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Bacterial cellulose grown from kombucha: Assessment of textile performance properties using fashion apparel tests

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Abstract

Bacterial cellulose (BC) has been suggested as a sustainable alternative textile for apparel. Previous studies have evaluated the production of BC sheets and the suitability of these to form garment shapes. The laboratory measured physical performance characteristics of BC from an apparel perspective remain relatively unexplored.

The aim of this study was to produce reproducible sheets of BC, enabling the evaluation of the performance of the BC in an apparel textile testing context, and comparison to other textile materials. Grown in sterile black tea with glucose, the BC presented as a mesh of non-woven nanofibers, and thus comparison was made with three non-woven fabrics. It has also been suggested that BC could be used as 'vegetable' leather; therefore, performance comparisons were conducted with animal skins.

Utilizing British, European and International standard test methods, the selected fabrics were evaluated for their performance in tensile, elongation, moisture vapor permeability and abrasion tests, relevant for an apparel end-use.

Tensile strength testing revealed that BC is weaker than its animal counterparts but does display similar physical characteristics at the point of failure; however, it displayed a higher tensile strength than the non-woven fabrics chosen for comparison.

BC was the least breathable and most moisture-retentive of all the fabrics tested, raising questions regarding its suitability and comfort for apparel applications in its untreated state.

However, BC displayed superior performance when tested for resistance to abrasion, suggesting it could be best utilized in the form of encapsulated patches in items subjected to this type of damage.

Keywords

Bacterial cellulose, textiles, performance, fashion, apparel, sustainability

By 2030 global apparel consumption is estimated to be 102 million tonnes, a 63% increase from figures collected in 2019.[1] This consumption puts a huge strain on the environment and natural resources, with United Nations' estimates suggesting the equivalent of approximately three planets worth of resources being required by 2050 to sustain the growth in demand.[2] The impact of apparel on the environment is wide reaching; every stage of the manufacturing process is resource-hungry and contributes to environmental pollution from chemicals used in fiber production, processing techniques in fabric creation and manufacturing practices in apparel construction. In addition, environmental pollution is continued during the lifetime of the garment via pollutants due to washing and wear (for example, as detergents and microfibers), with estimates of over 300,000 tonnes of clothing being discarded every year, and approximately 20% of this being sent to landfill.[3]

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There are concerns around both natural and synthetic fibers. Synthetic fibers are currently largely made from virgin plastics and whilst they use less water than natural fibers in their production, they are mostly non-biodegradable and therefore make a higher contribution to greenhouse gas emission than their natural counterparts. However, natural fibers such as cotton and wool require larger amounts of water and synthetic chemicals in their processing to enable them to withstand the demands of the modern consumer. In addition to addressing the issues regarding manufacturing 'traditional' fabric types, the textile industry is seeking alternative sources of raw material to address environmental concerns.

Bacterial cellulose (BC) is one such alternative material. Commonly described in the apparel industry as 'vegetable leather,' it is reported to have numerous 'enhanced' properties in comparison to its plant counterpart, such as high tensile strength, high water retention, extreme insolubility to solvents, the ability to be molded into shape and high degrees of polymerization and high crystallinity. In addition, its production yields cellulose in a pure form, without the presence of impurities and waxes such as lignin, pectin and hemicellulose,[4] which require heavy processing to remove from naturally produced textiles. However, the study of BC as an alternative textile in the fashion apparel industry has been limited, with relatively few studies exploring the application of BC in this field.[5–7]

'Bacterial (or microbial/nano) cellulose is a form of cellulose that is produced by bacteria.'[8] It forms as a product of the microbial metabolic process and can be thought of as a generated protective layer for the bacterial cell, due to the reported protective properties from ultra-violet light and the retention of moisture. BC is generated as micro- (or nano-) fibrils via pores on the surface of the microbial cell, generally at the interface of liquid and air,[9] forming as a mat, or a pellicle. This structure can be considered a biofilm.[8]

BC is produced most vigorously by the bacterium *Komagataeibacter xylinus* (also known as *Gluconacetobacter xylinus* and *Acetobacter xylinus*).[8,10,11] In laboratory conditions, techniques such as the aseptic inoculation of sterile media (e.g., Hestrin and Schram or Yamanaka) are used to develop BC sheets. However, *K. xylinus* is also found in kombucha, known colloquially as Kargasok tea, tea fungus, Haipao and Manchurian mushroom,[12] which is a fermented drink that has been consumed for several thousands of years. This has led to an artisanal approach to the development of BC material with researchers growing sheets in large containers of unsterile tea and sugar, inoculated with kombucha starter cultures, with varied results.

A kombucha pellicle can be considered a consortium of yeasts and bacteria.[10,13] The composition of the pellicle is determined by its geographic and climatic conditions of cultivation,[13] but it is suggested that a kombucha mat consists of a 'core' consortium of bacteria and yeasts[13] that always possesses cellulose-forming properties.[13,14] There have been many studies to evaluate the microbial composition of kombucha cultures and assess the optimum conditions for tea brewing.[10,15–18] Some studies have attempted to replicate the original culture in media other than tea. These have included complex media such as pineapple, watermelon and orange juice,[19–21] coconut water[22] and beer.[23]

Efforts to create a defined medium, essential for reproducibility, are ongoing, but such media have required the addition of complex yeast extract to stimulate pellicle growth.[24,25] Schramm and Hestrin[26] developed the 'standard' (but undefined) complex growth medium (commonly known as H&S) consisting of glucose, bactopeptone and yeast extract.[23,25,27,28] This medium is commonly used in experiments that remove the developed pellicle/biofilm from the surface of the liquid medium, rinsing using distilled water and NaOH to lyse any residual bacterial cells. The biofilm is then dried using various methods (most commonly ambient air-drying) until a constant weight is achieved, from which the overall yield of BC (in terms of weight rather than purity) is calculated.[23,25,27–29]

Studies examining the performance of BC as a textile in apparel have focused on the production of BC sheets,[30,31] the ability of the sheet to be formed into garment shapes[32] or the response of the sheet to textile coloration and finishing techniques from an aesthetic viewpoint.[33,34] Whilst previous studies have postulated the use of BC as an apparel textile, with some suggesting it could be seen as a replacement to animal leather,[7,35] to the authors' knowledge, no studies to date have specifically tested the sheets as an apparel textile to establish their performance characteristics and suitability for fashion garment end-use. If the BC sheet is to be considered as an animal leather alternative in the apparel industry, tests commonly used to assess the performance of leather during garment wear, including tensile strength and abrasion, should be carried out. In addition, wearer comfort in apparel is associated (in part) with the moisture transmission characteristics of a textile, and thus should be evaluated for any textile proposed for apparel purposes.[36–38]

Such work is critical if BC is to be used as a viable alternative textile in fashion apparel. This study aimed to identify the best practice for simple but reproducible small batch fabrication of a BC biofilm so that more reliable data could be generated relating to the textile performance properties of the resultant material, thus allowing evaluation of BC performance against 'comparable' textiles (such as animal leathers, nonwovens and cellulose-based structures) for use in the fashion garment arena.

Materials and methods

Fabric samples

Bacterial cellulose sheets. A commercially available 200 g Kombucha pellicle in 100 ml of green tea was purchased from 'Happy Kombucha' (https://happykombucha.co.uk/) and stored on a bench top at room temperature in its original green tea broth (as provided) until required for experiments. To produce a standardized inoculum, 100 g of the starter culture was placed in a 500 ml sterile pot containing 250 ml sterile H&S medium. A lid was loosely placed on the pot, which was stored in an incubator (30°C) for 15 days. After 15 days, solids (=pellicles) were removed from the pot by filtration, with the remaining liquid broth used as inoculum.

To determine the most suitable medium to support BC sheet generation, a variety of growth media were used to grow kombucha pellicles (Table 1).

In this study, coconut water was selected for its 'natural' origin.[39] Beer already contains yeast extract and previous studies have suggested that enhanced yeast extract content helps support pellicle development.[41] The exact content of yeast in the supermarket-purchased beer was unknown. Black tea broth was prepared using recipes collected during the literature review as guidance (3 g leaf tea steeped in 1 l boiling water for 15 min).[10,41]

To determine whether sterile conditions were necessary to produce the BC pellicles, each medium was split into two parts; one half was autoclaved and after cooling to ambient temperature, and 10 ml aliquots of media were aseptically dispensed into 30 sterile 25 ml containers. The other half was not autoclaved, and 10 ml aliquots of media were dispensed directly into 30 sterile 25 ml containers.

Each container was then inoculated with 1 ml of original kombucha pellicle tea broth. The lid was placed loosely on top, and the container incubated at 30°C with conditions monitored using a USB datalogger (model: Easylog USB, manufacturer: Lascar Electronics, Wiltshire, UK). Visual observations of pellicle development and sampling took place 27, 34 and 42 days after inoculation (10 pots per sample date).

Pellicles on the surface of the liquid media were removed with sterile forceps and placed on dry filter paper to remove any excess surface moisture. These pellicles were then removed from the paper using forceps and individually placed in petri dishes and weighed twice – (i) in the wet state and (ii) after drying for 24 hours in a fan oven at 60°C (which equaled constant weight, as determined in preliminary work; results not included in this paper).

The weight of BC produced per volume of liquid (% w/v) was calculated.[25,26] Mean and standard deviations of the weights recorded were calculated with outliers removed using the interquartile range statistical method.[42]

The presence of a cellulosic molecular structure in the pellicle samples was confirmed using Fourier transform infrared spectroscopy (FTIR) (model: FTIR UATR Spectrum 2, manufacturer: Perkin Elmer). To determine any differences in the morphology, samples of each of the pellicles were observed under a scanning electron microscope (SEM) (model: Supra 40VP, manufacturer: Carl Zeiss Ltd). The samples were prepared for viewing by storing in a desiccator[42] before being mounted on a metal stub using a sticky carbon disc and sputter coated in gold to 10 nm thickness.[43,44]

Comparison fabrics for assessment. Fabrics were chosen for comparison to the BC according to their physical morphologies (determined by visual assessment, and by

Table 1. Media used for pellicle/biofilm growth

Type of medium	Preparation	Comments
Coconut water	Pre-packaged coconut water[39] was purchased from a local supermarket. The liquid was centrifuged to extract any residual solids.	After preparation/purchase of the media, each liquid was decanted into separate sterile 500 ml Duran bottles and sterilized in an autoclave for 10 min @ 115°C (the lower temperature was used to reduce risk of glucose caramelization).
Bitter	Own brand bitter (2.8%) – Morrisons supermarket[40]	
Black Tea	Tea broth was prepared by steeping 1 tea bag (Yorkshire brand black tea) in 1 l boiling water for 15 min (approx. 3 g tea/l). The bag was removed and 100 g glucose added (10%).[10,41]	
H&S	2% Glucose, 0.5% bactopeptone, 0.5% yeast extract added to 1 l distilled, deionized water.[24]	

reference to BC SEM images), mass per unit areas, thickness and composition.

The purpose of the study was to evaluate BC as an alternative textile for fashion apparel, and therefore common textile performance tests relevant to this field were chosen: tensile strength and elongation, abrasion and moisture permeability. Tests such as thermal insulation/conductivity and air permeability were not considered in this work as these are usually characteristics associated with performance clothing.

Mass per unit area

Three $10\,\text{cm} \times 10\,\text{cm}$ square specimens were cut with fabric shears at randomized points from each sample fabric. These samples were weighed individually on a precision laboratory balance (Sartorius, Germany) and the mean of these readings was calculated. The arithmetic mean was multiplied by 100 to determine the mass per unit area of the fabric in g/m^2.

Thickness

Using a thickness gauge (Mercer, UK; model 110), readings were taken at five randomized points for each sample fabric. The arithmetic mean of these readings was calculated to determine the thickness of each fabric sample in mm.

Tensile strength and elongation (BS EN ISO 13934)

In accordance with the specified method, three specimens were taken at randomized points from each sample fabric. The samples were mounted on the tensile tester (Instron, UK; model 33R4465), with a jaw separation width of 100 mm. The machine was set to an extension rate of 100 mm/min and all specimens were extended to breaking point with maximum force at break (N) and breaking elongation (mm) recorded.

Martindale abrasion (BS EN ISO 12947-1)

In accordance with the specified method, three specimens were taken at randomized points from each sample fabric. The samples were mounted on the Martindale Abrasion tester (James Heal, UK: model NU 864) in accordance with test standard BS EN ISO 13934 and the machine set to rub at 5000 revolution intervals against an abrasive cloth (James Heal, UK: original SM25), with a 9 kPa weight per specimen. The specimens were assessed after each 5000 rubs and removed at the point of destruction with the number of rubs recorded.

The test was repeated using a 12 kPa weight for the animal skin and BC specimens only and specimens were assessed after each 5000 rubs and removed at the point of destruction with the number of rubs recorded.

Taber Abraser (BS EN ISO 17076-1:2020)

In accordance with the specified method, three specimens were taken at randomized points from the animal leather, animal suede and BC sample fabrics. The samples were mounted on a Taber Abraser (Taber Industries, USA; model 5135), using Calibrase CS-10 (Taber Industries) abrasive wheels, 1000 g weights and a textile specimen clamp with double-sided tape to ensure no movement of the sample on the mount during the test. The appearance and weight each sample was assessed and noted before the test and at 1000 revolution intervals until the sample broke down or a total of 10,000 revolutions was reached.

Breathability: water vapor transmission (BS 7209:1990)

In accordance with the specified method, three 90 mm diameter circular specimens were taken at randomized points from each sample fabric and individually weighed. Each sample was mounted on an individual pot containing 40 ml distilled water and a gauze cover affixed covering the fabric sample and the pot. Each pot was weighed, mounted on the rotating disc for 24 hours, removed and reweighed, in accordance with test standard BS 7209:1990. The fabric samples were removed from the pots and reweighed immediately.

The water vapor transfer (WVP) of each fabric was calculated by comparing the mass of the pot at the start and end of the test and using the following calculation

$$\mathrm{WVP} = 24M/At$$

where M is the mass lost (g), t is the time (hours), A is the area (m^2), $A = (\pi d^2/4) * 10^{-6}$ and d is the diameter of the dish (mm).

Water vapor absorbed by the fabric and still present at the end of the test was calculated as a percentage mass by weight as follows

$$\begin{aligned}&((\text{Mass (g) of sample at end of test–Mass (g) of}\\&\text{sample at start of test)}\\&/\text{Mass (g) of sample at start of test}) * 100\end{aligned}$$

As an additional measure in this test (not specified in the standard test method), each fabric sample was weighed before and after the test was completed, and these weights compared to establish the moisture retention of the material.

Results and discussion

Bacterial cellulose sheet development

Across all the media studied, samples prepared under sterile conditions gave higher yields of BC sheet than their non-sterile counterparts (Figures 1(a)–(c)). It is likely that contaminants might affect the yield, so it is always preferable to maintain an aseptic technique and sterile conditions when appropriate.

Sterile tea always gave the highest yields of BC at each time point and a general trend of increase in yield across time was observed. This contrasts with the other media, which displayed almost constant yields/a slight decrease in yields between 27 and 42 days. However, it should also be noted that the standard deviation of yield measurements was also largest in the sterile tea broth.

H&S broth samples gave the lowest yield of all media across all timepoints observed, and the difference in yield from sterile and non-sterile H&S broths was less than for the other samples measured. It was also noted that H&S broths gave measurements with the lowest standard deviation. It could therefore be considered that whilst the H&S BC yield is low, it is also the most consistent in terms of yield. However, as the tea broth gave the greatest yield of BC sheets, this broth was selected to grow further material for evaluation.

To develop larger sheets of BC in tea, sterile tea liquid was prepared as detailed in the methods section above. Some 300 ml of tea liquid was dispensed into plastic containers (170 (l) × 50 (d) × 110 (w) mm) and inoculated with 30 ml of original Kombucha pellicle tea broth. Lids were loosely placed on the containers and the BC sheets allowed to develop for 40 days. The sheets were removed, rinsed with water and left to dry for 1 week in ambient conditions on a laboratory bench.

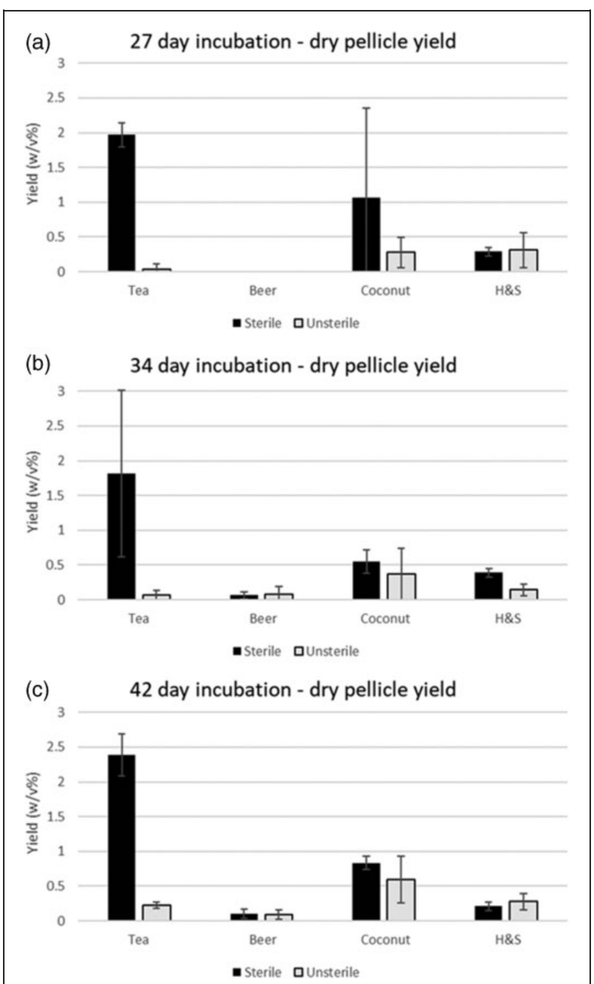


Figure 1. Dry pellicle yield after (a) 27 days, (b) 34 days and (c) 42 days. H&S: Hestrin and Schramm medium.

Physical morphologies and selection of comparison fabrics

FTIR traces performed on the pellicle samples displayed peaks in the regions shown in Table 2. Neera et al.,[43] Dima et al.[45] and Halib et al.[46] all concur that these peaks are indicative of the presence of a cellulosic structure.

There was very little difference in the spectral data in terms of the occurrence of peaks across the growth media permutations, indicating the same molecular structure across the samples.[19]

SEM images (Figure 2) revealed BC sheets to be a random mesh of nanofibers, arranged in a similar structure to a traditional non-woven fabric structure (such as those seen in felt or non-woven interlining fabrics), regardless of the growing liquid.[8,17] The nanofibers all measured a similar diameter (approximately 100 nm).

Non-woven fabrics are defined as textile structures that are created from fibers and formed into webs by bonding or interlocking via mechanical, thermal, chemical or solvent processes.[47–49] Therefore, three non-woven fabrics were selected for comparison, a plant-derived cellulose fiber sheet (mechanically manufactured), a woolen felt (mechanically manufactured)

Table 2. Indicative bacterial cellulose Fourier transform infrared spectroscopy wavelength peaks

Wavelength peak (cm^{-1})	
3350	O-H stretching
2800–2900	C-H stretching
1160	C-O-C stretching
1035–1060	C-O stretching
1300	C-H bending
1400	CH_2 bending

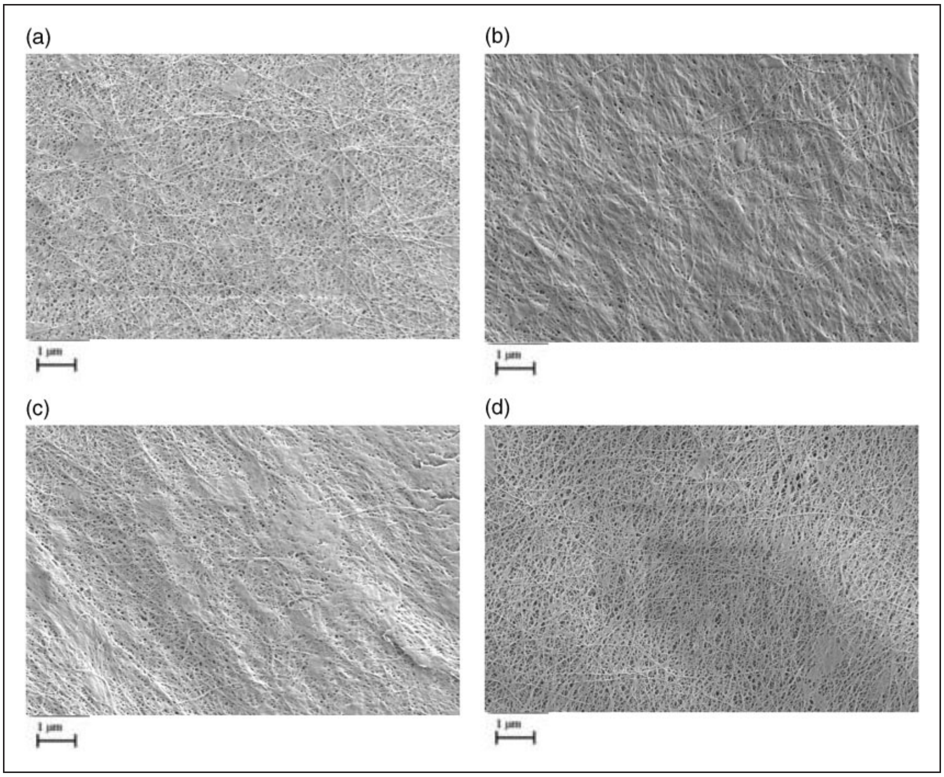


Figure 2. Scanning electron microscope images of bacterial cellulose sheets grown in different liquids (×10 k magnification). H&S: Hestrin and Schramm medium. (a) Tea; (b) beer; (c) coconut and (d) H&S.

Table 3. Fabrics selected for comparison to bacterial cellulose

Sample fabric	Comments
Bacterial cellulose	Vegetable leather sheet.
Animal skin (suede)	Cow hide, napped surface.
Animal skin (leather)	Cow hide, natural grain surface.
Cellulose sheet	Mechanically compressed cellulose fibers.
PA interlining	Mechanically and chemically manufactured sheet
Wool felt	Mechanically engineered wool fibers.

PA: polyamide.

and a polyamide (PA) sheet (thermally and chemically manufactured) (Table 3).

BC is often referred to as vegetable leather, with some studies suggesting it is a viable alternative to animal hide. Therefore, two types of cow hide were selected for comparison: natural grain (leather) and napped surface (suede) (sourced from university fabric stores) (Table 3).

Mass per unit area and thickness

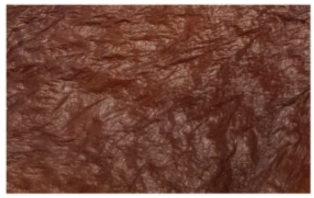
The wool felt, PA, animal suede and cellulose non-woven were of similar weight (169–234 gm^{-2}). BC was slightly heavier (323.67 gm^{-2}), with animal leather displaying the greatest mass per unit area (685.00 g/m^{-2}). However, measurements of the thickness revealed the cellulose non-woven material to be the thickest material (1.88 mm) and animal suede the to be thinnest (0.60 mm). These results can be explained by the physical structure of the materials; the cellulose non-woven is constructed of plant cellulose fibers, mechanically bound together into a loose and open fabric structure (Table 4). The animal suede, leather and BC sheet are much denser in physical structure with fewer visible gaps between their constituent fibers (Table 4). The samples were deemed acceptable for further comparison as they were representative of fabrics used in apparel applications.

It is also worthy of note that the chosen materials had different surface morphologies when examined using the naked eye. The animal leather displayed a relatively smooth surface and the animal suede was napped/raised, whilst the BC had an undulating surface. All the manufactured non-wovens have similar fibrous surface characteristics (Table 3).

Textile testing

To choose the most relevant textile testing methods, it is important to understand textile performance characteristics when designing and manufacturing apparel to

Table 4. Sample mass and thickness

Sample (image ×2 magnification)		Mean mass per unit area (g/m^{-2})	Mean thickness (mm)
Bacterial cellulose		323.67 (SD 2.87)	0.62 (SD 0.14)
Animal skin (suede)		234.64 (SD 0.47)	0.60 (SD 0.02)
Animal skin (leather)		685.00 (SD 0.82)	1.31 (SD 0.06)
Cellulose non-woven		178.67 (SD 2.36)	1.88 (SD 0.14)
Polyamide non-woven		208.33 (SD 0.47)	0.95 (SD 0.03)
Wool felt		169.00 (SD 2.83)	1.09 (SD 0.04)

ensure the garment meets the wearer's expectations in terms of comfort and fitness for purpose. To this end, there are many laboratory-based tests that can establish the physical performance of a textile and therefore its suitability for specific end-uses.[50–53]

Non-woven fabrics are generally used in apparel as a 'support' to give structure and shape definition for the main body fabric used in the garment.[54] There are several textile testing methods that have been modified to cater for the 'unique' structure of non-wovens[49]; however, as this study aimed to establish the suitability of BC as an apparel outer fabric (and not a 'support' fabric), the modified versions of the standard tests were not used.

As BC has been suggested as an animal leather alternative, the most likely apparel end-use is outerwear or apparel that is expected by consumers to have levels of superior durability. Tensile performance and abrasion resistance were therefore chosen as the most relevant indicative tests of these characteristics.

However, as previously mentioned, comfort characteristics cannot be overlooked. It is well documented that moisture management of textiles and clothing is a critical factor in wearer comfort.[37,38,55–59] Moisture vapor transfer and moisture retention capacity were chosen to establish the performance of the sample fabrics.

Tensile strength and elongation. Animal leather, animal suede and BC displayed definite and abrupt points of failure, with 'clean' break points visually observed in the fabric samples (Figure 3(a)). However, the BC withstands lower forces and elongates less before rupture (0.196 kN at 17.85 mm) than its animal leather (0.844 kN at 29.77 mm) and suede (0.515 kN at 59.32 mm) counterparts (Figure 3(b)).

The wool, PA and cellulose non-wovens all displayed low and comparable forces at failure (Figure 3 (b)). Figure 3(a) illustrates the gradual, less abrupt breakdown of the fabric structure in comparison to the abrupt failure observed in the animal skin and BC samples. The wool felt extended most at its failure point and it is suggested this is likely to be due to friction of scales on the wool fiber holding the structure together.[60] By comparison, the cellulose and PA fibers have a smoother surface morphology therefore less mechanical friction between fibers to hold them together, resulting in lower breakdown force and extension.[61]

These results indicate that BC would not be suitable as an animal skin replacement in apparel applications where resistance to stress is critical, but it could still be considered in applications where non-wovens are currently used. Closer fitted garments (such as leather jackets) generally require higher tensile strength performance due to the strain applied to the fabric when the body moves. However, non-woven fabrics can be used in looser fitting garments (such as personal protective equipment (PPE) gowns or outer coats), suggesting the tensile and elongation performance of BC does not completely exclude this from apparel applications.

Moisture performance. Moisture vapor permeability (MVP) measures the rate of transmission of water vapor through a material. In textiles, this is often used to describe the 'breathability' of a fabric; that is, the rate at which the textile allows perspiration moisture to move away from the body, pass through the textile clothing and subsequently evaporate into the atmosphere. The higher the reading from the test, the more transmissible water vapor through the fabric.[62] The breathability of a fabric can be affected by the fiber composition, fabric construction and thickness.[36]

The MVP test suggested the most breathable fabrics were the non-woven plant cellulose, PA and wool structure, with results of 659.65, 685.32 and 690.03 g/ m^{-2} . 24 h, respectively (Figure 4). These structures have larger gaps between the fibers than their animal skin and BC counterparts, thus allowing moisture vapor to travel more freely through the structure. Conversely, the more densely structured animal skin samples showed less breathability (leather 671.96 and suede 531.28 gm^{-2} . 24 h) (Figure 4). BC showed the least degree of breathability (205.39 gm^{-2} . 24 h), more than 60% less breathable than animal suede (Figure 4).

Marked differences were also observed when examining residual moisture in the samples. The synthetic PA non-woven retained the least moisture (0.26%) and the 'natural' fabrics (cellulose non-woven, wool felt, animal suede, animal leather) retained between 2.06% and 5.34% (Figure 5). These differences can be explained by previous studies; natural fibers have a greater ability to absorb moisture than synthetics.[36,58,63]

However, BC retained a markedly larger percentage of moisture (14.67%) than the other fabrics tested (Figure 5). Again, this is not surprising, as a characteristic of BC is its enhanced ability to absorb moisture.[8] This also explains the poor moisture vapor transfer result for BC; the material can absorb moisture from the surrounding atmosphere but cannot easily release this. This is an issue for clothing where the textile is in direct contact with the skin; such moisture retention would lead to wearer discomfort.[37,56,57] However, in application such as, for example, wound dressings[64,65] or beauty products (e.g., face masks),[66–68] this degree of water retention could be advantageous and enhance the product performance.

Abrasion durability performance. The Martindale abrasion test is a useful measure of the potential of a fabric to 'wear out' over a lifetime of use. As the test specimens are rubbed over an abrasive cloth, it could be suggested that the thicker specimens should show greater resistance to wear, with thinner specimens potentially failing the test more rapidly. However, various studies have illustrated that it is factors such as fabric/yarn structure, fiber composition[69,70] and molecular structure[71] that are of the most significance when determining resistance to abrasion.

Traditional textile non-woven fabrics are known for their poor abrasion characteristics in comparison to traditional woven and knitted textile structures.[49,72] This is illustrated by the results of the Martindale abrasion test, with the cellulose and PA non-woven fabric

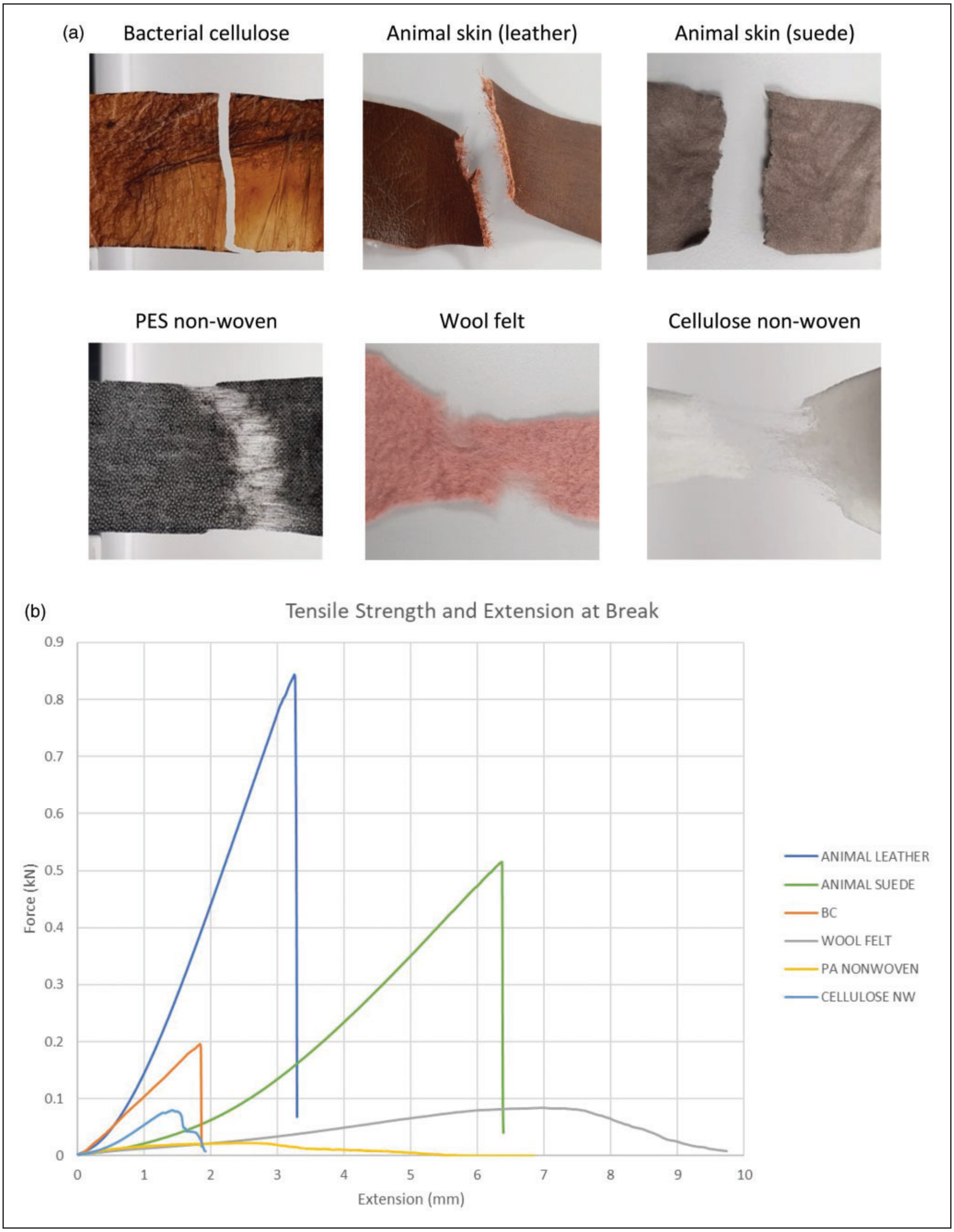


Figure 3. (a) Physical breakdown of samples after the tensile test. (b) Tensile strength and elongation. PES: polyester; BC: bacterial cellulose; PA: polyamide; NW: non-woven.

breaking down at 5000 and 10,000 rubs @ 9 kPa, respectively. Non-woven wool felt performed better, with total breakdown at 15,000 rubs @ 9 kPa (Figure 6). In a similar way to the tensile performance discussed above, this performance could be attributed to the surface morphology of the constituent fibers; scales on the protein wool fiber could cause an interlocking effect and thus enhance the abrasion durability of the fabric in comparison to the smoother surfaces of the cellulose and PA non-woven fabric fibers.

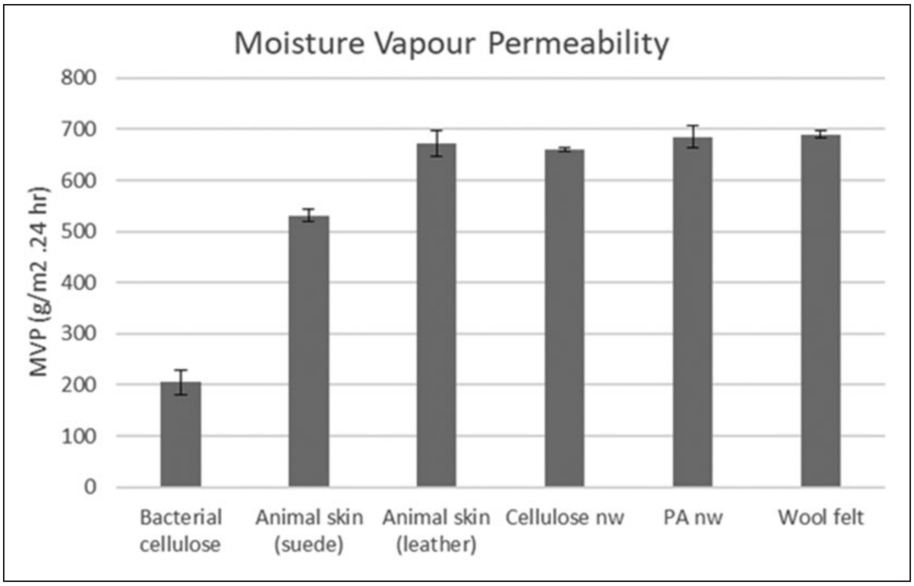


Figure 4. Breathability of the sample fabrics. MVP: moisture vapor permeability; NW: non-woven; PA: polyamide.

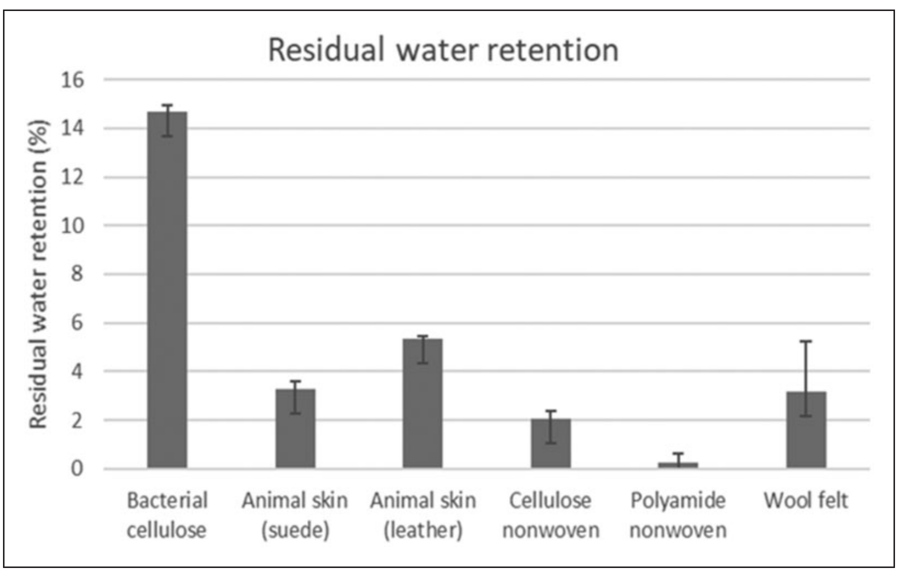


Figure 5. Water retention of the sample fabrics.

The BC, animal suede and leather resisted a much greater number of rubs and were therefore tested using both the 9 and 12 kPa weights (Figure 6). Whilst apparel performance is normally assessed using 9 kPa, superior textile performance (normally attributed to upholstery and other high-performance textile applications) is ascertained using 12 kPa; Martindale abrasion testing for leather is normally conducted using a 12 kPa weight.

BC displayed excellent abrasion resistance, with superior performance to animal skin at 9 kPa. BC showed no signs of breakdown at 150,000 rubs with a 9 kPa weight, whilst animal suede broke down at 90,000 (Figure 6). This level of abrasion is classed as superior performance for everyday apparel applications.[52,72,73]

At 12 kPa BC failed at 105,000 rubs, displaying a similar performance to animal leather (100,000 rubs). Both were superior to animal suede, which failed at 15,000 rubs (Figure 6).

As the BC and both animal leathers displayed superior abrasion characteristics during the Martindale abrasion test, the three materials were subjected to the Taber Abraser test, which is considered a harsher, more destructive test normally reserved for technical textiles where a high degree of abrasion resistance is required.[73]

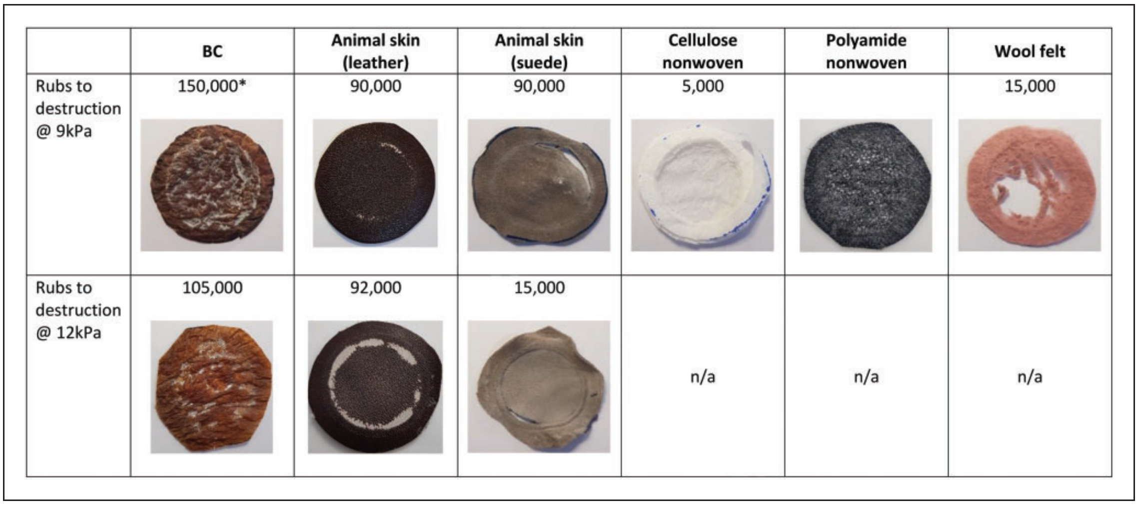


Figure 6. Martindale abrasion sample appearance at end of the test. *No failure, specimen still intact – test abandoned. BC: bacterial cellulose.

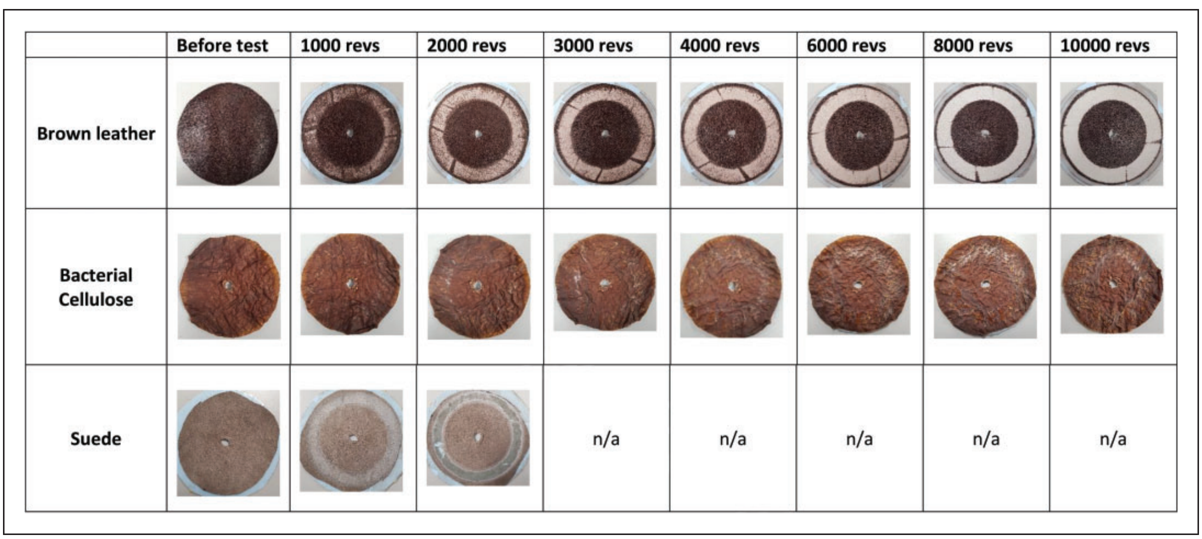


Figure 7. Taber Abraser sample appearance.

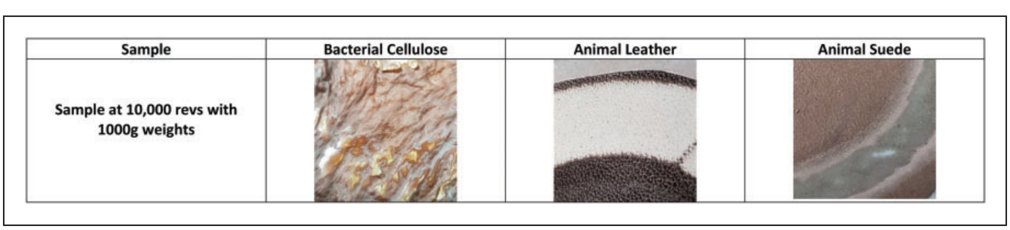


Figure 8. Taber Abraser: sample damage at 10 k revs (suede total breakdown at 2 k).

BC and animal leather were comparable in performance during the Taber Abraser test (Figure 7): animal suede broke down rapidly to failure after 2000 revs (Figure 8). However, BC and animal leather showed a steady and comparable degree of mass loss to 10,000 revs, at which point the test was abandoned as all the surface of the animal leather had been removed (Figure 9). As an indication of the level of performance, European Standard EN388-2016 (protective gloves against mechanical risks) states that at the highest level

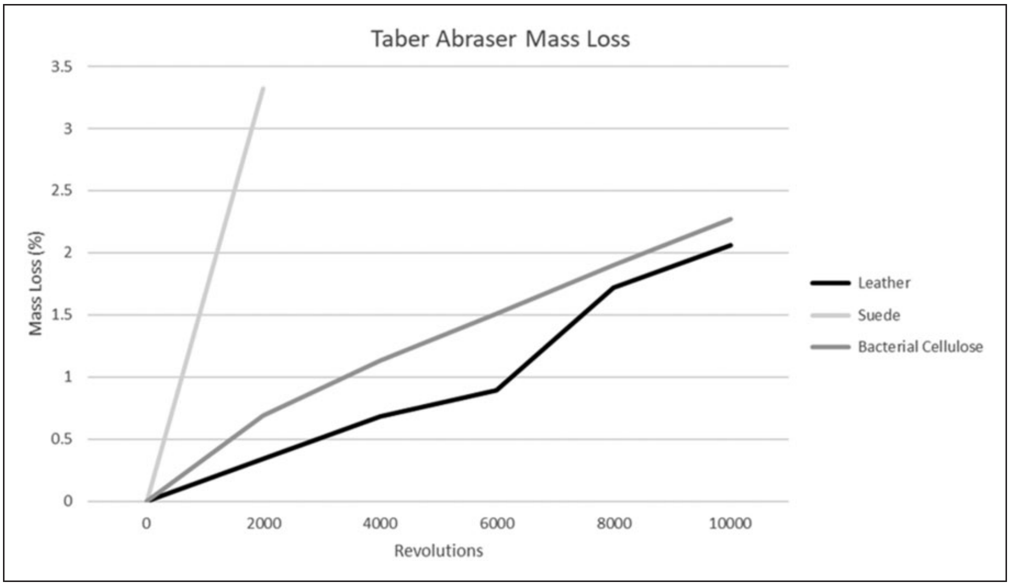


Figure 9. Taber Abraser – sample mass loss over time.

of protection a textile should withstand 8000 revs at 1000 g.[74] Upon visual examination, neither of these samples displayed complete physical breakdown, with very little surface damage noted on the BC sample (Figure 8). It could therefore be suggested that the BC is more durable to abrasion than the animal leather sample tested and could be suitable as a high-performance abrasion resistant textile. However, as noted above, the moisture retention properties of BC mean that this material would not be suitable to be worn against the skin, so it is suggested that encapsulation of BC within the structure of the garment would need to be explored. The encapsulant would need to be carefully chosen as to not inhibit the performance of BC.

Conclusion

This study first determined the optimum method for fabrication of reproducible small batch manufacture of BC sheets. To our knowledge, it is the first study to assess BC as a textile for potential fashion apparel applications. Evaluation of BC against standards for textiles used in fashion clothing is important if BC is to ever be considered as a replacement for traditional textile sources in this field.

Whilst laboratory-manufactured liquid growth medium (H&S) gave the most consistent yields, sterile black tea and sugar produced the highest yield of BC sheets. Sterile black tea with glucose was therefore used to grow larger pieces of BC for textile performance evaluation.

SEM examination of the BC sheets revealed a nanofibrillar mat structure, which was directly comparable to the structure of 'traditional' non-woven fabric, thus a selection of non-woven fabrics was used for performance comparison to BC. As many practitioners have suggested BC could be a replacement for animal leather, animal skins were also selected for performance comparison to BC.

There are many test criteria that could be applied when assessing the performance of a textile for an apparel end-use and they are largely dependent on the expectations of the wearer. However, as this study explored the application of BC in fashion apparel, it focused on the aspects of strength and durability in wear (tensile strength and abrasion) and the moisture transfer properties considered important when assessing elements of wearer comfort.

Tensile strength and elongation testing revealed that whilst BC physically behaves as animal skin in terms of abrupt breakdown, the forces and elongation required to elicit this breakdown are considerably lower for BC than its animal skin counterparts. However, BC withstood higher forces at break than the comparable nonwoven structures, suggesting that BC could have applications in looser fitting apparel where tensile strength is not a prohibitive factor.

The moisture transfer capabilities of fabrics are critical for the consideration of comfort of apparel. BC was the least breathable of all the samples tested and retained the most moisture at the end of the test. This indicated that BC would not be suitable for use in a garment worn in direct contact with the skin. However, there may be applications for BC in fashion outerwear where moisture absorbance/repellency performance is not a limiting factor in fabric selection (e.g., fashion clothing not designed for wet weather protection).

BC outperformed all other samples in terms of abrasion resistance, showing no signs of breakdown even after points of failure for the animal leathers. This result is of greatest interest from the study, as the BC tested exceeds the most rigorous requirements of European Standards for clothing designed to protect against abrasion.

These findings suggest the BC would not be suitable in close fitting apparel due to its tensile, elongation and vapor transfer/moisture retention characteristics. The application of a specialist finish could go some way to counter this, although this may compromise the sustainable aspect of the BC and require re-evaluation of the performance characteristics to ensure there are no adverse effects. However, the superior abrasion performance of BC could render it useful in clothing for protection; it is suggested from these results that the BC could be used as sealed-in patches in clothing (to prevent moisture absorbance and thus potential negative effects on abrasion performance) rather than the whole garment (for example, in high-impact wear such as motorbike leathers and areas of potential high abrasion (such as knees) in workwear clothing). We would suggest further performance trials of BC in this context. Furthermore, extending the apparel testing regime to include properties such as thermal insulation/conductivity, air permeability and performance to laundering could allow for a wider range of apparel applications to be suggested.

Declaration of conflicting interests

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References

1. Parliament EAC-U. Fixing fashion: clothing consumption and sustainability – Sixteenth Report of Session 2017–19 In: Committee EA (ed.) London: Environmental Audit Committee, UK Parliament, 2019.
2. UN. Sustainable Development Goals; Goal 12: Ensure sustainable consumption and production patterns, https://www.un.org/sustainabledevelopment/sustainable-consumption-production/ (accesssed 19th September 2022).
3. WRAP. *Textiles* 2030. Banbury, 2021, Oxford, UK.
4. Ashjaran A, Yazdanshenas ME, Rashidi A, et al. Overview of bio nanofabric from bacterial cellulose. *J Text Inst* 2013; 104: 121–131.
5. Fernandes M, Gama M, Dourado F, et al. Development of novel bacterial cellulose composites for the textile and shoe industry. *Microb Biotechnol* 2019; 12: 650–661.
6. García C and Prieto MA. Bacterial cellulose as a potential bioleather substitute for the footwear industry. *Microb Biotechnol* 2019; 12: 582–585.
7. Fairs M. Microbes are the "Factories of the Future". Dezeen and mini frontiers exhibition, 2014.
8. Dufresne A. *Nanocellulose: from nature to high performance tailored materials*. Berlin/Boston, MA: Walter de Gruyter GmbH Co.KG, 2012.
9. Brown RM, Willison JHM and Richardson CL. Cellulose biosynthesis in acetobacter xylinum – visualization of site of synthesis and direct measurement of invivo process. *Proc Natl Acad Sci USA* 1976; 73: 4565–4569.
10. Jarrell J, Cal T and Bennett JW. The kombucha consortia of yeasts and bacteria. *Dept Cell Mol Biol* 2000; 14: 166–170.
11. Reva ON, Zaets IE, Ovcharenko LP, et al. Metabarcoding of the kombucha microbial community grown in different microenvironments. *AMB Expr* 2015; 5: 1–8.
12. Kurtzman CP, Robnett CJ and Basehoar-Powers E. Zygosaccharomyces kombuchaensis, a new ascosporogenous yeast from 'Kombucha tea'. *FEMS Yeast Res* 2001; 1: 133–138.
13. Teoh AL, Heard G and Cox J. Yeast ecology of kombucha fermentation. *Int J Food Microbiol* 2004; 95: 119–126.
14. Chakravorty S, Bhattacharya S, Bhattacharya D, et al. Kombucha tea fermentation: microbial and biochemical dynamics. *Int J Food Microbiol* 2016; 220: 63–72.
15. Četojević-Simin DD, Velićanski AS, Cvetković DD, et al. Bioactivity of lemon balm kombucha. *Food Bioproc Technol* 2012; 5: 1756–1765.
16. Gaggìa F, Baffoni L, Galiano M, et al. Kombucha beverage from green, black and rooibos teas: a comparative study looking at microbiology, chemistry and antioxidant activity. *Nutrients* 2019; 11: 1.
17. Wood J, van der Gast C, Rivett D, Verran J, et al. Reproducibility of bacterial cellulose nanofibers over sub cultured generations for the development of novel textiles. *Front Bioeng Biotechnol* 2022; 10. DOI: 10.3389/fbioe.2022.876822
18. Marsh AJ, O'Sullivan O, Hill C, et al. Sequence-based analysis of the bacterial and fungal compositions of multiple kombucha (tea fungus) samples. *Food microbiol* 2014; 38: 171–178.
19. Castro C, Zuluaga R, Putaux J-L, et al. Structural characterization of bacterial cellulose produced by Gluconacetobacter swingsii sp. from Colombian agroindustrial wastes. *Carbohydr Polym* 2011; 84: 96–102.
20. Jahan F, Kumar V, Rawat G, et al. Production of microbial cellulose by a bacterium isolated from fruit. *Appl Biochem Biotechnol* 2012; 167: 1157–1171.
21. Kurosumi A, Sasaki C, Yamashita Y, et al. Utilization of various fruit juices as carbon source for production of bacterial cellulose by Acetobacter xylinum NBRC 13693. *Carbohydr Polym* 2009; 76: 333–335.
22. Kongruang S. Bacterial cellulose production by acetobacter xylinum strains from agricultural waste products. *Appl Biochem Biotechnol* 2008; 148: 245–256.

23. Shezad O, Khan S, Khan T, et al. Production of bacterial cellulose in static conditions by a simple fed-batch cultivation strategy. *Kor J Chem Eng* 2009; 26: 1689–1692.
24. Schramm M, Gromet Z and Hestrin S. Synthesis of cellulose by Acetobacter xylinum. 3. Substrates and inhibitors. *Biochem J* 1957; 67: 669–679.
25. Yamanaka S and Sugiyama J. Structural modification of bacterial cellulose. *Cellulose* 2000; 7: 213–225.
26. Schramm M and Hestrin S. Factors affecting production of cellulose at the air/liquid interface of a culture of Acetobacter xylinum. *J Gen Microbiol* 1954; 11: 123.
27. Setyawati MI, Chien L-J and Lee C-K. Expressing Vitreoscilla hemoglobin in statically cultured Acetobacter xylinum with reduced O_2 tension maximizes bacterial cellulose pellicle production. *J Biotechnol* 2007; 132: 38.
28. Singh R, Mathur A, Goswami N, et al. Effect of carbon sources on physicochemical properties of bacterial cellulose produced from Gluconacetobacter xylinus MTCC 7795. *E-Polymers* 2016; 16: 331–336.
29. Schramm M and Hestrin S. Synthesis of cellulose by Acetobacter xylinum. I. Micromethod for the determination of celluloses. *Biochem J* 1954; 56: 163.
30. Yim SM, Song JE and Kim HR. Production and characterization of bacterial cellulose fabrics by nitrogen sources of tea and carbon sources of sugar. *Proc Biochem* 2017; 59: 26–36.
31. Ng MCF and Wang W. A study of the receptivity to bacterial cellulosic pellicle for fashion. *Res J Text Apparel* 2015; 19: 65–69.
32. Chan CK, Shin J and Jiang SXK. Development of tailor-shaped bacterial cellulose textile cultivation techniques for zero-waste design. *Clothing Text Res J* 2018; 36: 33–44.
33. Han J, Shim E and Kim HR. Effects of cultivation, washing, and bleaching conditions on bacterial cellulose fabric production. *Text Res J* 2018; 8(6): 1094–1104.
34. Shim E and Kim HR. Coloration of bacterial cellulose using in situ and ex situ methods. *Text Res J* 2019; 89: 1297–1310.
35. Launch. Suzanne Lee: biocouture – launch, https://www.launch.org/innovators/suzanne-lee/ (2019, accessed 20th August 2020).
36. Watkins S. *Clothing the portable environment*. The Iowa State University Press, Ames, Iowa, USA, 1985.
37. Watkins SM and Dunne LE. *Functional clothing design: from sportswear to spacesuits*. New York: Fairchild Books; 2015.
38. Song G. *Improving comfort in clothing*. Oxford; Philadelphia, PA: Woodhead Pub., published in association with the Textile Institute, 2011.
39. Vitacoco. Vita coco, https://www.vitacoco.com/ (2020, 19th October 2020).
40. Morrisons. Morrisons, www.morrisons.com (2020, 10th October 2020).
41. Jayabalan R, Malbaša RV, Lončar ES, et al. A Review on kombucha tea—microbiology, composition, fermentation, beneficial effects, toxicity, and tea fungus. *Comprehens Rev Food Sci Food Saf* 2014; 13: 538–550.
42. O'Gorman TW. *Adaptive tests of significance using permutations of residuals with R and SAS*. Hoboken, NJ: Wiley, 2012.
43. Neera RKV and Batra HV. Occurrence of cellulose-producing Gluconacetobacter spp. in fruit samples and kombucha tea, and production of the biopolymer. *Appl Biochem Biotechnol* 2015; 176: 1162–1173.
44. Nguyen VT, Flanagan B, Gidley MJ, et al. Characterization of cellulose production by a Gluconacetobacter xylinus strain from kombucha. *Curr Microbiol* 2008; 57: 449–453.
45. Dima SO, Panaitescu DM, Orban C, et al. Bacterial nanocellulose from side-streams of kombucha beverages production: preparation and physical-chemical properties. *Polymers* 2017; 9: 374.
46. Halib N, Perrone F, Cemazar M, et al. Potential applications of nanocellulose-containing materials in the biomedical field. *Materials (Basel, Switzerland)* 2017; 10: 977.
47. ISO 9092:2011. Textiles - nonwovens - definition.
48. Denton MJ and Daniels PN. *Textile terms and definitions*. 11th ed. Manchester: Textile Institute, 2002.
49. Russell SJ and Textile I. *Handbook of nonwovens*. Boca Raton, FL/Cambridge: CRC Press/Woodhead Pub., 2007.
50. Slater K and Harrison PW, Textile I. *Physical testing and quality control: a critical appreciation of recent developments*. Manchester: Textile Institute, 1993.
51. Booth JE. *Principles of textile testing: an introduction to physical methods of testing textile fibres, yarns and fabrics*. 3rd ed. London: Butterworths, 1983.
52. Hu J. *Fabric testing*. Boca Raton, FL/Cambridge: CRC Press/Woodhead, 2008.
53. Saville BP. Textile I. *Physical testing of textiles*. Cambridge/Boca Raton, FL.: Woodhead Pub., in association with the Textile Institute; in North and South America by CRC Press, 1999.
54. Senthil KP and Punitha V. An overview of nonwoven product development and modelling of their properties. *J Text Sci Eng* 2017; 7. DOI: 10.4172/2165-8064.1000310
55. Li Y and Wong ASW. *Clothing biosensory engineering*. Cambridge: Woodhead Pub., 2006.
56. Fourt L and Hollies NRS. *Clothing: comfort and function*. Ann Arbor, MI: UMI Books on Demand, 2002.
57. Almeida L. *Functional finishes for textiles: improving comfort, performance and protection*. Cambridge: Woodhead Publishing, 2015.
58. Lyle DS. *Performance of textiles*. New York: Wiley, 1977.
59. McLoughlin J and Sabir T. *High-performance apparel: materials, development, and applications*. Oxford: Woodhead Publishing, 2017.
60. Mather RR and Wardman RH. *The chemistry of textile fibres*. Cambridge: Royal Society of Chemistry, 2011.
61. Bunsell AR. Textile I. *Handbook of tensile properties of textile and technical fibres*. Oxford: Woodhead Publishing, 2009.
62. Hu J. Textile I. Fabric testing. Boca Raton, FL/Cambridge: CRC Press/Woodhead; 2008.

63. Horrocks AR and Anand SC. *Handbook of technical textiles. Vol. 2, Technical textile applications*. Duxford: Woodhead Publishing, 2016.
64. Sulaeva I, Henniges U, Rosenau T, et al. Bacterial cellulose as a material for wound treatment: properties and modifications. a review. *Biotechnol Adv* 2015; 33: 1547–1571.
65. Beekmann U, Zahel P, Karl B, et al. Modified bacterial cellulose dressings to treat inflammatory wounds. *Nanomaterials (Basel, Switzerland)* 2020; 10: 2508.
66. Amnuaikit T, Chusuit T, Raknam P, et al. Effects of a cellulose mask synthesized by a bacterium on facial skin characteristics and user satisfaction. *Med Dev (Auckland, NZ)* 2011; 4: 77.
67. Ullah H, Santos HA and Khan T. Applications of bacterial cellulose in food, cosmetics and drug delivery. *Cellulose* 2016; 23: 2291–2314.
68. Bianchet RT, Vieira Cubas AL, Machado MM, et al. Applicability of bacterial cellulose in cosmetics – bibliometric review. *Biotechnol Rep (Amsterdam, Netherlands)* 2020; 27: e00502–e.
69. Miguel R, Lucas J, Carvalho L, et al. Garment abrasion strength evaluation: a comparative methods study. *Int J Clothing Sci Technol* 2007; 19: 194–203.
70. Shaw VP and Mukhopadhyay A. Impact of abrasion on strength, elasticity and elastic recovery properties of stretch-denim fabric. *Int J Clothing Sci Technol* 2022; 34: 241–261.
71. Uzun M, Kanchi Govarthanam K, Rajendran S, et al. Interaction of a non-aqueous solvent system on bamboo, cotton, polyester and their blends: the effect on abrasive wear resistance. *Wear* 2015; 322–323: 10–16.
72. Annis PA. *Understanding and improving the durability of textiles*. Oxford: Woodhead Pub., 2012.
73. Textor T, Derksen L, Bahners T, et al. Abrasion resistance of textiles: Gaining insight into the damaging mechanisms of different test procedures. *J Eng Fibres Fabr* 2019; 14. DOI: 10.1177/1558925019829481
74. BS EN 388:2016. Protective gloves against mechanical risks.