



Research article

Surface modification and improvements of wicking properties and dyeability of grey jute-cotton blended fabrics using low-pressure glow discharge air plasma



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HIGHLIGHTS

- The wicking properties and dyeability of the jute-cotton blended (40:60) fabrics were studied.
- 50% reduction of contact angle was observed after a plasma treatment time of 20 min.
- The presence of –OH, C–O, and COO[−] functional groups on the surface of jute blended cotton fabrics was seen.
- The absorption to scattered ratio, *K/S* of the fabrics was increased with the increase in plasma treated times.
- The dyeability and wettability of the fabric enhanced with the treatment times of LPGD air plasma.

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ABSTRACT

Herein, we reported the improvements of wicking properties and dyeability of the jute-cotton blended (40:60) fabrics due to the effect of low-pressure glow discharge (LPGD) air plasma under selected exposure times. The microscopic features, functional groups, wettability, contact angles, wetting area, wicking rates, and reflectance values of the jute-cotton blended fabrics were analyzed using numerous experimental techniques. The scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) techniques were used to investigate the morphological and compositional modifications of plasma-treated jute blended cotton fabrics. The compositional analysis confirmed various functional groups such as –OH, C–O, and COO[−] on the surface of jute blended cotton fabrics. The average pore radii and diffusion coefficient were calculated by using the modified Lucas-Washburn equation. The plasma-treated fabrics were shown to have an average pore radius of 0.93, 1.46, 2.26, and 4.8 μm under treatment time of 5, 10, 15, and 20 min. Nearly 50% reduction of contact angle was observed after a plasma treatment time of 20 min. The absorption to scattered ratio, *K/S* (determined using Kubel-Munk model) of the colored fabrics with 5 min pre-treated plasma was 6.47, although it was raised up to 8.51 after 20 min of pre-treatment. A reactive dye, Bezaktiv Red S–3B, was used for the dyeability test, and our findings showed that the dyeability and the wettability of the fabric were substantially enhanced with the treatment time of LPGD air plasma. Among the samples, only 10 min plasma pre-treated colored fabric exhibited a color difference of less than one compared to the standard one.

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1. Introduction

The worldwide natural fiber market is flourishing with the persistently expanding requests of customers. Synthetic content fibers have been phased out for people's awareness of the environmental issues in favor of natural fiber fabrics. Natural fiber is still an undiscovered segment where there is a comprehensive market with evident requests. Jute (also known as golden fiber) is the most available natural fiber (*Corchorus capsularis*) obtained from the white jute plant's bark that ranks second in terms of global production, has drawn constant hostility on account of its industrial applications [1]. Industrial activities of jute fiber shift to more competitive, environmentally friendly development with significant advances in science and innovation. Jute is a cellulosic fiber that is partially/fully reusable, renewable, degradable, inexpensive, and sustainable with low thermal conductivity, good tensile strength, sound, and heat insulation [2, 3, 4, 5, 6, 7, 8]. It is a lignocellulosic fiber composed of three different chemical compounds such as cellulose (58–65%), hemicellulose (20–24%), and lignin (12–15%). Jute also contains some other insignificant components such as protein (0.8–1.5%), pectin, and aqueous extracts [9]. Due to its numerous and flexible properties, cellulosic fiber makes jute unique from other natural fibers. Jutes have risen with mighty highlights and value alternatives to traditional materials for various uses in various sectors *i.e.*, ropes, window ornaments, carpets, packaging bags, and so on [10]. The most significant amount of raw jute is cultivated in Bangladesh, which is around 30% of the world's jute production, and right now leads the world by aching the second rank [11]. The geological outline of Bangladesh appearing in the areas from which foreign exchange earnings are depicted in Figure 1 [12]. The red color zone in Figure 1(b) shows the widespread jute cultivation districts in Bangladesh.

Traditionally it is not used in apparel textile products as it has some shortcomings like coarseness, stiffness, and washes ability [13]. Right now, conventional jute products have declined their export earnings. So, it is necessary to find diversified jute products with high value to drive economic growth, supporting millions of people who engage with this sector. Primarily used natural fiber cotton contains a high percentage of cellulose and lowers lignin compared to jute, making the jute fiber stronger than cotton [14]. Cotton may be a possible solution in mixing composites instead of other rural plant fibers that upgrade the moisture content, swelling, size, and shape for post-thermal provision [15]. It has the opportunity to be utilized as an appropriate reassurance for creating inexpensive composites [16, 17, 18, 19].

To fabricate the diversified jute products, it can be blended with other fibers such as cotton, wool, polyester, etc., in different ratios to improve its inherent properties. Combining jute and cotton yarns to several ratios of 30:70, 40:60, and 50:50 are designed by other researchers with a very distinctive approach [20, 21, 22]. To confirm its acceptance as a diversified product and gain its manufacturers' confidence and raise its commercial value, some significant criteria like physical and thermo-physiological comfort, dyeability, wettability, etc., are also needed to satisfy the product's outer bright appearance. Wetting and wicking are two essential properties of textile and have a significant role in dyeing. The surface wetting properties of a textile material can be modified by changing its chemical composition [23]. Usually, wet-chemical processes have been used in textile industries to alter the surface properties of textile substrates. All these processes consume various hazardous chemicals, and the release of untreated industrial effluents along the river banks is one of the primary reasons for water pollution. Despite the considerable economic contribution, the textile industry has become one of the leading polluting industries in

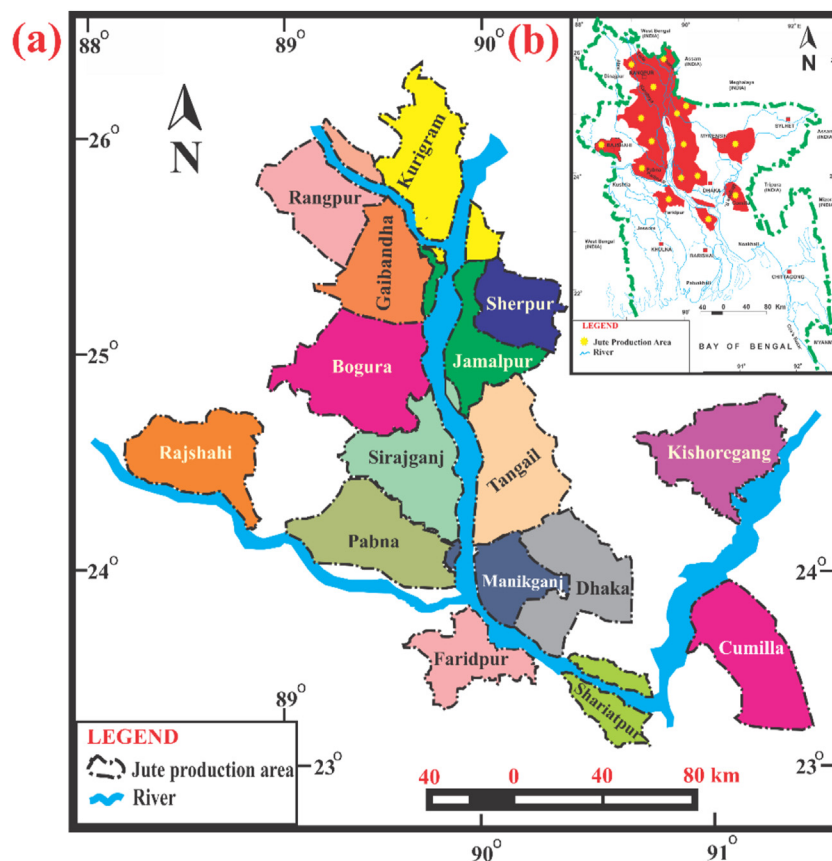


Figure 1. (a) The locations of foreign exchange earnings district by the jute fiber in Bangladesh and shortly symbolize them inset (b) with red color in the geographical map of Bangladesh.

Bangladesh [24,25]. It is projected that in 2016 around 217 million m³ of wastewater comprising a wide variety of chemicals generated from textile industries in Bangladesh. It is also anticipated that if they remain using the traditional dyeing process, these wastewaters will reach 349 million m³ by 2021 [26]. Considering human health and environmental safety issues, the researcher must practice great efforts to design and develop eco-friendly processes compared to the conventional chemical methods over the past few years [27]. Low-temperature plasma treatment can be applied as a green alternative to hazardous textile wet techniques while minimizing water, energy, and chemical consumption [28, 29, 30, 31]. It modifies the uppermost atomic layers (a few nanometers) of the surface and leaves the bulk properties unchanged [32]. Low-temperature plasma treatment has been used to change the surface properties of different fibers and fabrics [33, 34, 35, 36, 37, 38, 39, 40, 41]. As energy is applied to a gaseous medium by an electric discharge, the gas transforms into the fourth state of matter known as plasma. The energy of the surface is altered by hitting the nozzles according to the principle of plasma treatment. Different plasma treatment atmospheres have a more significant impact on the hydrophobicity of the fabric, such as O₂, N₂, He, etc., under the confining area.

The wicking behavior and the wettability improvements using the atmospheric plasma are prevalent in the literature [42, 43, 44, 45]. In contrast, the dyeability for the atmospheric pressure glow discharge plasma to modify different fabrics' surface properties is also seen [46]. According to these reports, several functional groups such as -OH, -NH, and -COOH are involved on the surface of fabrics due to the plasma treatment procedure. Other researchers reported that dyeability, the color intensity of fabrics was enhanced by non-thermal and dielectric barrier discharge air plasma, and they were increased with treatment time [47,48]. It was also found that plasma-treated silk fabrics exhibited better wicking properties than untreated ones even after 500 days [48]. Low-temperature plasma is also used to improve printability, flame resistance, adhesive bonding, thermal comfort, antibacterial activity, and soil resistance [49, 50, 51, 52, 53]. Although different kinds of plasma treatment were applied to study surface properties of several natural and synthetic fibers, no one focused on jute-cotton blended fabric. In this research, low-pressure glow discharge air plasma is used to introduce a suitable eco-friendly option to improve the wicking properties and dyeability of grey jute-cotton blended fabrics (grey state), bringing this research's essential novelty.

This paper introduces the surface morphology and compositional analysis of the jute-cotton blended fabrics and their microscopic features after plasma treatment using SEM imaging and Fourier transform infrared (FTIR) spectroscopic techniques. The fabrics' surface wettability improvements were examined by measuring contact angle, wicking rate, average pore radius, and diffusion coefficients. A dynamic approach was adopted to compute the average pore radius, and diffusion coefficients of the fabrics understudied. Plasma-treated fabrics were dyed with a reactive dye, Bezaktiv Red S-3B (2%), and pretreatment on the color intensity and color difference was also investigated using a spectrophotometer.

2. Materials and methods

2.1. Materials

In this experiment, the specimen grey jute blended cotton (40:60) fabric was provided by Bangladesh Jute Research Institute, Dhaka. The specifications of these samples are shown in Table 1. All samples were circular and had a diameter of 8 cm and 235 gm⁻². The warp and weft-wise tensile strength of the sample were 763.46 Nm⁻² and 247.90 Nm⁻², respectively. A reactive dye, Bezaktiv Red S-3B, obtained from Benzema (Germany) was used. Bezaktiv Red S-3B is one of the common commercial reactive dyes used for dyeing cotton fabric. Dyeing was performed in a laboratory dyeing machine (Eco Dyer, Xiamen Rapid Co. Ltd, China).

Table 1. Sample specifications.

| Sample | Wave design | Yarn count (Ne) | Threads per inch | Weight (g/m ²) |
|---------------------|-------------|-----------------|------------------|----------------------------|
| Jute:Cotton (40:60) | 1/1 Twill | Warp | 18/ | Warp 48 |
| | | Weft | 2 | Weft 28 |
| | | | 9 | |

2.2. Low-pressure glow discharge (LPGD) air plasma system

The schematic diagram of the low-pressure glow discharge (LPGD) air plasma system is shown in Figure 2. Plasma treatment was carried out on grey jute blended cotton (40:60) fabrics in an alternating current (AC) glow discharge plasma chamber in a capacitively coupled mode. A cylindrical pyrex glass bell-jar having 15 cm inner diameter and 18 cm length was used in a plasma chamber. Two circular plates of diameter 9 cm and thickness of 1 cm were used as electrodes, and the distance between them was 4 cm. The specimens were placed on the lower electrode during the plasma treatment procedures. A rotary pump was used to control the pressure inside the plasma chamber. The chamber was evacuated by the rotary pump after the fabric sample was placed. Plasma treatments were performed under selected time intervals of 5, 10, 15, and 20 min with 0.2 mbar pressure and a power level of 120 W.

2.3. Characterization of samples after plasma treatment

Scanning electron microscopy (using an SEM machine model No. EV018, Carl Zeiss AG, Germany) was employed to investigate the change of the plasma-treated samples' surface morphology. Attenuated total reflection Fourier transform infrared (ATR-FTIR) spectroscopy of the untreated and plasma-treated jute blended cotton fabrics were performed using a SHIMADZU FTIR-8900 spectrometer. For each fabric sample, 45 scans were executed to collect the ATR-FTIR data within a range of 800–4000 cm⁻¹. The acquired data were normalized using Origin (version 9.5) graphical analyzing software.

A water drop of 10μL was deposited on the surface of each fabric sample at a distance of 0.5 cm. An image of each drop was taken instantaneously utilizing a canon camera (model: EOS 600D) and measured contact angle with the help of photoshop. AATCC/ASTM test method was conducted to measure the water absorbency (drops of 100 μL) of the fabrics. The water absorbency of samples was determined by measuring the time taken to wholly absorbed into the fabric. The drop

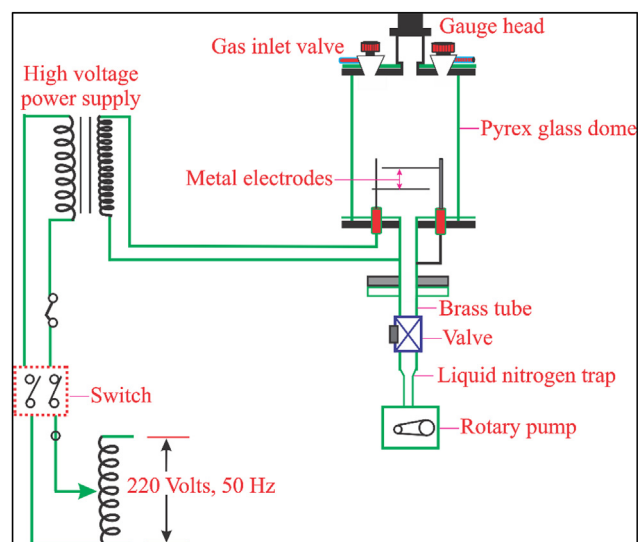


Figure 2. Schematic diagram of the low-pressure glow discharge air plasma system.

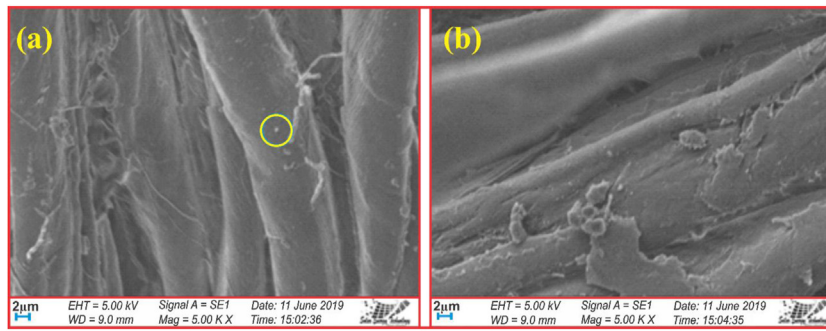


Figure 3. SEM images of jute blended cotton fabric: (a) Untreated, and (b) 15 min treated.

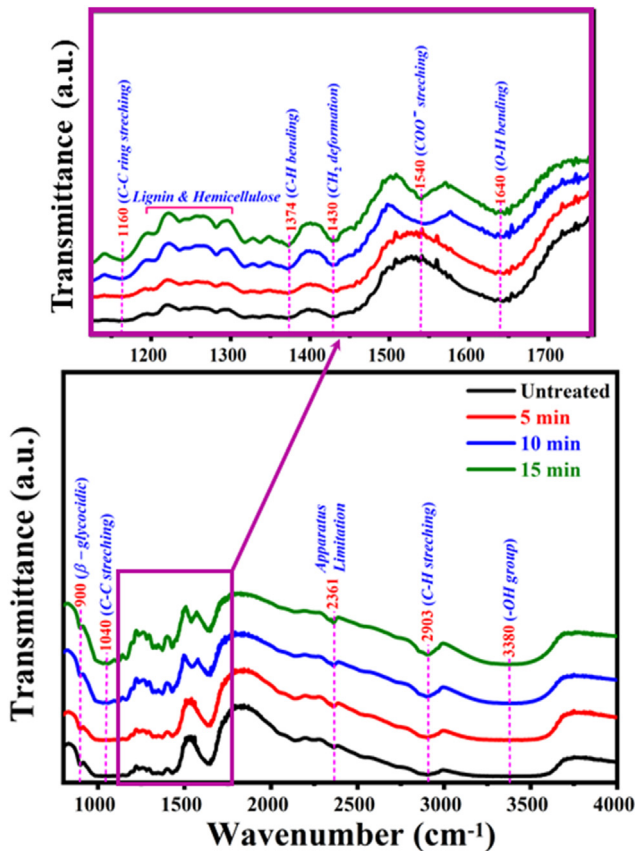


Figure 4. Normalized ATR-FTIR spectra of untreated; and 5 min, 10 min, and 15 min plasma treated fabrics in the wavenumber of 500 cm⁻¹ to 4000 cm⁻¹ region (inset rectangular box shows a magnified portion of the ATR-FTIR spectra in the wavenumber range of 1120 cm⁻¹ to 1760 cm⁻¹).

test method was used to measure the wettability of fabric samples. In this study, modified AATCC test method 79–2014 was used to measure the fabric sample's wetting area (diameter 8 cm) [54]. A drop of direct dye solution (100 µL) was deposited on the sample surface top of the plastic film to avoid the absorption of dye solution by the other substances. The surface of a sample was considered as non-wetting if it failed to wet entirely within 10 min. A fabric strip (1 cm × 8 cm) with a 5 cm marking scale was suspended vertically by using a stand. The lower edge of the sample was just immersed on the colored distilled water surface. The time needed for water to reach each desired height by capillary force was recorded by using a stopwatch. It was not possible to measure the wicking rate of untreated fabric samples due to the poor wettability. In this experiment, the warp wicking rate was examined. Although plasma treatment time on both warp and weft wicking rate has a similar shapeless wicking effect is examined in weft compared to

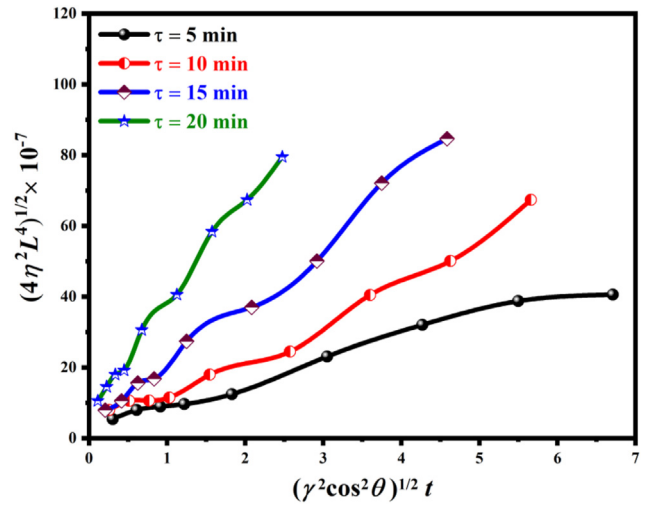


Figure 5. Effect of treatment time on the effective pore radius of jute-cotton blended fabrics.

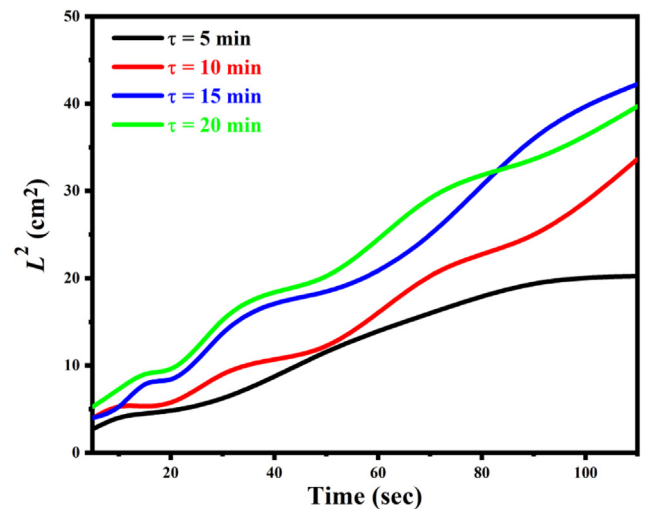


Figure 6. Plot for the determination of diffusion coefficient with respect to the plasma treatment times.

warp direction. This is because, in a woven fabric, weft yarns are covered by warp yarns. As a result, the plasma effect is more negligible for weft yarns, and the wicking rate is slightly low in the weft direction [45]. The average pore radius (R), and diffusion coefficient (D_c) of the plasma-treated fabrics were calculated using the modified Lucas-Washburn Eq. (1),

Table 2. Effect of the plasma exposure time on the average pore radius and diffusion coefficient of grey jute-cotton blended fabric.

| Treatment time (min) | Average pore radius (μm) | Diffusion coefficient (cm^2/s) |
|----------------------|---------------------------------------|--|
| 5 | 0.93 | 0.283 |
| 10 | 1.46 | 0.376 |
| 15 | 2.26 | 0.471 |
| 20 | 4.8 | 0.547 |

$$L^2 = \frac{R\gamma\cos\theta}{2\eta} \quad (1)$$

where R represents the size of capillary pore radius, L is the height reached by the liquid at a time, t . Here θ represents the contact angle. η and γ are the viscosity and surface tension of the liquid, respectively. Besides, the diffusion coefficient of the fabric at different plasma treatment times was estimated from Eq. (2).

$$L^2 = (D_c)t \quad (2)$$

where $D_c = \frac{R\gamma\cos\theta}{2\eta}$ is the diffusion coefficient.

2.4. Conventional pre-treatment, dyeing, color intensity, and color difference measurement

In conventional pretreatment process (scoured and bleached), required amount of NaOH (3 g/L), H_2O_2 (4 g/L), wetting agent (1 g/L), leveling agent (1 g/L), anti-creasing agent (1 g/L), and sequestering agent (1 g/L) were mixed with water on the dye bath. Then the grey jute-cotton blended fabric is immersed into the solution for 60 min. The temperature of about 100 °C and pH level of 10–11 is maintained throughout the process. Then the samples were washed and dried. Pre-treatment of fabric was followed by dyeing. Conventionally pre-treated and plasma pre-treated jute-cotton blended fabrics were immersed into a dye bath containing a reactive dye, Bezaktiv Red S–3B (2%), salt (40 g/L), leveling agent (1 g/L), and water. Soda ash (18 g/L) was added after the samples were dyed for 20 min at 60 °C and continued for 30 min. Then the samples were washed and dried at 70 °C temperature in an oven. The color intensity and color difference of the plasma pre-treated colored fabrics were evaluated by a spectrophotometer (X-rite Color iMatch, Version 9.4.10, USA) over a 400–750 nm wavelength range. The shade of the dyed fabric samples was compared under D65, A, and F02 light sources. The three-color coordinates of CIELAB (International commission on illumination) represent the color as three values. To find out the values of DL^* (difference in lightness/darkness), D_a^* (difference on Red-Green axis), and D_b^* (difference on Yellow-Blue axis) and to study the total color difference (DE), between standard (scoured and bleached prior dyeing) and batch samples (plasma treated prior dyeing) a spectrophotometer was used. The value of DL^* represents the lightness/darkness difference between the given sample and the standard one. A positive value of DL^* indicates the sample is lighter than the standard and a negative value of DL^* represents the darkness of the dyed fabrics. The yellowness of the plasma pre-treated fabrics after dyeing was measured from the values of Yellow-Blue axis of the CIELAB color space. A Negative value of D_b^* indicates bluish, while a positive value points out yellowness compare to the standard sample. The spectrophotometer evaluated the dyeability of LPGD air plasma modified jute-cotton blended fabric by calculating color intensity (K/S) values, representing the saturation colors on the fabric surface. The K/S values were calculated at the wavelength of maximum absorption (λ_{max}) of the color reflectance curve using the Kubel-Munk formula [55] given in the following Eq. (3),

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \quad (3)$$

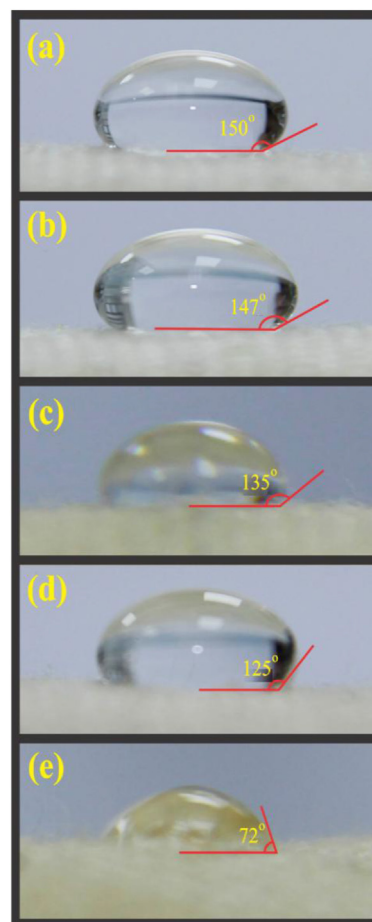


Figure 7. Contact angle of jute blended cotton fabrics: (a) Untreated, (b) 5 min treated, (c) 10 min treated, (d) 15 min treated, and (e) 20 min treated.

where, R , K , and S are the spectral reflectance percentage, absorbed, and scattered coefficients, respectively. The K/S values indicate the dyeing strengths.

3. Results and discussions

3.1. Surface analysis

Surface morphology of untreated and plasma-treated (treatment time:15 min) jute blended cotton (40:60) fabric under scanning electron microscopy are shown in Figure 3. SEM image indicates the change of surface features of the fabric after plasma treatment. The surface is important because of the chemical reactions that are primarily achieved around the absorbed top surface layers [56]. Initially, untreated fabric exhibited a smooth surface with some impurities (Figure 3 (a)). After the plasma treatment for a short time, the impurity of the fabric surface was removed. When the treatment was prolonged, the surface seemed damaged, and micro-cracks appeared on the fabric surface. The jute-cotton blended fabrics' surface became rougher after plasma treatment for the plasma etching technique [57,58]. The greater roughness of treated fabric arises from the fibrillation processes related to the energetic plasma and the treatment's moving route [59]. Plasma treated jute-cotton fabric surface introduces some black cracks visible in Figure 3(b). The ablation attribute caused by the plasma bombardment on the plasma-treated fiber surface was clarified due to the cracks, and as a consequence, the surface got to be rougher. Many researchers have used SEM technology to investigate the plasma-treated surface morphology

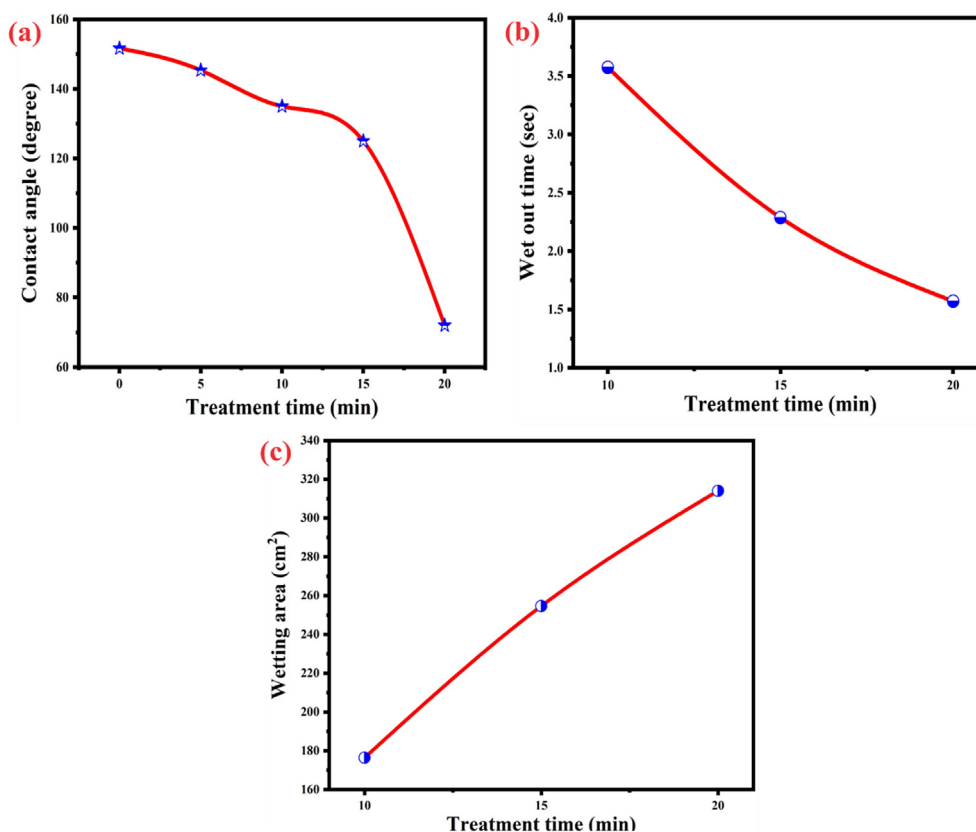


Figure 8. Graph of (a) Contact angle, (b) wet-out time, and (c) wetting area as a function of treatment time.

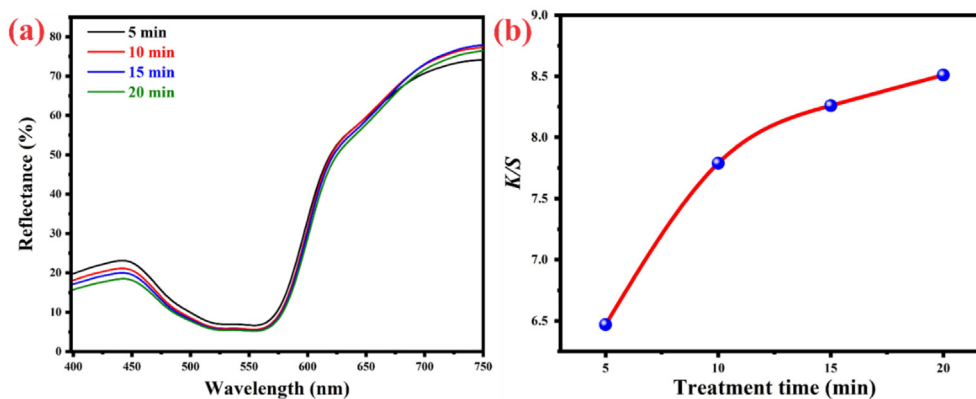


Figure 9. (a) Reflectance percentages curve of the fabrics as a function of exposure time at wavelength range of 400–750 nm and (b) K/S value of the fabrics as a function of exposure time at 550 nm wavelength.

with very near evidence like our findings [58,60,61]. Plasma contains highly excited ions, free radicals, and reactive species, and they are incredibly reactive with particles or contact surfaces. They are also highly energetic to separate chemical bonds [46]. Plasma reactive species can modify physical and chemical structures on the fabric surface. In the initial stage of the plasma process, reactive plasma species' interaction predominates on the amorphous regions than the crystalline region of the fabric surface. The amorphous portions of the cellulose are loosely bound as compared to the crystalline fragments. As a result, amorphous materials have been removed from the surface after plasma treatment and keep the crystalline region unchanged [62]. Changes in the surface's physical and chemical structure, including breaking chemical bonds and surface roughness, happened after a longer treatment time. This surface deformation plays a crucial role in improving wickability.

3.2. Compositional analysis

To evaluate the functional groups of jute blended cotton of untreated and plasma-treated fabric surface under the LPGD air plasma, the ATR-FTIR spectroscopy was used. The normalized ATR-FTIR data have been depicted in Figure 4. A rectangular zooming part in the range of 1120–1760 cm^{-1} has been added to the outer part of Figure 4. The spectroscopic curves show a homogeneous feature from 800 to 1120 cm^{-1} and from 1760 to 4000 cm^{-1} regions, whereas 1120–1760 cm^{-1} shows heterogeneous behaviors due to high intensity and fractional peaks. The wavenumber 1160 cm^{-1} , 1374 cm^{-1} , 1430 cm^{-1} , and 1640 cm^{-1} are associated with the C–C ring stretching, the C–H bending in cellulose, CH₂ deformation in lignin and O–H bending, respectively. The intensity of this peak gradually increased for plasma treatment time.

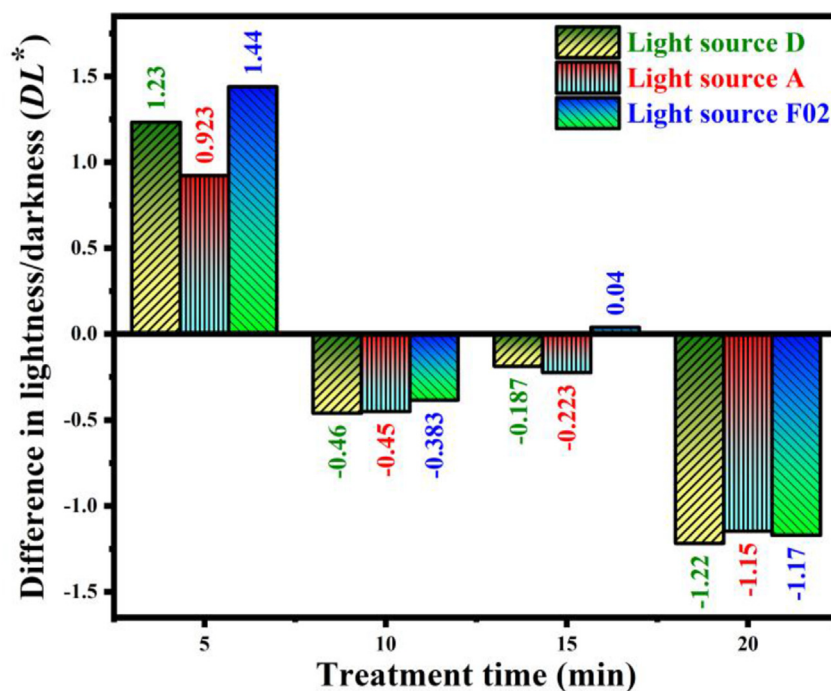


Figure 10. Comparison of darkness of plasma treated fabrics at different time intervals.

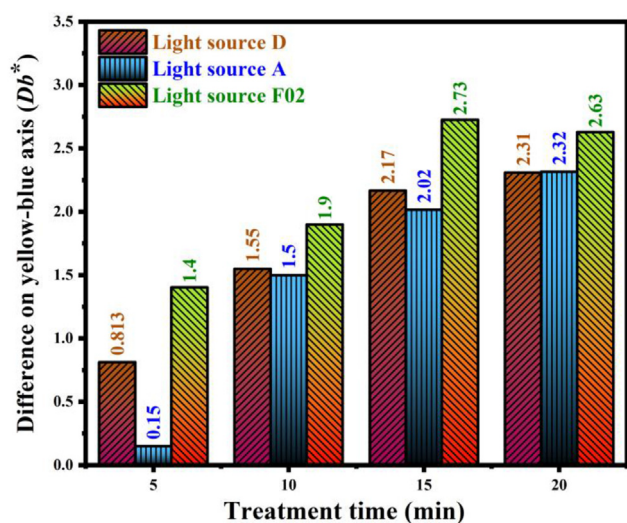


Figure 11. Comparison of yellowness of plasma treated fabrics at different time intervals.

Cellulose, hemicellulose, and lignin are the primary composition materials as a natural fiber in jute and cotton, where cellulose is prominent for both. The noticed region near about 1250 cm^{-3} with high intensity for treated samples introduces lignin and hemicellulose [63]. A new peak with high intensity at 1540 cm^{-1} is found after LPGD air plasma treatment which illustrates COO^- stretching vibration (anionic hydrophilic group) due to plasma oxidation reaction (see the zooming part of Figure 4). That reveals a significant fabric change under active hydrophilic carboxyl group, is executed by plasma treatment. The peaks at 900 cm^{-1} and 1040 cm^{-1} are introduced by β -glycosidic linkage and C-O (ether) stretching vibrational functional groups. The fibers show higher water absorbency because of hydroxyl (-OH) groups in cellulose for a solid and broad peak ($3000\text{--}3600\text{ cm}^{-1}$) and more stable for plasma treated fabrics with different effects such as time, light, and temperature [64, 65, 66]. The interaction of energetic plasma active particles on the

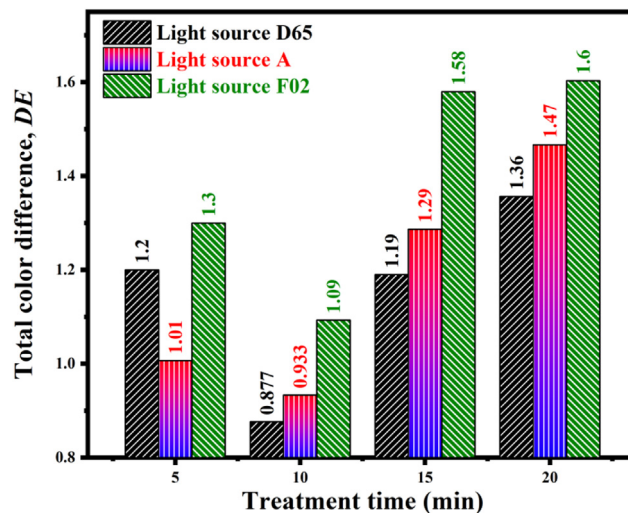


Figure 12. Comparison of color difference of plasma treated fabrics at different time intervals.

cellulose fibers results in a breakdown of the cellulose's chemical bonds. It illustrated that polar functional groups like $-\text{OH}$, and COO^- were enhanced into fabric surfaces. Consequently, the fabric's hydrophilicity will be increased. The symmetric vibration of CH_2 and CH_3 groups of glycolic acid is commenced by $2800\text{--}3000\text{ cm}^{-1}$ region. The decreased intensity patterns (after the plasma treatment) at 2903 cm^{-1} and 2361 cm^{-1} are related to the C-H stretching vibration (due to cellulose and hemicellulose) and the apparatus's limitations [67,68].

3.3. Average pore radius and diffusion coefficient

The graph of $(4\eta^2L^4)^{\frac{1}{2}}$ versus $(\gamma^2\cos^2\theta t^2)^{\frac{1}{2}}$ has been represented in Figure 5. This graph offers responsible linearity. The pore radius was determined from the slope of the line in Figure 5, and the plot of L^2 versus time graph is depicted in Figure 6. The slope of the line of this figure gives

Table 3. CIE lab values, color difference, darkness, and yellowness of the plasma treated grey jute-cotton blended fabric at different treatment times.

| illuminates | L* | a* | b* | c* | h ⁰ | | |
|-------------|----------------------|-------|--------|-------|----------------|------|------|
| D65-10 | 46.09 | 50.58 | -8.76 | 51.33 | 350.17 | | |
| A-10 | 51.85 | 48.08 | 3.17 | 48.18 | 3.77 | | |
| F02-10 | 45.77 | 39.26 | -10.83 | 40.72 | 344.58 | | |
| illuminates | Treatment time (min) | DL* | Da* | Db* | Dc* | DH* | DE |
| D65-10 | 5 | 1.23 | -2.55 | 0.81 | -2.65 | 0.37 | 1.20 |
| A-10 | | 0.92 | -2.25 | 0.15 | -2.24 | 0.31 | 1.00 |
| F02-10 | | 1.44 | -2.00 | 1.40 | -2.29 | 0.84 | 1.30 |
| | 10 | -0.46 | -0.71 | 1.55 | -0.94 | 1.42 | 0.87 |
| | | -0.45 | -0.45 | 1.50 | -0.32 | 1.53 | 0.93 |
| | | -0.38 | -0.63 | 1.89 | -1.08 | 1.68 | 1.09 |
| | 15 | -0.19 | -1.26 | 2.16 | -1.58 | 1.94 | 1.20 |
| | | -0.22 | -1.05 | 2.01 | -0.87 | 2.10 | 1.29 |
| | | 0.04 | -1.05 | 2.72 | -1.66 | 2.40 | 1.57 |
| | 20 | -1.21 | -0.73 | 2.31 | -1.07 | 2.18 | 1.36 |
| | | -1.14 | -0.33 | 2.32 | -0.12 | 2.34 | 1.47 |
| | | -1.17 | -0.68 | 2.63 | -1.29 | 2.39 | 1.60 |

the diffusion coefficient (D_c). The values of average pore radius and diffusion coefficient at selected exposure time are shown in Table 2. Pore radius as well as diffusion coefficient increase with the increase of treatment time. Wicking and wetting are correlated processes. Fiber wettability is essential to wicking. A liquid can wick into a fabric if it wet the fibers. Fabric pore size ordination affects fluid wicking characteristics [69]. Plasma treatment increased adequate pore size and reduced capillary pressure [36]. Hence, capillary flow increased, and it improved wickability. The diffusion coefficient (D_c) relies upon the porosity of the fabric. The liquid can quickly diffuse on the surface of the sample has high porosity [70,71]. Therefore, exposure time had a positive impact on improving the wicking properties of the fabric specimens.

3.4. Wettability analysis

The wettability of untreated and plasma-treated fabrics was assessed using the contact angle of a water drop. The wettability was calculated only on the plasma-facing side (front side) of the fabric layer. The contact angle of water drop on untreated and plasma-treated fabrics is shown in Figure 7 (a)-(e). Figure 8 reveals the change of contact angle, wet-out time, and wetting area with constant pressure and power level treatment time. The contact angle of the water drop on the jute blended cotton fabric was reduced to almost 70° after a plasma treatment time of 20 min on the fabric, whereas it was 150° for the untreated one (see Figure 8 (a)). A 50% reduction of the contact angle was detected for a 20-minute LPGD air plasma treatment. The plasma treatment was discovered to minimize the contact angle between the water and the jute fiber's surface, subsequently expanding its polarity [72,73]. The fiber's surface energy is inversely proportional to its hydrophilicity and thus to its contact angle [74]. As the fiber and the water's contact angle decreases, the fiber becomes more hydrophilic [75].

The change of wet-out time as a function of plasma treatment time is shown in Figure 8 (b). The same scenario was also observed in wet-out versus exposure time graphs. Considerable reduction of wet-out time with treatment time at constant pressure was observed. The untreated sample's wet-out time was more significant than 360 s, but it was reduced to 1.5 s after a treatment time of 20 min. The fabric surface having a wet-out time of more than 360 s was considered as a non-wetting surface. The surface of untreated and 5 min plasma treated fabrics was considered non-wetting because it failed to wet entirely within the time limit of 360 s. The wetting area of plasma-treated fabrics at different treatment times is depicted in 8 (c). The wetting area increases linearly with treatment

time. But it was not possible to calculate the wetting area of the 5 min treated fabric because of the arbitrary shape of its wetted surface.

All the analyses mentioned above reveal the improved wettability of the plasma-treated fabrics compared with untreated ones. Highly excited ions, free radicals, and reactive plasma species resulting from electron and gas molecules' collision are highly reactive with contact surfaces. When the fabrics are treated for a long time, the amount of plasma reactive species interacting with the fabric surface increases. Hence the topmost hydrophobic layer of the fabrics is removed, and a rougher surface is created. As a result, the effective surface area of the fabric is increased. Surface roughness increased the wickability and decreased the capillary pressure [42], which is evident from our SEM analysis results. Previous results also inform that plasma treatment enhanced the effective pore size of the fabric. High porosity helps liquid diffuse easily on the fabric. Thus, the deformation of the fabric surface increases the capillarity, and the sample acquires hydrophilicity. In addition, it is the plasma oxidation process that plays a vital role in the improvement of wettability [76]. Oxygen contains hydrophilic functional groups (-OH, COO⁻) produced in plasma oxidation reactions attached to the fabric surface and are too small and primarily unimportant [77]. The presence of these functional groups on the fabric surface improved the wicking properties [69]. The improved wicking rate is due to fiber's expanded wettability due to the modified surface properties induced by the plasma treatment [78], which supports our diffusion coefficient analysis.

3.5. Dyeability modification of the jute blended cotton fabrics

The contact angle and wicking rate measurements indicated the difficulty of dye untreated jute-cotton blended fabric because of its poor wettability as plasma treatment can change the fabric's surface properties and improve the dyeability. Figure 9 (a) shows the reflectance curves of plasma pre-treated fabrics after dyeing at the wavelength range of 400–750 nm. It presents that each fabric exhibits its lowest reflectance value at 550 nm. It was also noticeable that the reflectance percentage (% R) at a particular wavelength declined with the increase of treatment time (5 > 10 > 15 > 20 min). A low value of reflectance indicates the high color intensity of the fabrics.

Figure 9 (b) shows the change of K/S value of plasma pre-treated fabrics after dyeing at 550nm wavelength under selected treatment time. An increasing trend of K/S value (6.47–8.51) with treatment time is observed in the figure. Longer the exposure time, the higher the K/S value. A fabric showed a higher K/S value when more dye was absorbed or fewer reflection properties by the fabric [79]. Evidence of improved dyeability of plasma pre-treated fabrics is also found in Figure 10. It shows that the darkness of the plasma pre-treated dyed fabric gradually increased with treatment time. The plasma pre-treated fabrics were becoming darker because they absorbed more amounts of dyes due to better wicking properties. Plasma treatment removes the wax layer and generates micro-cracks on the fabric's surface [80,81]. The plasma treatment results in a rougher surface and produces a larger effective surface area. Besides that, the plasma treatment increases the effective pore size and diffusion rate. As a result, the dye solution has been quickly diffused from the fabric surface towards the core. The FTIR analysis also indicated that the hydrophilic functional groups such as O-H, C-O, and COO⁻ were enhanced into the fabrics after plasma treatment. These functional groups play a vital role in dye fixation, resulting in improved dyeability [62]. Hence it is concluded that plasma treatment promotes the dyeability of the jute-cotton blended fabric.

Figure 11 reveals the gradually increased values of D_b^* , which indicates that the plasma pre-treated dyed fabrics are more yellow than the conventionally pre-treated dyed fabrics. Thermal oxidation on fabric surfaces due to plasma treatment is mainly responsible for this effect [82]. The plasma may induce the fragmentation of the surface and new functional groups' formation [83]. Figure 12 shows the color difference (DE) values of plasma-treated samples at different time intervals. It shows that all the trial samples except 10 min plasma processing samples have

color differences greater than 1. Color difference less than or equal to one means it is not noticeable by the human eye. This confirms that the jute-cotton (40:60) blended fabric pre-treated by 10 min LPGD air plasma had a similar color intensity to the conventionally pre-treated fabric before dyeing. Brief details about the CIE lab values, color difference, darkness, and yellowness of the plasma-treated grey jute-cotton blended fabric at different treatment times have been summarized in Table 3.

4. Conclusions

The LPGD air plasma's impact on wicking properties and dyeability as a function of treatment time was investigated for the grey jute blended cotton (40:60) fabric without any addition of chemical ingredients. The SEM images indicate that the roughness of the fabric surface is enhanced with the plasma treatment processes. The ATR-FTIR results confirmed the change of chemical composition and the existence of the polar functional groups on the fabric surface after the plasma treatment. The decrease of contact angle of the water drop on the fabrics from 150° to 72° (nearly 50%) after a 20 min plasma treatment was a sign of the significant improvement of the surface wettability. Over and above, this wet-out time linearly decreased, the wetting area and color intensity (K/S) enhanced with the increase of plasma treatment time. The porosity of the blended jute cotton fabric was also connected to the plasma treatment times and maintained a proportional relationship. Among the four samples, only 10 min of plasma processing fabric had a color difference of less than one compared to the standard one. It achieved the desired color strength under conventional wet-chemical processes. Furthermore, all the experimental results showed a substantial effect of LPGD air plasma on improving the blended jute-cotton fabric's surface wicking properties and dyeability. Thus, the dyeing of LPGD air plasma treated jute-cotton blended fabric can be considered to be a suitable eco-friendly candidate for replacing hazardous textile processes that may open up a new path to develop environmentally sound and sustainable diversified jute products.

Declarations

Author contribution statement

M. Hedayet Ullah, Hasina Akther: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

M. Mahbubur Rahman: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

A. B. M. Foisal, M. Mahmud Hasan, S. M. Amir-Al Zumahi, Amun Amri: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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