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Recycling of cotton apparel waste and its utilization as a thermal insulation layer in high performance clothing

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Abstract

Recycling and converting textile waste into value-added products with enhanced functional properties pave the way toward a circular economy for sustainability. This research investigates the utilization of recycled cotton fiber from apparel cutting waste for fabricating high-performance thermal barrier fabrics. The physical characterization of the developed fabrics revealed a regular arrangement of fibers, consequently the uniform thickness of the fabric with no distortion on fiber surfaces due to the recycling operation of cotton waste. The developed fabrics also demonstrated a high softness index and low compression and bending average rigidity compared to the commercial fabric with similar thickness. The heat protection performance revealed an increase in fabric conductive and radiative heat resistance with increasing the amount of recycled cotton fiber in the fabrics. The inherent thermal resistance of cotton fiber and the low inter-fiber spacing because of their uniform orientation in the fabric lead to the high thermal resistance of developed fabrics. In the case of fabric air permeability concerning the clothing thermal comfort, no significant difference in breathability was observed among the test specimens. Besides, the moisture management profile of developed fabrics indicated the capability to create favorable thermal comfort within the clothing-skin microenvironment because of improved liquid transportation and diffusion of perspiration vapor through the fabric.

Keywords: Apparel waste, Recycled cotton fiber, Thermal liner, Heat protective clothing, Waste utilization

Introduction

One of the essential basic needs of human life is considered textile or clothing, which entwined very closely with the human being from the early stage of its civilization. The growth of the world population with the rapid change in fashion trends considerably increases the production of apparel and its consumption over time (Bhardwaj & Fairhurst, 2010). However, the second-most industrial polluting sector of the world is the textile and apparel industry (Echeverria et al., 2019), and the industry is greatly criticized for its harmful environmental impacts such as carbon footprint, waste generation, and consumption of resources (Aus et al., 2021). The manufacturing process of textiles and clothing is associated with the generation of an extensive amount of solid and liquid wastes from raw materials to finished apparel. Ecological concerns related to the waste textiles are intensifying over time due to increasing volumes of apparel production and consumption (Kim & Damhorst, 1998).

The solid waste generated in the fashion or apparel industry can be categorized as industrial manufacturing, pre-consumer, and post-consumer waste (Ramkalaon & Sayem, 2020). Industrial apparel manufacturing waste typically consists of cutting and sewing waste, fabric swatch and sample waste, rejected fabrics, end-of-roll waste, unsold apparel, and so on (Bizuneh & Tadesse, 2022; Tomovska et al., 2017). These waste fabric materials with a full lifespan are disposed of without any use (Dissanayake et al., 2018). Because of the increasing volume of apparel production, managing the waste of textiles and apparel has become a crucial issue in the world, particularly in countries where textile manufacturing industries are located.

Among the textile fibers, cotton is the most renowned and extensively used natural fiber globally because of its excellent hydrophilicity, wear comfort, biodegradability, and low thermal conductivity (Bhuiyan et al., 2017, 2019a, 2019b; Jain et al., 2019). Such favorable characteristics make cotton a prominent natural fiber in the field of conventional and technical textiles for versatile applications. However, due to the long sequence of manufacturing processes and the generation of waste in every stage of processing, a huge volume of waste is produced during the production of cotton apparel (Akter et al., 2022). A large portion of the waste is incinerated or landfilled due to the lack of waste utilization strategies (Moazzem et al., 2021; Nayak et al., 2020), creating social and ecological hazards by contaminating groundwater and formation of greenhouse gases, including carbon dioxide, methane, nitrous oxide, and hydrogen sulfide upon degradation (Yousef et al., 2020). The problems associated with these hazards are a matter of great concern to the environmental ecosystem throughout the world (Bhuiyan et al., 2016). Therefore, it is an urgent need to develop a sustainable waste management system through proper reusing and recycling of textile waste.

The scope of recycling cotton waste and its diversified applications in many areas has been extensively investigated in several contemporary research studies. Sakthivel et al., (2020) fabricated chemically bonded nonwovens by using recycled cotton/polyethylene terephthalate (PET) and used the nonwovens for thermal insulation in building construction. Sezgin et al., (2021) designed thermal and acoustic insulation composite panels by using 100% recycled cotton fiber reinforced with polyethylene/polypropylene. Dissanayake et al., (2021) developed a sound insulation material by mixing cotton/polyester waste with natural rubber. Kamble and Behera (2020) demonstrated automotive applications of thermosets composites reinforced with recycled cotton fibers extracted from apparel cutting waste. All the studies revealed the potential techniques and challenges associated with the scope of recycling waste cotton in an open-loop system, where the materials are reprocessed and recovered into a different product instead of being returned to the original manufacturers. However, a minimal research study is conducted on fabric-to-fabric recycling of cotton apparel cutting waste in a closed-loop method. The closed-loop recycling is considered a fundamental approach to a circular economy for sustainability where the flow of resources can be optimized by circulating the resource materials recurrently, thereby reducing the consumption of virgin materials (Dissanayake & Weerasinghe, 2021).

This research is intended to develop fabric-to-fabric recycling by utilizing recycled cotton from apparel cutting waste and fabricating a high-performance thermal liner for heat-protective clothing. Three types of fabrics were designed by incorporating different ratios of waste cotton fiber, and the thermal resistance of the developed fabrics was assessed and compared with a commercial fabric. Apparel comfort parameters, including softness, moisture management performance, and air permeability were also investigated to evaluate the prospective utilization of recycled cotton fiber as thermal insulation materials in barrier clothing systems.

Experimental

Materials

Apparel cutting waste as source material for recycled cotton fiber was collected from the local garment factories. Virgin polyester staple fiber (1.2 Denier, 38 mm and off-white color) to blend with recycled cotton of different ratios was purchased from the local market. Commercial quilt fabric composed of 100% polyester fiber as a reference fabric in the current study was brought from an export-oriented local apparel company. The commercial quilt comprises three layers, including a hydrophobic inner and outer woven fabric and a thermal insulating barrier layer.

Methods

Material preparation

The fabrication of thermal barrier fabric using recycled cotton fiber involved an initial fragmentation of apparel cutting waste into shoddy by employing a fabric-breaking machine. The shoddy was precisely mixed, opened, and cleaned through passing into the Blowroom (Digital blowing machine, DSBL, China). The fiber flocks were then converted to a carded web by the individualization and parallelization of fibers using a mini carding machine (Digital carding machine, DSBL, China). Finally, a thermal liner was developed by laying the fiber web with the required thickness and sandwiching it into outer and inner layer fabrics following the quilting process. The manufacturing of newly developed fabrics is shown schematically in Fig. 1.

The experimental investigation of the current study was conducted by preparing three types of cotton/polyester fabric specimens, which were coded as PC1, PC2, and PC3, respectively. The commercial fabric used as a standard sample was coded as CF. The constituent fibers and mass of the developed and commercial fabrics are presented in Table 1.

Measurement and characterization

Physical properties of the fabric The morphological investigation of the developed and commercial fabrics was performed by using scanning electron microscopy (SEM) (SU 1510, Hitachi, Japan), with a low vacuum mode and 10 kV accelerating voltage. The specimens were coated with Au for 60 s using a sputter coater (Q 150R ES, Quorum, England) before conducting the SEM investigation. Fabric thickness was measured following the standard ASTM D1777–15 using a fabric thickness tester. The measurement of softness

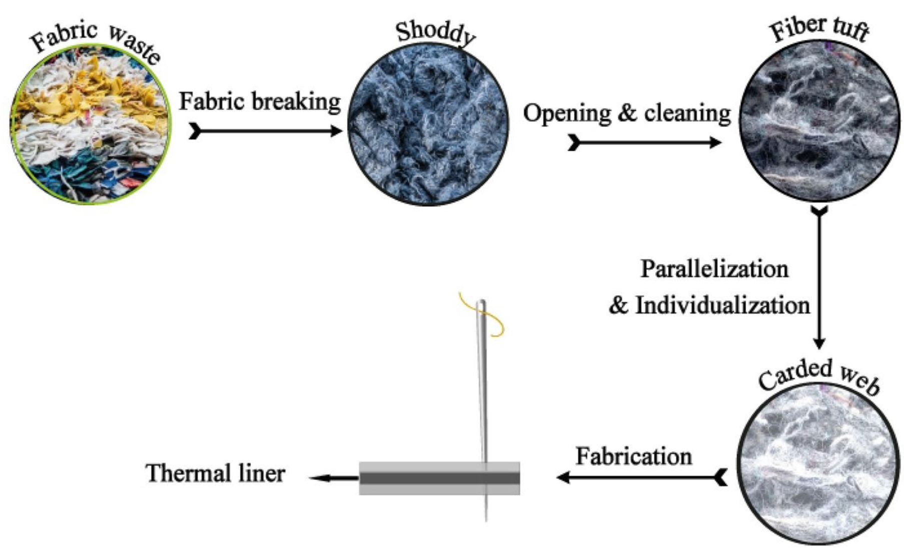

Fig. 1 Schematics of manufacturing quilt fabric using recycled cotton fiber

Table 1 The component fibers and mass per unit area (mean ± SD) of developed and commercial fabrics

Fabric	Fiber ratio Cotton/Polyester	Fabric mass (g.m^{-2})
Polyester-Cotton1 (PC1)	50/50	242 ± 2.32
Polyester-Cotton 2 (PC2)	75/25	272 ± 2.65
Polyester-Cotton 3 (PC3)	0/100	295 ± 2.78
Comercial Fabric (CF)	100/0	230 ± 1.75

index, compression work, compression average rigidity, bending work, and bending average rigidity of fabric was conducted using a fabric touch tester (FTT) (M290, SDL Atlas, Hong Kong). The fabric touch tester determined all the above-mentioned parameters directly based on different principles and methods as mentioned in the operation manual. During the investigation, fabric specimens were cut in L shape as per instructions provided by the machine manufacturer. A constant temperature of 293.0 ± 0.1 K and 65 ± 2% RH of the test chamber was maintained throughout the experiment.

Thermal analysis The thermal performance of the developed fabrics was assessed by measuring the thermal and radiative heat resistance and compared with the commercial fabrics. The test of thermal resistance was performed in the steady-state condition following the standard BS 4745:2005 using a two-plate method with a fixed pressure procedure as stated in the manual. The radiative heat resistance was determined by exposing the fabrics to a radiant heat source, an incandescent lamp of 60 W, at a 20 cm distance from the specimens. The rise of temperature opposite to the exposed fabric was recorded by a heat sensor for 30 min. Besides, a thermographic infrared camera (FLIR T400-series) was employed to visualize the change of fabric surface temperature after placing it on a hot surface of 310.0 ± 1.0 K. The thermal imaging of fabric specimens was conducted at a distance of 40 cm for 90 s in a test chamber of the standard atmospheric condition. Apart from this, the quantitative value of thermal resistance was statistically analyzed using one-way ANOVA analysis at a 95% significance level.

Fabric wear comfort The air permeability i.e., the breathability of fabric was measured according to EN ISO 9237:1995 using a TEXTEST air permeability tester (FX 3300, TEXTEST, Switzerland). The mean air permeability was calculated from the airflow readings (mL cm^{-2} s^{-1}) of five specimens from each fabric tested. The moisture management profile of fabric was investigated following the AATCC-TM-195-2009 using a moisture management tester (M 290, SDL Atlas Ltd.).

Results and Discussion

Analysis of fabric physical characteristics

The SEM image in Fig. 2a shows the recycled cotton fibrous structure with a typical ribbon-like convolution, and no obvious deterioration of surface properties due to the recycling of cotton waste was observed. Additionally, the compact and regular arrangement of cotton fibers was also observed in the SEM micrograph of the developed fabric specimen (PC3). On the other hand, the uniform surface morphology with a rod-like configuration of polyester fiber was observed in the SEM image of commercial fabric (CF) (Fig. 2b). Figure 2b also confirms the random arrangement and the presence of numerous open holes owing to the high inter-fiber spacing of fibers in the fabric. Such irregular arrangement of fibers is predicted to have an impact on breathability and the overall thermal performance of clothing.

The compressional behavior of fabric is one of the basic mechanical properties that are closely associated with fabric softness and fullness. This property is also co-related to fabric structure, surface property of fibers/yarns, and the lateral compressional properties of fibers/yarns in the fabric (Matsudaira & Qin, 1995). Fabric thickness is considered a key indicator of fabric warmth, heaviness, or stiffness. Besides, fibers in the fabric enclose a large amount of air, which in conjunction with other relevant fiber properties, is responsible for good thermal insulation of clothing. Fabric bending behavior is another important mechanical property directly related to the physiological comfort of clothing, including the stiffness, handle and drape of the fabric. The nature of constituent fibers or yarns, fabric construction, and importantly any treatment given to the

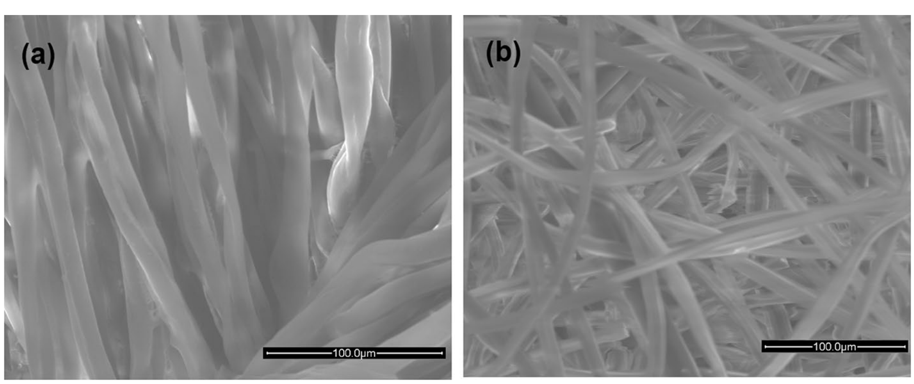

Fig. 2 Scanning electron microscope (SEM) images of (**a**) developed fabric (PC3), and (**b**) commercial fabric

fabric are some mentionable factors that collectively affect the bending nature of a fabric (Abrishami et al., 2019).

The experimental results of thickness, softness index, bending, and compressional properties of the developed and commercial fabrics are shown in Fig. 3. Although no significant difference was observed between the thickness of commercial and developed fabrics (Fig. 3a), an increasing trend of softness was observed for the developed samples (Fig. 3b). The maximum softness index among all the specimens was noticed for the fabric PC3 with 100% cotton fiber. On the other hand, a descending trend with respect to cotton fiber content was notified for the bending and compression behavior of the developed fabrics (Fig. 3c). Accordingly, fabric PC3 exhibited the lowest compression work (4415.41 gf mm) and compression average rigidity (28.24 gf mm^{-3}), indicating its maximum flexibility among all the specimens. This enhanced pliable nature of the fabric PC3 is also recognized by the lowest bending work and bending average rigidity of 2527.27 gf mm rad and 753.99 gf mm rad^{-1}, respectively (Fig. 3d). Hence, it can be stated that the extent of cotton fiber in the developed specimens positively contributed to the pliable nature of the fabric, which in turn will make more flexible and drapable clothing materials with enhanced comfortability, providing physiological comfort to the wearer in various special purposes.

Thermal performance of fabric

Fabric thermal resistance is a key parameter for estimating the biophysical characteristics of clothing employed for various special purposes (Nayak et al., 2018). It represents the ability of the fabric to resist the transfer of dry heat through the clothing assembly by

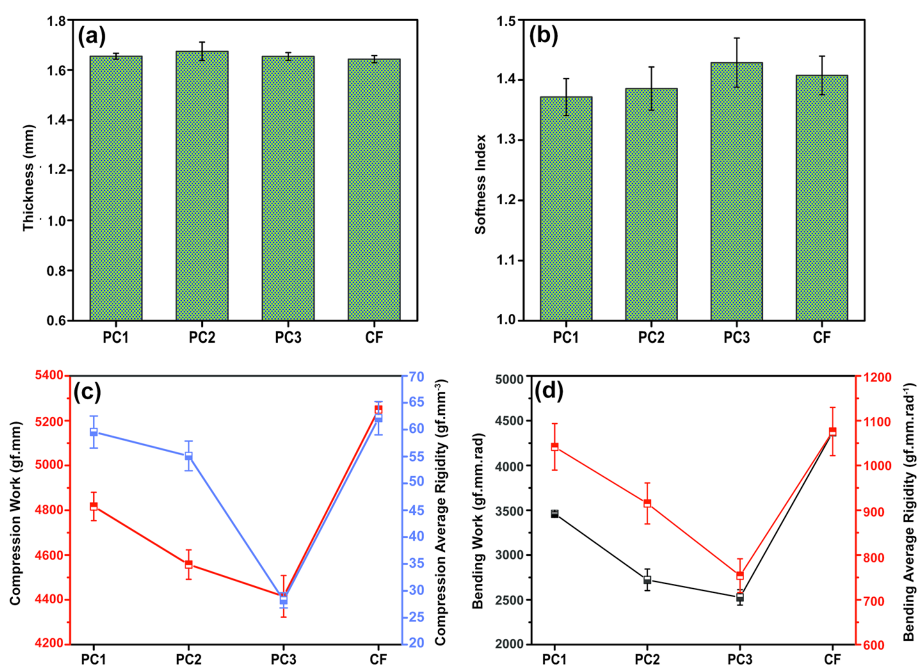

Fig. 3 Comparative physical properties of developed and commercial samples; (**a**) thickness, (**b**) softness index, (**c**) compression work and compression average rigidity, and (**d**) bending work and bending average rigidity of fabric. Polyester-Cotton1 (PC1), Polyester-Cotton2 (PC2), Polyester-Cotton3 (PC3), and Commercial Fabric (CF)

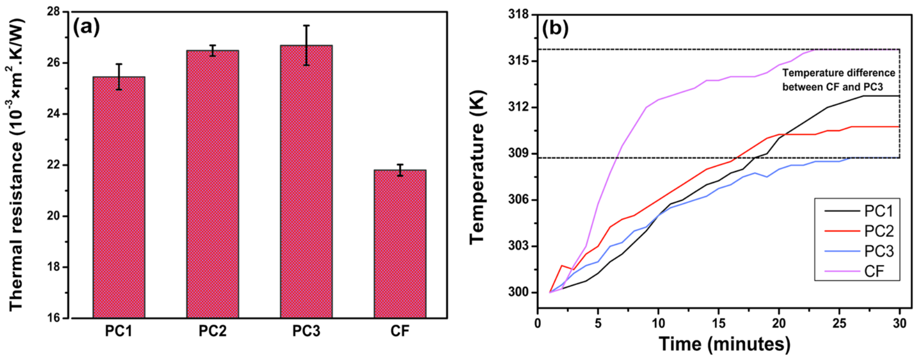

Fig. 4 Comparative thermal performance; (**a**) conductive thermal resistance, and (**b**) radiative heat resistance of fabric specimens. Polyester-Cotton1 (PC1), Polyester-Cotton2 (PC2), Polyester-Cotton3 (PC3), and Commercial Fabric (CF)

Table 2 One-way ANOVA parametric on the performance of thermal resistance

Source of variation	SS	df	MS	F	P-value	F critical
Between groups	46.27	3	15.42	34.08	6.62×10^{-5}	4.06
Within groups	3.620	8	0.452			
Total	49.89	11				

conduction, convection, and radiation (Pelanne, 1977). A low thermal conductive material can be used to minimize conductive heat transfer through the clothing, and radiated heat transmission can be reduced by its absorbing or reflecting surfaces (Islam & Bhat, 2019).

The comparative thermal and radiative heat resistance of the developed and commercial fabric specimens is shown in Fig. 4. All the developed fabrics demonstrated higher conductive and radiative heat resistance compared to their commercial counterpart. Besides, a progressive increase was observed for both conductive and radiative heat resistance in parallel with increasing the amount of recycled cotton fiber in the fabric (4a & b). This resemblance of conductive and radiative heat measurement collectively suggests the superior heat-retaining capability of the developed fabric specimens, especially fabric PC3. The thermal resistance of apparel is directly related to its structure and thickness, as well as the thermal conductivity of the component fibres (Houshyar et al., 2015). Accordingly, the high thermal conductivity (140 mW/m K) of polyester fiber (Hearle & Morton, 2008) was attributed to the lowest resistance against the thermal and radiative heat of commercial fabric (CF). On the other hand, the low heat conductivity (71 mW/m K) of cotton fiber (Bhuiyan et al., 2019a, 2019b) and its proportion in the fiber assembly can be correlated with the gradual improvement of the thermal performance of developed fabric specimens. Besides, the regular and compact arrangement of fiber also contributed to such high thermal resistance of developed fabrics. Since the compact structure can increase the absorption or scattering of radiation by creating a convoluted path and therefore reduces the transfer of heat through the clothing.

The results of one-way ANOVA analysis in Table 2 signifies the existence of significant difference in the thermal resistance between commercial and the developed samples, exhibiting the greater calculated value of F (34.08) than the F-critical value (4.07). The critical value of F is derived from F-distribution table. Besides, the obtained value of P is < 0.05, which indicates the rejection of null hypothesis (no significant difference exist).

The thermal performance of the test specimens has also been verified by using an infrared thermal camera. The thermography images in Fig. 5 show the change of fabric surface temperature after placing on a heat source of 310 K. All the samples exhibited a trend of rising temperature over time, which has been visualized by the color change of surface images at a particular interval of 30 s. Fabric CF demonstrated the least thermal resistance and showed an elevated rise in temperature with time (304.8 K, 305.5 K, 306.0 K, and 306.3 K at 1 s, 30 s, 60 s, and 90 s, respectively). The high heat conductive nature of the polyester fiber, as discussed earlier, contributed to such a decrease in thermal resistance and reduced the temperature differences between the inner and outer surface of the fabric. Conversely, a slowest rate of increasing temperature (301.5 K, 301.6 K, 301.9 K, and 302.0 K at 1 s, 30 s, 60 s, and 90 s, respectively) was observed for fabric PC3 (Fig. 5), suggesting that this fabric has the highest thermal resistance among all specimens, and therefore demonstrated a maximum temperature difference between the inner and outer surface of the fabric. Due to this high thermal resistance, the developed fabric (PC3) can therefore be predicted as a heat insulating material, which will provide satisfactory thermal protection by retarding the heat transfer from the human body to the environment and vice versa.

Fabric wear comfort

The moisture management performance concerning the thermal wear comfort of clothing refers to its ability to absorb liquid sweat by the constituent fibers and transportation of perspiration vapor to the atmosphere for maintaining the heat balance of the body

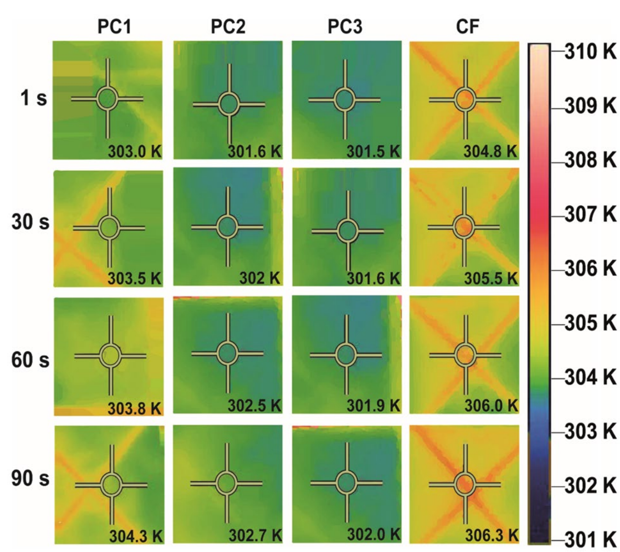

Fig. 5 IR thermography images of developed and commercial fabrics at different times. Polyester-Cotton1 (PC1), Polyester-Cotton 2 (PC2), Polyester-Cotton3(PC3), and Commercial Fabric (CF)

(D'Silva et al., 2000; Hu et al., 2005). The process of liquid transmission through clothing is multidimensional, and the liquid absorption is associated with hydrophilicity as well as the porosity of the fabric. The sticky sensations and thermophysiological discomfort of clothing are, therefore closely related to the one-way liquid transport capacity (OWTC) and overall moisture management capacity (OMMC) of the fabric (Shaid et al., 2018).

Figure 6 represents the complete moisture management performance of the developed and commercial specimens. The fabric PC1 and CF demonstrated a negative one-way transport index (OWTI) (-767.95 and -161.45, respectively) and the maximum wetting time (120 s) (Fig. 6a, d), which collectively indicates that liquid was not allowed to penetrate from the top to bottom surface of the specimen. The zero bottom absorption rate, wetted radius, and spreading speed also signify this fact. Therefore, the developed fabric (PC1) and commercial fabric (CF) can be categorized as waterproof fabric that are unable to transfer of body sweat or any such liquid through the clothing. On the other hand, fabrics PC2 and PC3 exhibited an efficient moisture management performance (Fig. 6b, c), which was attributed to the excellent hydrophilicity of cotton fibers, facilitating the penetration and spreading of water and aqueous solution through the fabric (Fig. 6e). Thus, the lowest wetting time (8.42 s), the highest absorption rate (114.71%/s) and liquid spreading (0.58 mm/sec) to the bottom surface was observed for the fabric PC3. Accordingly, the highest OWTI value (484.41) of this fabric indicates the ability to provide moisture comfort by rapid transfer of liquid sweat

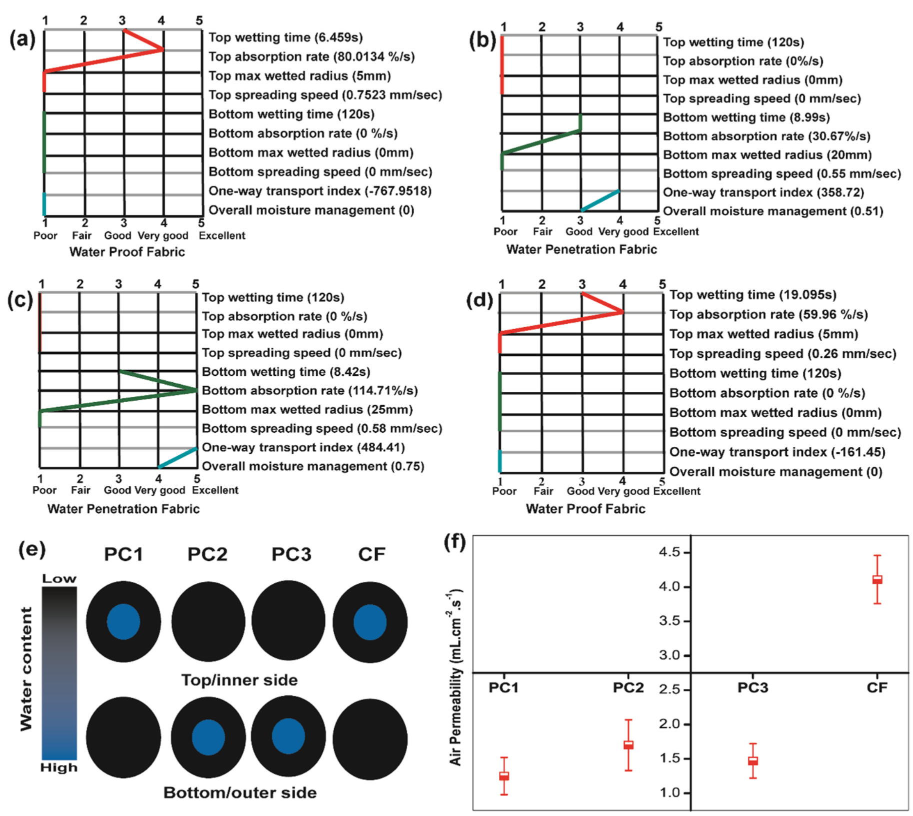

Fig. 6 The moisture management performance profile of fabric; (**a**) Polyester-Cotton1 (PC1), (**b**) Polyester-Cotton 2 (PC2), (**c**) Polyester-Cotton3 (PC3) & (**d**) Commercial Fabric (CF); (**e**) water location diagram of the top and the bottom surface of the fabrics; and (**f**) fabric air permeability

from the body to the environment and keeping a dry apparel-skin microenvironment of the wearer.

Another important parameter of clothing thermal comfort is air permeability, which deals with the measurement of flowing air through the test specimen under a specified pressure difference over a given time (Bhuiyan et al., 2019a, 2019b). This particular characteristic of fabric is influenced by the cloth cover factor (i.e., cloth openness or compactness) and the construction of the fabric, and it is commonly utilized in evaluating and comparing the 'breathability' of various clothing materials usually employed for special purposes (Bhuiyan et al., 2020; Kothari & Newton, 1974). In general, apparels after wearing create a barrier against the flow of air from body to environment and vice versa. Thus, the fabric having good breathability facilitates the evaporation of perspiration vapor and offers comfort to the wearer in hot and humid conditions by reducing the body temperature.

In Fig. 6f, fabric CF exhibited the maximum air permeability (4.11 mL cm^{-2} s^{-1}), indicating its superior breathability among all the specimens. This high permeability was attributed to the random arrangement of fibers and the presence of numerous open holes in the fabric (Fig. 2b) that assist the permeation of air. On the other hand, a slight decrease in air permeability was observed for all the developed fabrics (1.25, 1.7, and 1.47 mL cm^{-2} s^{-1} for PC1, PC2, and PC3, respectively). This was due to the compact structure and regular arrangement of fibers which hindered an easy flow of air through the fiber assembly. Although air permeability of clothing assembly is considered a key factor for determining its breathability, it seems that the developed fabrics with low air permeability can create a negative impact on clothing wear comfort. However, this low permeability has a positive effect on the thermal protection of clothing by limiting the heat flow from the body to the environment and maintaining the elevated skin temperature in cold-weather conditions.

Conclusions

The recycling of cotton apparel waste and its potential utilization for the fabrication of thermal barrier clothing has been investigated in the current study. The performance of the developed fabrics was evaluated by analyzing their physical characteristics, thermal protection performances, breathability, and moisture management properties and comparing with the commercial fabric. The physical characterization through morphological investigation of the developed thermal liner showed good alignment of fibers in the fabric. The clear fibrous structure and no surface rupture of waste cotton fibers due to recycling operation were also observed during the microscopic investigation. The high softness index and low compression and bending average rigidity of the developed fabrics compared to their commercial counterpart revealed the fabric capability of providing more physiological wear comfort to the wearer. The developed fabrics demonstrated an improved thermal and radiative heat resistance than the commercial clothing owing to the inherent low thermal conductivity of cotton fiber. A slight difference in air permeability was observed between the developed and commercial fabrics. The developed fabrics with a high proportion of cotton fibers, however, demonstrated improved one-way liquid transfer capability consequently better moisture management properties. Hence, a favorable thermal comfort environment between the apparel and skin can be created by diffusing the perspiration vapor through the clothing assembly. The overall performance of the developed fabric suggests the fabric-to-fabric recycling of cotton waste and its utilization in heat-protective clothing is an innovative approach toward the circular economy for sustainability where the consumption of virgin materials was minimized through reclaiming of resource materials.

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Authors' contributions
MARB contributed to conceptualization, formal analysis, writing original draft. AA contributed to methodology, writing original draft. MM contributed to conceptualization, investigation, writing original draft. MFH contributed to experimental investigation and data analysis. ANK and LW contributed to review & editing of the manuscript. All authors read and approved the final manuscript.

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Declarations

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