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Research paper

Characterization of sustainable bacterial cellulose fabricated with Vietnamese ingredients for potential textile applications: Tensile and handle properties

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ABSTRACT

There has been growing demand for biomaterials due to their natural origin, nontoxicity and biodegradability properties. Bacterial cellulose (BC) is one such material with potential for a wide range of applications in medicine, packaging, food, tissue engineering, cosmetics, fashion and textile. This research has attempted to explore the potential of BC in fashion and textile applications fabricated with the indigenous ingredients available in Vietnam. A range of BC samples were fabricated and characterized for various properties such as pH, thickness, areal density, bursting strength, stiffness, drape and crease recovery angle to explore potential applications in fashion and textile. The results showed that the pH of BC samples was mostly acidic, with a pH range of 2.6 to 4.4. Hence, they were treated with commonly available bases to bring the pH within the skin-friendly range for textile applications. Some bursting strength results showed closer values for the textile sample, indicating its potential for textile applications. However, the stiffness and drape values of the BC samples were significantly higher, and crease recovery was significantly lower, indicating its appropriateness for applications where higher stiffness and lower crease recovery properties are desired. Keeping the properties in mind, the authors successfully designed products such as wallets and decorative paintings using the harvested BC samples.

1. Introduction

Fashion and textile industries are well known for their environmental pollution [27]. Until recently, fashion and textile products have been manufactured from natural, as well as synthetic fibres [37]. Both the fibres have several negative environmental impacts, which are mainly related to water, land and air pollution; resource depletion; and solid waste generation. For example, the most widely used natural fibre, cotton, uses large amounts of toxic chemicals and fresh water during cultivation [32,34]. Synthetic fibres on the other hand are energy intensive as their manufacturing involves high energy consumption. Another famous textile material, natural leather, is associated with toxic chemicals, water pollution and animal cruelty. In the drive towards sustainability, researchers are trying several approaches such as selecting green materials, advanced technologies, energy saving and recycling to reduce the negative environmental impacts. Biomaterials such as BC are one of these approaches under the green materials category having the potential to replace several products produced from synthetic raw materials [15,54].

Recently, there has been a notable increase in research relating to the use of BC such as Kombucha to replace plastic, primarily due to its potential as a sustainable and biodegradable alternative to conventional plastics [16,45]. Both the BC and plant cellulose are formed from the naturally occurring cellulose; however, they exhibit distinct characteristics [43]. BC exhibits enhanced mechanical properties compared to plant cellulose, which can be attributed to its higher purity and crystallinity. Further, BC possesses greater porosity, resulting in an increased capacity for water retention and a higher degree of hydrophilicity [53]. Unlike synthetic materials, BC is found to be nontoxic, biodegradable, and biocompatible, rendering it appropriateness for a wide range of applications. Hence, in a drive towards sustainability, BC is considered to be one of the sustainable materials for future fashion.

Additionally, some researchers have explored the creation of preformed patterns in specific dimensions that can be utilized directly for apparel production, thereby bypassing traditional weaving and knitting processes [8]. This approach can also streamline several other stages,

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including fabric sizing, desizing, and scouring, as well as spreading and cutting. The versatility of Kombucha has been highlighted in various applications, including paper manufacturing, fashion, filtration membranes, smart textiles, high-quality speaker diaphragms, biomedical devices, and artificial skin [29,40]. Consequently, numerous studies have been conducted to enhance Kombucha production using cost-effective media.

In the last decade or so, there has been a growing interest in the fabrication and characterization of various biomaterials including BC for a range of applications [31,47,48]. Several earlier research attempts have focused on characterizing the BC samples from the perspective of understanding only some of their properties such as surface morphology; chemical structure; thermal and mechanical properties [9,52]. However, there have been limited attempts to wholistically understand the properties of BC for fashion and textile applications. There are a range of potential applications of BC in the field of fashion and textile, which include clothing, fashion accessories, footwear and wearable electronics. In order to understand the potential application of BC for clothing, footwear and fashion applications, this research has focused on characterizing BC samples for a range of properties.

Costa et al. [9] evaluated two bacterial cellulose (BC) films as a potential textile surface for the production of clothing prototypes. This study revealed that integrating flat fabric with BC-based biomaterials presents a feasible option for the novel application of BC films in apparel manufacturing, particularly following the enhancement of the mechanical properties of the material. Phan et al. [41] analyzed the influences between physical and thermal dehydration on end-use performance of BC in textile applications. They established the BC possessed a good appearance, oriented fiber arrangement, good water absorbency, water vapor transmission, and resistance to water penetration. Two of the recent review papers have intensively analyzed the potential applications of BC in fashion and textiles [2,35]. The paper by Bao et al. [2] focuses on the systematic literature review (SLR), whereas the paper by Nayak et al. [35] focuses on the applications in fashion and textiles.

The research interest for BC is growing rapidly as it is a biodegradable material derived from natural ingredients [2,44]. Compared to traditional textile manufacturing processes, BC can provide benefits of zero-waste manufacturing, biodegradability, renewability and reduced environmental impacts [36]. Recently, a study by Nam et al. [33] compared the performance of sustainable shoes made with composites of BC and commercial leather shoes using an experimental research design. This study evaluated the performance of sustainable shoes through a biomechanical approach, in contrast to commercially available leather shoes, through human wearer trials. The results of this study validated the comparable characteristics of BC and commercial material-based shoes, as well as the potential for employing a prototype of a men's sustainable shoe as an alternative to leather, particularly regarding kinematic and kinetic aspects.

Despite several advantages of BC, there are some limitations associated with the fabrication process. For example, the incorporation of fresh ingredients into the culture medium requires the recycling of tea and coffee waste post-fermentation, in alignment with circularity principles [35]. The scaling-up process and need for durability may necessitate the use of additives or finishes, which could potentially lead to environmental pollution [2]. The alkaline purification process necessitates the use of water and neutralizing agents to generate materials that possess a neutral pH. Hence, it may be essential to treat wastewater to ensure its cleanliness before discharging the water [4]. Further, the fabrication of BC is comparatively costly due to constraints in scale and elevated processing expenses, which impede its commercial viability [19]. The important factor influencing its cost is the duration required for cultivating the BC, along with the necessary space and equipment. Utilizing waste or by-products from the fruit and beverage sectors can lower the cost associated with raw materials during the scaling process, thereby decreasing overall costs.

In the preliminary stage, the authors have intensively reviewed the properties of BC specimens, factors affecting their growth, potential applications in fashion and textile in addition to the sustainable benefits (in terms of SDGs) [35]. This paper focuses primarily on investigating several properties of BC that are essential for fashion and textile applications, which have not been investigated much in detail earlier. This research employed various ingredients indigenously available in Vietnam to grow the BC samples, which may not be available in many countries. By doing so, the research presented a pathway to produce BC with localized resources in addition to opening the avenues for understanding the interplay between different cultivation conditions and the resultant BC properties for various fashion and textile applications.

The authors have performed in-depth study to investigate the growing conditions of BC and characterized the BC samples to explore the potential applications in fashion and textile. This paper delves into characterizing the BC samples mainly for fashion and textile applications. Various properties such as pH, thickness, areal density, bursting strength, stiffness (in terms of bending length, flexural rigidity and bending modulus), drape coefficient and crease recovery angle of BC samples were evaluated in this paper. Further, some products were fabricated using BC to investigate the potential for fashion and textile applications.

2. Materials and methods

2.1. BC samples and standard fabric

Six different BC samples were used for this research as listed in Table 1. The BC samples were different as the sources of nitrogen and carbon used to fabricate them were varied. Further, the number of days to grow the BC samples was also different. In addition to the BC samples, a knitted fabric (standard single jersey-SS) used to manufacture T-shirt was included in this study as a reference material for comparison of properties of BC for textile applications. The SS sample had areal density of 155 GSM (grams per square meter), which was produced from 20^s Ne cotton yarn, with a stitch density of $190.2/cm^2$. Other properties of sample SS are discussed in the "Results and discussion" section.

2.2. Conditioning of BC samples

Before performing any tests for textile materials, it is essential to condition the samples at standard testing atmosphere. This practice ensures a consistent result and avoids errors associated with the changes in properties due to absorption and desorption of moisture as moisture can alter the properties of textile materials. All the BC samples were conditioned in the standard testing atmosphere (temperature of 20 ± 2 °C and relative humidity (RH) of 65 ± 5 %) before performing any test for at least 24 h [12].

2.3. pH testing

The pH value was monitored in both the culture medium and the final BC samples using a calibrated pH meter. The pH data was collected at the beginning of the experiment and at the end of the cultivation period. Before pH testing, the electrodes were calibrated using a standard buffer solution. Then the pH testing was done by inserting the electrode in the culture medium, which indicates the pH at the beginning. The pH of the culture medium with the final BC samples at the end represents the pH after harvesting. The pH tests were performed in the wet state of the samples. The procedure used for pH measurement followed the ISO standard test method [21] (ISO 3071:2020(en) Textiles-Determination of pH of aqueous extract).

2.4. Thickness and areal density

Thickness of fabrics gives an indication of stiffness and warmth that

Table 1
List of BC samples used for this research.

Sample code	Carbon source (Sugar)	Nitrogen source (Tea)	Starter SCOBY	Growing duration (days)	pH after harvesting	pH at the beginning	Detergent soaking	Fresh water soaking
S1	Brown sugar (300 g)	Black tea (30 g)	Mother 1A	15	2.9	4.3	4 days	1 day
S2	Sugar cane + white sugar	Black tea	Mother 1A	17	2.6	3	5 days	3 days
S3	White sugar	Black tea	Mother 1B	7	2.8	3.2	5 days	3 days
S4	Red dragon fruit	Black tea	Mother 1B	6	3.6	4	0 (wash with water only)	
S5	White sugar	Cape jasmine seed (80 g)	Mother 1C	18	3.3	4.2	0 (wash with water only)	
S6	White sugar	Blue peas	Mother 1C	14	3.6	4.4	0 (wash with water only)	

can be obtained from textile materials [1]. The thickness measurement of BC samples was essential as it influences the drape, feel, and aesthetic appeal when they are utilized in fashion and textile applications. Thickness of BC samples was determined using a digital fabric thickness tester as per the ISO 5084:1996 standard [22] (Determination of thickness of textiles and textile products). During thickness measurement, the BC sample was held between the two fixed surfaces of the equipment at a constant pressure. The thickness was measured as the gap between the upper and the lower surface. Measurements were taken across 10 different points on each sample to account for any variations in thickness and the average value was calculated.

Fabric areal density (GSM) was measured as per ISO 9073–1:2023 standard [23] (Nonwovens- Test methods, Part 1: Determination of mass per unit area). The GSM was calculated from the weight of BC samples of 100 cm^2 area. Square specimens of 10 cm × 10 cm were cut from the BC samples and weighed. The average weight of three samples was multiplied with 100 to get the GSM of the BC samples.

2.5. Bursting strength of BC samples

The BC samples are subjected to a range of multi-directional forces during their use. Hence, it is essential to measure the strength properties to understand the nature of deformation and point of failure of the BC samples. Generally, tensile strength is not an appropriate method for BC as it does not have a specific warp and weft direction like the woven fabrics. Hence, the strength properties of the BC samples were evaluated by testing the bursting strength in a hydraulic bursting strength tester. Hydraulic bursting strength better represents the strength of textiles than the ball bursting strength and the results may not be comparable.

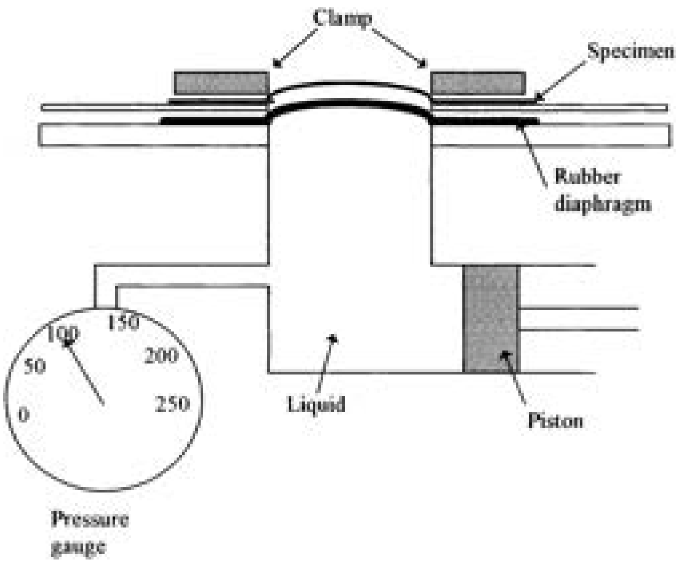

Fig. 1. Hydraulic bursting strength tester [46].

The bursting strength was evaluated using the SDL Auto-burst (Fig. 1), digital bursting strength tester as per ISO standard [26] (ISO 13938-1:2019 Textiles-Bursting properties of fabrics, Part 1: Hydraulic method for determination of bursting strength and bursting distension). Bursting strength was measured by stressing the BC specimens in all directions at the same time. The BC samples were subjected to multi-directional stress over a diaphragm (until it broke) that was inflated by a fluid at the rate of 100 cm^3/min. Then the diaphragm was inflated to the same height and same rate without the BC sample. The difference between the readings of the BC sample with diaphragm and only the diaphragm was expressed as the bursting strength of the BC samples. The final pressure (in kPa) at which the specimens ruptured was expressed as the bursting strength.

2.6. Stiffness measurement

The stiffness of a fabric indicates rigidity which resists its bending [46]. Fabric stiffness is measured in terms of bending length, which is the length of the fabric that bends under its own weight to a specific angle ($\theta = 41.5°$) [11]. The stiffness of BC samples was measured in both length and width directions following the cantilever test method as per ISO standard [24] (ISO 9073-7:2024 Nonwovens-Test methods for determination of bending length). The test was done by pushing a horizontal strip of BC sample covered by a ruler and allowing one side of the strip to hang under its own weight. The bending length (l) was measured from the scale, which was used as the indication of stiffness. The schematic of the principle of cantilever testing including the stiffness tester is shown in Fig. 2.

Bending length was calculated from the average of three specimens (of size 20 × 2.5 cm) each in the length and width direction. The flexural rigidity (G in μJoule/m) was then calculated using Eq. (1) and the bending modulus (N/m^2) was calculated using Eq. (2).

$$\text{Flexural rigidity (G)} = 1.421 \times 10^{-5} \times w \times l^3 \tag{1}$$

$$\text{Bending modulus} = \frac{12 \times G \times 10^3}{T^3} \tag{2}$$

Where, w = mass per unit area (g/m^2) of BC sample, l = bending length (mm) as shown in Fig. 2 and T = sample thickness in mm.

2.7. Drape measurement

Drape is the property of a fabric that relates to its rigidity or fluidity [11]. It gives an indication of the way a fabric falls under its own weight [49]. As such there is no good or bad drape as some fabric should closely follow the body contours, which indicate high fluidity; and others need to have low fluidity (or high rigidity) [18]. Fabrics such as chiffon, silk, and satin fall under the former category, whereas fabrics such as drill, denim, and corduroy fall under the latter category. Drape is measured by drape coefficient, which is indirectly related to fabric drape. A fabric with good drapability should have low drape coefficient and vice versa.

The drape coefficient of BC samples was measured using a Cusic

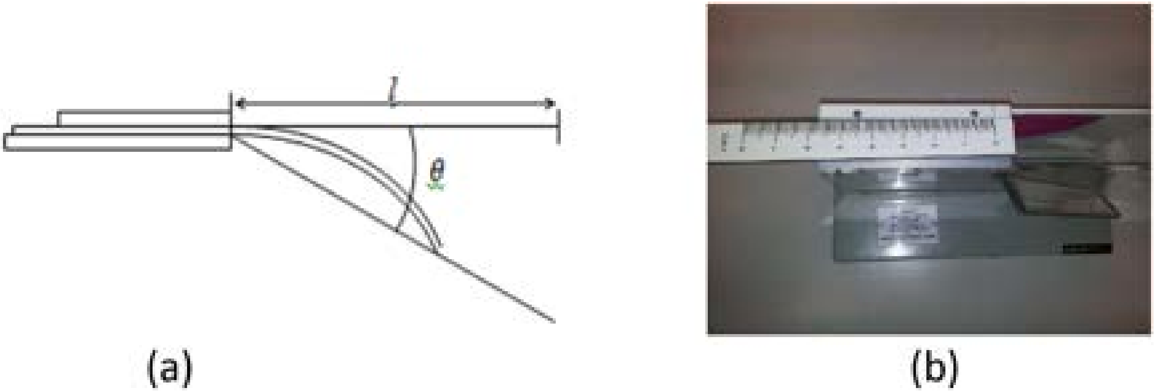

Fig. 2. Fabric stiffness tester: (a) cantilever principle (l = bending length, θ = bending angle) and (b) stiffness tester [46].

drape tester as per the ISO standard [25] (ISO 9073-9:2008 Textiles-Test methods for nonwovens-Part 9: Determination of drapability including drape coefficient). In this method a round fabric sample is held between two small concentric horizontal discs, then it is allowed to drape under its own weight. A light source is illuminated underneath the BC sample, which is reflected by a mirror. The image of the BC sample's shadow is captured in a piece of paper as shown in Fig. 3. From the area (or the weight) of the papers the drape coefficient is calculated using Eq. (3).

$$\text{Drape coefficient} = \frac{\text{mass of fabric shadow}}{\text{total mass of paper ring}} \times 100\% \tag{3}$$

For stiffer BC samples, the area of its shadow is generally higher than the limper samples. The areas of the whole paper ring and the shadow part of the ring were calculated by the corresponding weight of the paper assuming a constant weight per unit area of the paper. Generally, the drape coefficient of a flowy fabric (i.e., high drape) such as satin will be much lower than a stiff fabric such as cotton drill. Rigid materials such as a still plate will have a drape coefficient of 1.

2.8. *Crease recovery angle*

A textile fabric forms folds during its usage (in a garment), which is often undesirable, leading to a change in appearance [56]. The resistance of a fabric to crease depends on the type of fibre, and fabric structure [55]. For example, cellulosic fibres such as cotton, linen and viscose have poor crease resistance properties compared to animal fibres such as wool and silk. To improve the cease resistance of cellulosic fabrics, they are treated with special finishes such as resin finishing [17]. Crease resistance is desired in some garments such as cotton shirting and suiting. On the other hand, some garment sections need crease retention such as at the pleats of a shirt and folds of a skirt.

The Shirley crease recovery tester was used to measure creasing properties of BC samples as per the ISO standard [20] (ISO 2313-1:2021Textiles- Determination of the recovery from creasing of a folded specimen of fabric by measuring the angle of recovery, Part 1: Method of the horizontally folded specimen). A small rectangular BC sample was folded in the center and placed under a specific load to form crease for a fixed amount of time. Then the load was removed, and the sample was allowed to recover for an additional length of time. Finally, the angle of the crease that remained in the BC sample was measured as crease recovery angle (CRA). A higher CRA indicates better crease resistance of the BC sample. A low value of CRA indicates there is low recovery from creasing, whereas an angle of 180 ° indicates no residual crease in the sample. However, these extreme conditions are rarely achieved by any textile fabric. The Shirley crease recovery tester used for measuring crease recovery properties of BC sample is shown in Fig. 4.

2.9. *ANOVA results*

Single factor analysis of variance (ANOVA) statistical analyses was performed on the thickness, bursting strength, stiffness and crease results using Microsoft Excel 2016 ($p \leq 0.05$). ANOVA is an essential test to understand whether there were statistically significant differences among the mean values of the test results. The difference between the test results was significant when the F_{value} was larger than $F_{critical}$. The F_{value} is the ratio of two mean square values, whereas the $F_{critical}$ of the test results must exceed to reject the null hypothesis. A higher F_{value} results in greater variation among the group averages.

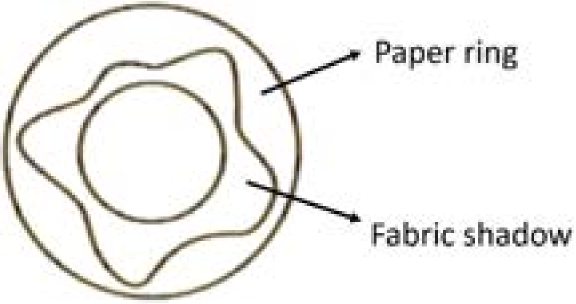

Fig. 3. Image of the draped specimen while measuring drape coefficient.

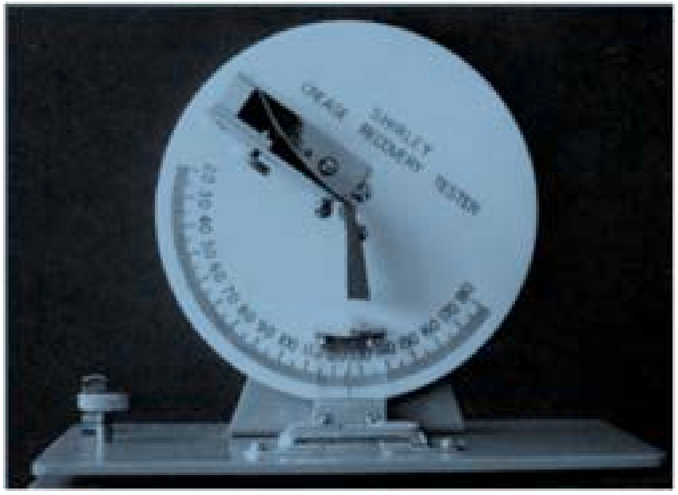

Fig. 4. Shirley crease recovery tester used for measuring crease resistance.

3. Results and discussions

3.1. pH results

The growth of BC samples depends on the pH level of the culture medium. A lower pH (i.e., acidic medium) is favored for BC to grow as the microorganisms producing enzymes for glucose fermentation, are adapted to acidic medium [5]. It was reported that a pH range of 4.0 to 5.0 produces the best result for the growth of BC [50]. Klemm et al. [28] had earlier reported that a pH of 3.5 was the optimum value for the growth of BC. The pH level is important as it can mediate microbial activity during cultivation, affecting the physical properties and comfort characteristics of the final material, especially in skin contact applications. Generally, a pH value of 7 (neutral pH) is appropriate for several textile applications. Higher acidic or alkalinity pH levels in the samples will lead to skin irritations.

The pH value plays an important role in relation to the application of BC in fashion and textile. A closer value to the neutral pH (pH value of 7), preferably in the range of 6–7 is needed for many fashion and textile applications that come in direct contact with the skin [10]. Any pH that is alkaline (pH value > 8) or very acidic (pH value <4) can irritate the skin. The pH values of all the samples before the growth started and after the samples were harvested were measured in wet condition, and the results shown in Fig. 5. It can be observed that the pH of S4 to S6 are in the closer proximity ranging from 3.3 to 4.4; S2 and S3 are in the proximity of 2.6 to 3.2; and S1 and S5 pH ranges from 2.9 to 4.3. The higher pH range of S4 to S6 can be due to the presence of red dragon fruit, cape jasmine and blue peas, which increases the pH due to the pH of these fruits lie in the range of 4.5 to 6.5. The lower pH of S2 and S3 is due to the black tea, which has lower pH than the fruits present in S3 to S6.

The results show that the pH of BC samples before fabrication lies between 3.0 to 4.4. The pH values had decreased producing a more acidic medium when the samples were harvested, ranging from 2.6 to 3.6. Several publications have reported that the pH values decreased below 4.0 (or 3.0) after the formation of BC [30,38]. The formation of different types of organic acids such as ethanoic acid and gluconic acid has also been reported by several researchers, which are responsible for lowering of the pH values. However, for fashion and textile applications, low pH values of the harvested BC are not suitable. The samples would need to be treated with an alkaline solution such as calcium carbonate ($CaCO_3$) to raise the pH to a neutral value (pH close to 7) [10,51].

3.2. Thickness and areal density

The thickness of textile materials is important in determining the types of applications as it influences fabric properties such as thermal resistance, stiffness and abrasion resistance [11]. The thickness results of dried BC specimens are shown in Fig. 6. It can be observed that the thickness of the BC sample fabricated with black tea, white sugar, and sugar cane (i.e., S2) is the highest. Similarly, the thickness of the samples produced with blue peas and white sugar (i.e., S6) is the lowest. The highest and the lowest values of thickness values were 1.26 and 0.21 mm, respectively. The thickness order from highest to lowest was S2 $>$ S3 $>$ S5 $>$ S1 $>$ S4 $>$ S6. The thickness of textile specimen (fabric SS), that was used as a reference for comparison of properties has also been shown in Fig. 6. The SS sample produced from 20^s Ne cotton yarn, had a thickness of 0.64 mm. The thickness results for samples, S2, S3 and S5 were higher than 'SS', whereas it was lower for the samples S1, S4 and S6.

In general, several studies have established that the higher the number of days to grow BC, the higher is the thickness while keeping other parameters constant [13]. However, factors such as the type of carbon and nitrogen sources greatly impact on the thickness of BC. The reason for the greater thickness of S2 can be attributed to the richer carbon source, due to the mixture of white sugar and sugar cane juice in addition to a rich nitrogen source. The richer carbon and nitrogen sources led to higher thickness in earlier research [3]. On the other hand, sample S6 showed the lowest thickness, which might be due to the poor nitrogen source derived only from the blue peas. As blue peas have lower nitrogen content (2–3 %) [14] compared to the black tea (4–6 %) [42], the growth of BC was lower leading to the lowest thickness. Further, it can be observed that the black tea samples produced higher thickness than that of the other sources. The difference between the thickness was statistically significant across the six BC samples ($F = 4.21$, at $p < 0.05$).

The areal density of BC samples is given in Fig. 7. It can be observed from the GSM values that GSM is the highest for sample S4 (grown with red dragon fruit and black tea) and the lowest for sample S1 (grown with

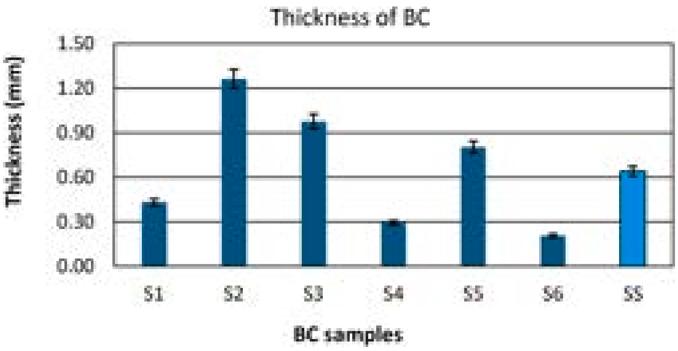

Fig. 6. Thickness results of BC samples.

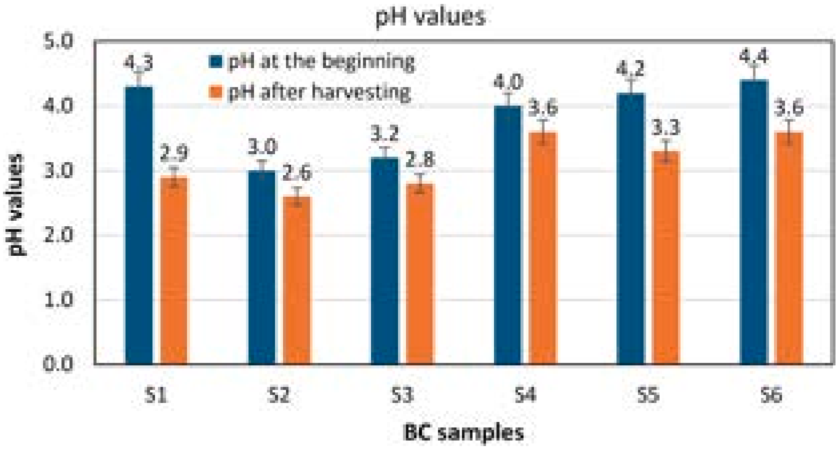

Fig. 5. pH values of BC samples (before and after harvesting).

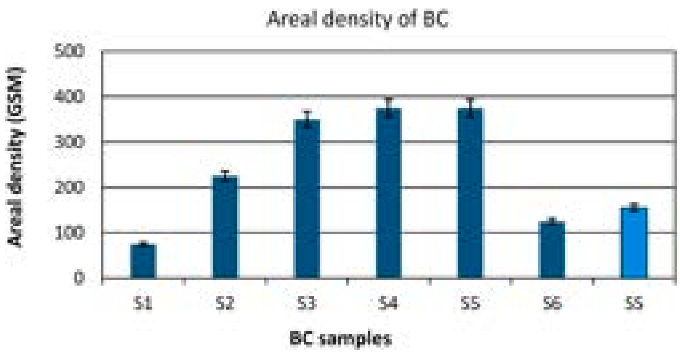

Fig. 7. Areal density (GSM) of BC samples.

brown sugar and black tea). There is no direct relationship between thickness and GSM values. For example, sample S2 has the highest thickness, whereas its GSM is the fourth largest among all the samples. This might be due to the differences in the structure and morphology of the BC samples and the growing conditions. The highest thickness sample might have a low density leading to low weight of the samples. BC samples S2, S3, S4 and S5 are very close to each other in GSM values and are heavier than the others. These types of heavy wight BC specimens can be used to produce heavier products such as bags, skirts, trousers and pants. Samples S1 and S6 are lower in GSM compared to the reference textile specimen, SS. Hence, it can be used for some light wight clothing such as shirting or dresses. However, the BC samples have low resistance to flexing and can't be washed easily, which restricts their applications in clothing.

3.3. *Bursting strength of BC samples*

The mechanical properties of BC can be better evaluated by the bursting strength as the samples can break through multi-directional force rather than a unidirectional tensile force [46]. The bursting strength is a measure of durability of the fabric or similar textile materials such as BC. Bursting strength was done by hydraulic test method as the results are more stable with low standard deviation. The bursting strength results (in kPa) of BC samples are shown in Fig. 8. It can be observed that the bursting strength of sample S4 is the lowest (234.2 kPa) and the bursting strength of the sample S2 is the highest (671.3 kPa). The bursting strength of the samples are in the decreasing order of S2 > S3 > S5 > S6 > S1 > S4.

The bursting strength of the textile fabric (shown by SS in the graph) used for clothing application was used to compare the values of BC samples. It can be observed that the BC samples showed lower bursting strength values compared to the SS fabric (100 % cotton fabric), except the sample, S2. The thickness values (Fig. 8) for S2, S3 and S5 BCE samples are higher than the reference cotton fabric (SS). However, the bursting strength of S3 and S5 are lower than the SS fabric. This shows that there is not a direct relationship between thickness and bursting strength. The difference among the bursting strength values were statistically significant among all the six BC samples ($F = 6.7$, at $p < 0.05$).

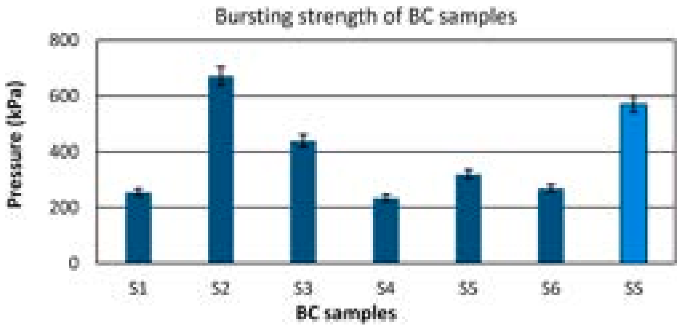

Fig. 8. Bursting strength of BC samples.

The textile fabric SS has higher bursting strength than the BC samples (except S2). This can be due to the intermeshing of yarns in the knitted fabric structure in the form of loops. The bursting strength of S2 is higher than SS, which might be due to the significantly higher thickness of the BC sample. Earlier studies have shown that the higher the fabric weight and fabric thickness, higher is the bursting strength [39]. BC is composed of an extremely fine network of cellulose nanofibers (between 3 and 8 nm), that are predominantly oriented in a uniaxial manner. This 3D configuration of BC contributes to a significantly elevated level of crystallinity (60 to 80 %) and imparts remarkable physicochemical and mechanical characteristics. However, the lower bursting strength of BC samples compared to the SS sample can be attributed to the uneven surface with thick and thin places. The presence of a thin place works as a weak spot on the surface leading to premature failure that lowers the bursting strength. It can be concluded that BC samples can be grown to the required thickness for achieving bursting strength results that are equivalent to the textile fabrics made from 100 % cotton.

3.4. *Stiffness results*

BC samples were tested for stiffness properties to investigate their bending behavior. The lower the bending length, the lower is the stiffness of the material or the resistance to bending. Lower bending length values will facilitate the ergonomics of wearability as the fabric can bend according to the body contours. The bending length values are shown in Table 2 and Fig. 9. It can be observed that the bending length value is the highest for sample S3 and the lowest for sample S4. It can also be observed that there is no direct co-relation between the bending length and the thickness of the BC samples. For example, sample S2 has the highest thickness, however, the bending length values are the highest for sample S3. The standard fabric sample SS showed bending length of 17.9 mm and 28.6 mm, in warp ad weft direction, respectively.

For textile applications such as basic shirts, the bending length values should be as low as 15 mm up to 40 mm [7]. The results of the BC samples indicate that they are quite stiffer for textile applications such as shirting as the shirt will be unable to bend and flex as per the body movement. This can be attributed to high degrees of purity and crystallinity of BC compared to plant cellulose. Only the sample S4 showed results, which are closer to the values for textile applications. The difference among the bending length values in length and width directions were statistically not significant among all the six BC samples ($F = 0.01$, at $p < 0.05$).

Table 2 also shows the flexural rigidity and bending modulus of all the BC samples, which are used for comparison purposes as they are independent of the size of the test specimen. Flexural rigidity indicates the small change in bending moment per unit width of the material to the corresponding small change in curvature, whereas the bending modulus indicates the intrinsic stiffness of the material. The flexural rigidity is the lowest for sample S4 and the highest for sample S3. However, the bending modulus is the lowest for sample S2 and the highest for sample S6. The bending modulus of the standard sample (SS) is one to three orders of magnitude lower than the BC samples. The stiffness properties of the BC samples are much higher than the required values for textile applications.

3.5. *Drape coefficient*

The drape coefficient results of BC samples are shown in Fig. 10. It can be observed from the figure that the drape coefficient of BC sample S3 is the highest and the sample S4 is the lowest. The drape coefficients of BC samples are in the decreasing order of S3 > S5 > S1 > S2 > S6 > S4. While compared with the standard fabric sample, SS, the drape coefficient is 0.28, which is less than half of the lowest value obtained for sample S4. The drape coefficient values of BC samples range from 0.57

Table 2
Stiffness results for BC samples (Shirley stiffness tester).

Samples	S1	S2	S3	S4	S5	S6	SS
Bending length (length in mm)	113.4	85.8	133.4	38	120.8	68.4	17.9
Bending length (width in mm)	118	88	139.8	37.2	118.2	72.6	28.6
Flexural rigidity (length in μNm)	1072.9	1394.2	8150.9	201.9	6484.9	392.4	8.7
Flexural rigidity (width in μNm)	1208.9	1504.2	9381.2	189.4	6075.1	469.2	35.6
Bending modulus (length in N/m^2)	1.58E+08	8.30E+06	1.05E+08	9.60E+07	1.50E+08	5.33E+08	3.99E+05
Bending modulus (width in N/m^2)	1.78E+08	8.95E+06	1.21E+08	9.00E+07	1.41E+08	6.38E+08	1.63E+06

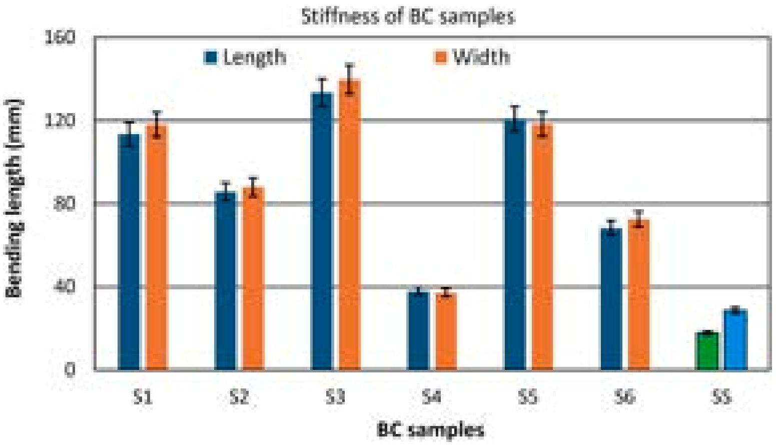

Fig. 9. Stiffness results (bending length) of BC samples.

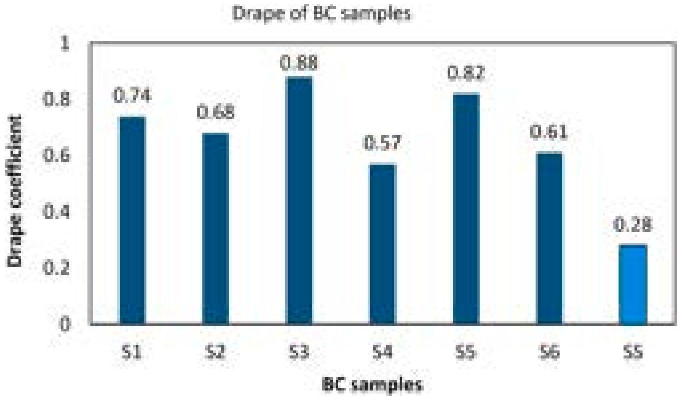

Fig. 10. Drape coefficient of BC samples.

to 0.88, indicating higher rigidity. The high drape values can also be explained based on high crystallinity and purity of BC samples compared to plant cellulose. The drape coefficient values can range from 0 to 1, where 0 indicates complete fluidity (that is hard to achieve) and 1 indicates absolute rigidity (like a still plate). The difference among the drape coefficient values were statistically significant among the six BC samples ($F = 10.2$, at $p < 0.05$).

From the drape coefficient values, it can be concluded that the BC samples lack fluidity for softer garments. They cannot be utilized for manufacturing apparels such as T-shirts, shirts, dresses or soft trousers that will follow the body contours easily. The apparels made from BC samples will lack drapability, hence, they will stay away from the skin. Some of the apparels that can be produced using BC include skirts, jumpers, jackets, suits and workwear, subjected to achieving satisfactory results for other test parameters. To make them more useful for a range of clothing, they should be manufactured in lower thickness values in addition to making them fluid by suitable approaches. On the other hand, the high drape coefficient results are needed for manufacturing fashion accessories such as wallets, handbags, clutch bags and card holders.

Looking at the high stiffness and high drape coefficient values, the project team attempted to design some fashion accessories using biomaterial samples of BC (Fig. 11). Fig. 11(a) shows a wallet and Fig. 11 (b) shows a decorative painting using BC samples, which were produced by the participants of this project. These were prepared during the project the authors carried out with the local community in Vietnam. It can be observed that the BC samples have some flaws present in them. This can be attributed to the cultivation conditions of BC while growing as well as the harvesting conditions. The presence of air-bubbles leads to holes in the sample, which is then translated to the final product. To improve the quality of the products, they should be grown and harvested meticulously. Further, they can be used along with textile fabrics to produce a range of clothing and fashion accessories.

3.6. *Crease recovery angle*

The crease recovery angles of BC samples are shown in Fig. 12. It can be observed that the crease recovery angle of BC samples lies in the narrow range of 21° to 32° The highest value of CRA was observed for the sample S1 in the length direction (32°) and the lowest value of the CRA was observed for the samples S4 (length wise-21°) and S2 (width wise-21°). There was no specific trend observed for CRA in the length and width direction. Further, establishing a relationship between the CRA and other properties such as GSM or drape was not possible as a trend was not observed. The difference among the CRA values were statistically insignificant among all the six BC samples in warp and weft directions ($F = 0.7$, at $p > 0.05$).

While comparing the CRA values of the standard fabric sample (SS) with the BC samples, it can be observed that the CRA values for textile fabrics is much higher than the BC samples. The low value of CRA for BC can be attributed to the creases being retained by the samples due to the inherent tendency of BC to hold the creases. Once the load was removed the recovery process was slow and the creases formed were set in the BC samples. Hence, these samples will be good for the purpose where crease

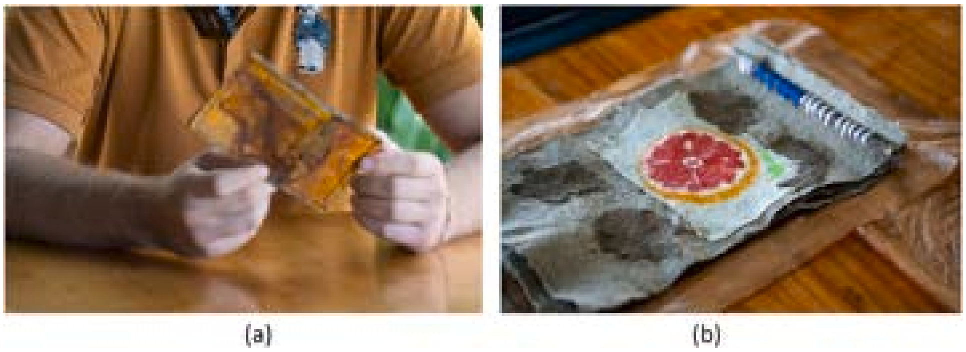
(a) (b)

Fig. 11. Fashion accessories produced using biomaterials (BC): (a) wallet and (b) decorative painting.

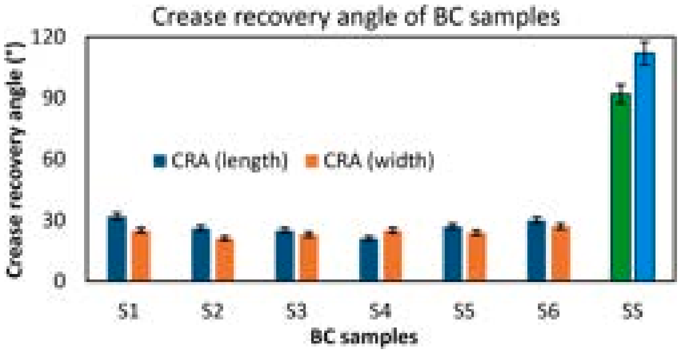

Fig. 12. Crease recovery angle of BC samples.

retention is important rather than crease recovery. The CRA of the SS sample was 92° and 112° in warp and weft direction, respectively. The CRA of a wrinkle-free treated suiting fabric will be higher than 120°, indicating very good recovery properties. To improve the CRA of BC sample for textile applications, they need to be treated with some chemicals, which may alter other properties. The summary of ANOVA results is given in Table 3. As discussed, thickness, bursting strength and drape values showed statistically significant difference from each other, whereas the bending length and crease recovery results were not significantly different.

3.7. *Achieving the desired properties*

From the above discussions, it is evident that BC meets some of the properties needed for fashion and textile applications. However, some properties need to be improved to make them ideal sustainable materials for fashion and textile applications [6,35]. Fig. 13 shows a flowchart displaying various treatments, which can improve the properties of BC. For example, the aesthetics can be improved simply by the process of coloration with natural and synthetic dyes, which can be applied both in-situ and ex-situ. Mechanical properties can be improved by the treatment of biopolymers such as polylactic acid (PLA) and polyurethane (PU). Flexibility can be improved by treating with some chemical softener, whereas durability can be improved by the treatment of proteins (such as soy and mushroom protein). The treatment of fatty acids and wax can improve the hydrophobicity of BC samples.

Table 3
Summary of ANOVA results.

Property	F-value	p-value	Significance
Thickness	4.21	$p < 0.05$	Yes
Bursting strength	6.7	$p < 0.05$	Yes
Bending length	0.01	$p < 0.05$	No
Drape	10.2	$p < 0.05$	Yes
Crease recovery	0.7	$p < 0.05$	No

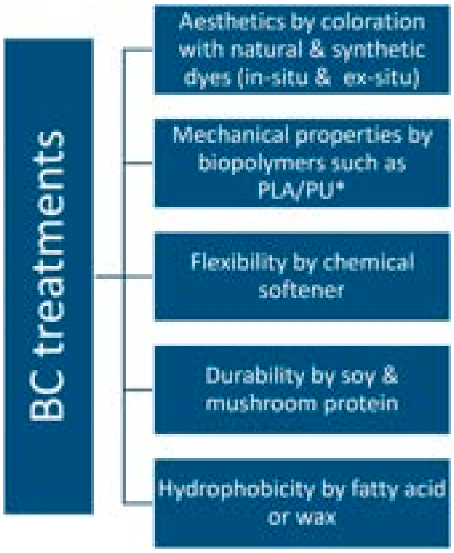

Fig. 13. Flowchart displaying various treatments to improve properties of BC for textile applications (*PLA: polylactic acid & PU: polyurethane).

4. Conclusions

4.1. *Significant findings*

BC are becoming one of the promising sustainable materials for future fashion and textile applications. This research focused on fabricating and characterizing various properties of BC to understand its potential for a range of fashion and textile applications. In this paper the authors have evaluated some important properties of BC samples produced from Vietnamese indigenous ingredients. Various properties such as pH, thickness, areal density, bursting strength, drape and crease recovery of BC samples were evaluated following the standard test methods to explore their suitability for fashion textile applications. A standard fabric sample was also evaluated for comparison with BC to understand the differences in properties while making fashion and textile products from BC. The pH of BC samples was found to be acidic before, during and after fabrication, with some samples close to the skin-friendly pH range of 7. BC samples with acidic pH need to be treated with commonly available bases to bring the pH close to neutral for fashion and textile applications.

Some areal density (GSM) values of BC samples were lower (compared to the textile sample), which can be applied for light-weight textile applications, and some were higher, which can be applied for appropriate applications. It was observed that the BC samples produced with black tea resulted in higher thickness and the absence of teas resulted in lower thickness due to limited amount of nitrogen source. Some of the BC samples showed higher thickness compared to commercially available fabric samples produced from 100 % cotton. The bursting strength of BC samples were investigated by hydraulic bursting strength tester, and it was found that the bursting strength of five BC samples were lower than the 100 % commercial cotton fabric. The higher bursting strength of one BC sample can be attributed to its higher thickness value. From bursting strength results it can be concluded that the BC samples may break easily if subjected to multidirectional stress and strain during the use of the product.

The stiffness values were significantly higher than the reference sample used for textile applications. There was no significant difference between the bending length values in the length and the width direction of BC samples. The drape coefficient values were found to be much higher than the reference sample to provide the necessary fluidity for making softer garments. However, they can be used for designing some heavier garments that stay away from the skin. The crease recovery angle values were significantly lower compared to the reference sample used for fashion and textile applications. This indicates that BC fabric can't recover from the creases created during the usage of the product. To overcome this, some special finishes should be applied to the BC samples to improve the creasing properties. Products such as wallets and wall paintings were produced using the BC samples fabricated in this research.

In a nutshell, it can be concluded that the BC samples meet some of the properties needed for fashion and textile applications. In some cases, such as stiffness and drape, the properties were suitable for designing garments where fluidity is not needed. Properties such as bursting strength and crease recovery need to be improved (with special finishes) for durability and good appearance, respectively. With proper optimization of growing conditions and application of finishes, BC can become an ideal sustainable material for future fashion.

4.2. Implications of the study

The study has attempted to fabricate and characterize BC with the indigenous ingredients available in tropical countries such as Vietnam. Vietnam is gaining significant importance in the global fashion and textile value chain as indicated by the rapid growth of the export market. However, Vietnam is one of the countries with the highest plastic pollution, discharging significant amount of plastic to the ocean. Through this research, we have fabricated several BC samples to replace plastic-based products with biomaterials such as BC. Some products were designed using the BC samples fabricated in the research. Further, this study also focused on educating the local community to fabricate BC and produce BC-based products. The findings of the study can be applied to other developing countries such as Bangladesh, Cambodia and Laos, which are becoming important global manufacturing hub for fashion and textiles.

4.3. Limitations and recommendations

This study investigated the properties of BC fabricated from the ingredient indigenously available in Vietnam for fashion and textile applications. Some important properties relating to pH, drape, strength, stiffness and crease recovery were evaluated in this research. The future research should focus on further investigations of launderability, wrinkling properties, dimensional stability and weather resistance properties of BC. The BC samples can be colored with various natural ingredients using both in-situ and ex-situ processes to improve their aesthetics. These samples can then be evaluated for their fastness properties to light, washing, rubbing, and dry cleaning. Other properties such as abrasion resistance, and pilling propensity can also be evaluated for fashion and textile applications.

Future research can also focus on fabricating BC from the wastes of tea and coffee (nitrogen sources) in addition to some waste produced in sugar industries (carbon sources). The growth rate of BC is quite slow, which makes it difficult to achieve the desired volume of output needed for the fashion and textile sector. Future research should focus on improving the scalability of BC to meet the high demand. Further, future studies should focus on improving the uniformity of BC samples and fabricating them without any defects. Various finishes can be applied to the BC samples to improve their functional and performance properties. With a range of defect-free BC samples, a proper plan can be made to make them compatible to be used with the existing textile materials.

Ethical approval

The authors have obtained ethics approval from RMIT University's Ethics Committee. The authors also have obtained the consent to participate and consent to publish.

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CRediT authorship contribution statement

Rajkishore Nayak: Writing – original draft, Funding acquisition, Conceptualization. **Donna Cleveland:** Writing – original draft, Funding acquisition, Conceptualization. **Frances Joseph:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships, which may be considered as potential competing interests: All the authors reports financial support was provided by RMIT International University, Vietnam and CSIRO, Australia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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