (FAA).

28. KURUPPU KADD. Chapter 5: Aircraft fabric covering. 2020, https://pdfslide.net/documents/chapter-5-aircraft-fabric-covering.html (accessed 14 May 2020).

29. Xue CH, Jia ST, Chen HZ, et al. Superhydrophobic cotton fabrics prepared by sol–gel coating of TiO$_2$ and surface hydrophobization. *Sci Technol Adv Mater* 2008; 9(3): 035001.

30. Airframe handbook, Aircraft fabric covering. Federal Aviation Administration, United States of America, chap- ter 3, vol. 2. Federal Aviation Administration (FAA).

31. Yang CQ. FTIR spectroscopy study of the Ester crosslinking mechanism of cotton cellulose. *Text Res J* 1991; 61(8): 433–440.

32. Vukusic SB and Katovic D. Crease proof finishing using phosphono-based catalyst with polycarboxylic acids. *Colourage Annua* 2000; 47: 87–94.

33. Yang CQ. Effect of pH on nonformaldehyde durable press finishing of cotton fabric: FTIR spectroscopy study, Part II: formation of the anhydride intermediate. *Text Res J* 1993; 63(12): 706–711.

34. Choi H-M, Welch CM and Morris NM. Nonphosphorus catalysts for formaldehyde-free DP finishing of cotton with 1,2,3,4-butanetetracarboxylic acid. Part II: sodium salts of fumaric, maleic, and itaconic acids. *Text Res J* 1994; 64(9): 501–507.

35. Vincena B. Durable press finishing of cotton with polycarboxylic acid. *Fibres Text East Eur* 1996; 4: 69–71.

36. Vukusic SB, Katovic D and Soljacic I. Polycarboxylic acid in crease-proof finishing. *Tekstil* 1999; 48(11): 549–561.

37. Soljacic I and Katovic D. Durable press finishing of cellu-lose materials and formaldehyde problems. *Tekstil* 1992; 41(11): 545–555.

38. Vasconcelos DCL, Costa VC, Nunes EHM, et al. Infrared spectroscopy of titania sol-gel coatings on 316L stainless steel. *Mater Sci Appl* 2011; 2: 1375–1382.

39. Šauperl O, Stana-Kleinschek K and Ribitsch V. Cotton cellulose 1, 2, 3, 4 buthanetetracarboxylic acid (BTCA) crosslinking monitored by some physical–chemical methods. *Text Res J* 2009; 79(9): 780–791.

40. Qu Q, Geng H, Peng R, et al. Chemically binding carboxylic acids onto TiO$_2$ nanoparticles with adjustable coverage by solvothermal strategy. *Langmuir* 2010; 26(12): 9539–9546.

41. Sharifvaghefi S and Zheng Y. Deoxygenation of stearic acid with a novel Ni(CO)-MoS$_2$/Fe$_3$S$_4$ catalyst. *Can J Chem Eng* 2018; 96: 231–240.

42. Claessens HA, van Straten MA and Kirkland JJ. Effect of buffers on silica-based column stability in reversed-phase high-performance liquid chromatography. *Chromatogr A* 1996; 728: 259–270.

43. Esmaryan KD, Castano CE, Bressler AH, et al. Rapid synthesis of inherently robust and stable superhydrophobic carbon soot coatings. *Appl Surf Sci* 2016; 369: 341–347.

44. Federal Aviation Administration. Chapter 3: Aircraft fabric covering. 2012, https://www.kingaeroaviation.com/ama_Ch03.pdf (accessed 14 May 2020).

45. Federal Aviation Administration. Chapter 5: Aircraft fabric covering. 2012, https://pdfslide.net/documents/chapter-5-aircraft-fabric-covering.html (accessed 14 May 2020).