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Fabrication of poly lactic acid incorporated bacterial cellulose adhered flax fabric biocomposites

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ABSTRACT

Bacterial cellulose (BC) can be used as an efficient reinforcement material in biopolymers. In this study, the surface of flax fabric was used as a support material to deposit BC on its surface produced by *Gluconacetobacter liquefaciens* (MTCC 3135) through 1 week fermentation process. After the growth of BC on flax fabric, the surface of flax fabric has been modified to get BC modified flax fabric. Production of BC on flax fabric after fermentation was confirmed by the increase in weight of dried flax fabric and the total quantity of BC deposited was measured to be 9.45 ± 0.46%. The water uptake of BC modified flax fabric decreased from 59.19 ± 4.60% to 46.35 ± 0.07% indicating hydrophobic nature of flax fabric after deposition of BC on it. Green biocomposites was successfully prepared by incorporating Cereplast PLA into the neat and BC modified flax fabric. FT-IR results indicated that the PLA was successfully incorporated into both unmodified and BC modified flax fabric as the ester group present in PLA peak was observed at 1760 cm^{-1}. Mechanical properties, water uptake behavior, and the optical micrograph of both unmodified and BC modified flax fabric and their composites were carried out. A significant increase in the Young's modulus and decrease in water uptake were observed in case of BC modified flax fabric biocomposites contributing to its stiffness. BC modified flax fabric based biocomposites showed zone of inhibition indicating antimicrobial nature of the biocomposites.

1. Introduction

Research for producing cellulose from alternative resources such as microbial fermentation has been in great progress. Bacterial cellulose (BC) which is not associated with lignin and hemicelluloses can serve as a promising biofibre because of their excellent properties. BC is produced by certain bacteria such as *Gluconacetobacter, Sarcina*, *Agrobacterium* and the material possesses high elastic modulus and other improved mechanical properties when compared to cellulose from natural fibres (Mathur et al., 2015; Costa et al., 2017; John et al., 2013). Costa et al. reported that when the acetic acid bacterium *Gluconacetobacter liquefaciens* is fermented along with flax fabric, it produces white leathery pellicle at the air-liquid interface (Costa et al., 2017). BC in form of small pellets or granules instead of pellicles can be produced by submerged fermentation through aeration or agitation (Shah et al., 2010; Mormino and Bungay, 2003). However, BC pellets of agitated fermentation reflect a lower degree of polymerization, mechanical strength and crystallinity. BC mainly consists of microfibrils, which are around 2–4 nm in diameter and which in turn build up fibres with an approximate size of less than 100 nm (John et al., 2013). Additionally, BC is also less prone to attack by microbes as it consists of well arranged three dimensional nanofibrils that create an expanded surface area and highly porous matrix (Costa et al., 2017). Pommet et al., proposed a green way to modify the surface structure of hemp and sisal fibres by depositing BC pellicles on its surface produced by *Gluconacetobacter xylinus* BPR2001 during fermentation (Pommet et al., 2008). BC has been explored as artificial skin for temporary covering of wounds and potential scaffolds (Petersen and Gatenholm, 2011; Sherif, 2014). Several natural and synthetic polymers such as collagen, chitosan, thermoplastic starch, and polylactic acid (PLA) in presence of BC have been explored as scaffold or biomedical materials (Pircher et al., 2014, Osorio et al., 2014; Panaitescu et al., 2016a, 2016b; Quero et al., 2010). Tome et al. and Panaitescu et al. fabricated transparent bionanocomposites obtained from PLA and BC with improved mechanical properties up to 6% of nanofiber loadings (Tome et al., 2011; Panaitescu et al., 2017). Recently, Kanno and Uyama examined the unique morphology and contact angle of PLA monoliths having a BC framework (Kanno and Uyama, 2018). Woven and nonwoven fabrics have been incorporated in PLA to get reinforced and structural biocomposites. BC can be used as an acoustic or filter membrane, as ultra-

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strength paper and as reticulated fine fiber network with coating and binding characteristics with suitable matrix.

PLA from Cereplast, Inc is 100% compostable and biodegradable product with starch incorporated in it and Kumar et al. used the PLA from Cereplast, Inc to fabricate biodegradable plastics and biocomposites by reinforcing with woven and non woven flax fabric (Kumar et al., 2010a, 2010b, 2014).

The majority of previous studies used the approach of incorporating PLA at high amount i.e., maximum of 70% (w/w) with respect to fiber or fabric for the fabrication of biocomposites (Kumar et al., 2010a, 2010b). However, to utilize the properties of BC that is adhered to fabric because of the growing support material, it is important to reduce the wt% of PLA in fabric. Recently, the antibacterial nature of BC sheet with PLA layer on it has been reported (Foong et al., 2018). The current study investigates the growth of BC by taking flax fabric as a support. After that almost equal amount of PLA wrt flax fabric was incorporated into BC modified and unmodified flax fabric to fabricate biocomposites. BC modified flax fabric and their composites were characterized for mechanical properties, water uptake and antimicrobial studies.

2. Materials & methods

2.1. Materials

Flax woven fabric (M_w = 180 g/m^2) with 19 threads/cm in warp and 21 threads/cm in weft was kindly supplied by Libeco Inc. (Belgium, Europe). The cellulose producing bacterial strain *Gluconacetobacter liquefaciens* (MTCC No. 3135) was purchased from Microbial Type Culture Collection and Gene Bank, CSIR-IMTECH (Chandigarh, India). Starch incorporated PLA resin [CP-INJ-1001EZC with high melt flow index (MFI) of 10–12 g/10 min] was procured from Cereplast, Inc. (Howthorne, NY, USA). Chloroform was obtained from Patna Chemicals & Scientific Stores (Bihar, India). All the chemicals used were of laboratory grade and were used without further purification. *Escherichia coli* DH5α strain was procured from Gbiosciences. Luria Bertani (LB) powder was purchased from HiMedia.

2.2. Culture revival

The *Gluconacetobacter liquefaciens* cultures were streaked and spreaded onto nutrient agar plates and kept at 30 °C for 3 days in an incubator. The components of nutrient broth were 1 g/L beef extract, 2 g/L yeast extract, 5 g/L peptone and 5 g/L NaCl. After incubation, white to cream coloured bacterial lawn was observed as shown in Fig. 1.

Fig. 1. Nutrient agar plates showing growth of *G. liquefaciens* at 30 °C.

2.3. Sample preparation

Six woven fabric mats of dimension 8 × 5 cm designated as were cut and weighed followed by drying in hot air oven at 60 ± 5 °C for overnight. Then weight of each fabric mat was measured after keeping in desiccator for 30 min at 0% relative humidity so that the fabric attains room temperature without absorbing the moisture again (maintained by using silica gel). Except one fabric, remaining five fabric samples were autoclaved (121 °C, 15 psi pressure) for 20 min and dried in hot air oven at 60 ± 5 °C for overnight. Keeping one autoclaved fabric sample, the remaining four fabric samples (Fabric A, Fabric B, Fabric C and Fabric D) were used for further studies.

2.4. Surface modification of flax fabric through fermentation

Surface modification of flax fabric was introduced by growing cellulose pellicles on the flax fabric. This was achieved in fermentation medium consisted of 50 g/L fructose, 5 g/L yeast extract, 5 g/L peptone, 2.7 g/L Na_2HPO_4 and 1.15 g/L citric acid. The above mentioned medium with fructose in place of glucose was taken as mentioned in the literature (John et al., 2013).

Fermentation studies were carried out in 250 mL conical flasks containing 90 mL of autoclaved (121 °C temperature, 15 psi pressure) fermentation medium inoculated with 10% (v/v) of 3-day old broth of a previous culture of *G. liquefaciens*. Fabric mats (8 × 5 cm) were put in the fermentation medium and incubated at 30 °C for 8 days in an incubator shaker with rotation per minute of 220. BC production by the bacteria on the fabric surface was monitored by the appearance of viscous fermentation medium after one day of incubation. Bacterial growth was also monitored by taking optical density (600 nm) of cell mass at an interval of 24 h through the 8-day incubation period. The experiment was performed in doublets. After fermentation, the modified (BC adhered flax fabric) and the unmodified fabric samples were designated as MFF and UFF, respectively.

2.5. Sodium hydroxide extraction of modified flax fabric

Production of BC pellicles by the acetic acid bacteria on the fabric surface was confirmed by NaOH extraction method. Two samples of MFF were treated with 100 mL of 0.1 M NaOH solution at 80 °C for 20 min to make the fabric free from microorganisms, fermentation medium components, and soluble polysaccharides. Same treatment was also performed with UFF which was used as a control. After washing three times with distilled water, all the fabrics were dried in hot air oven at 60 ± 5 °C for 2 days and kept in desiccators at 0% RH. Weight of each fabric was measured before and after the extraction method to evaluate weight change in flax fabric.

2.6. Preparation of biocomposites

PLA incorporated flax fabric biocomposites was prepared through casting method (Kumar et al., 2010a). For this purpose, an optimization protocol was performed to ensure PLA uptake of around 100% of the fabric weight. For this following steps were followed. Fabric A, fabric B, fabric C and fabric D of dimension 5 × 4 cm were cut and weighed. PLA solution dissolved in chloroform was poured over the fabric surface kept in aluminium frame mould. The assembly was statically incubated at room temperature till the complete evaporation of chloroform followed by drying in a hot air oven at 60 ± 5 °C for overnight was accomplished.

Flax fabric with PLA uptake was again kept in desiccator for 30 min to remove moisture followed by weight measurement. The PLA uptake percentage was calculated and presented in Table 1.

We found that fabric C and fabric D could take around 100% PLA of

Table 1
The optimization protocol data for PLA uptake by flax fabric.

Sample Designation	Weight of fabric (mg)	Weight of PLA (mg)	Volume of $CHCl_3$ (mL)	Weight of composite (mg)	PLA uptake (mg)	PLA uptake (%)
Fabric A	355	355	7.5	490.83	135.33	38.12
Fabric B	357	355	7.5	502.52	147.52	41.32
Fabric C	363.89	700	3.75	695.71	331.81	91.18
Fabric D	349.10	700	3.75	750.12	401.12	114.9

their weight when the fabric and the PLA were taken in 1:2 ratios (w/w). Therefore, to prepare biocomposite, modified as well as unmodified flax fabric and PLA were taken in 1:2 ratios (w/w) and the prepared biocomposites were designated as UFF-PLA-S and MFF-PLA-S. Both the biocomposites were subjected to compression molding between two metallic plates, using Polymer press machine (Model PM-M-15) at 65 ± 5 °C temperatures (slightly above glass transition temperature of PLA) and 5 tones pressure for 10 min to distribute PLA completely over the fabric surface. The temperature for the compression molding was maintained slightly above the glass transition temperature of PLA for uniform distribution on the fabric. After cooling the compressed UFF-PLA-S and MFF-PLA-S designated as UFF-PLA and MFF-PLA were kept in desiccator at 0% RH so that the samples attain room temperature without absorbing the moisture again (maintained by using silica gel).

2.7. Water uptake

The water uptake of all the fabric samples viz. UFF, MFF, UFF-PLA, MFF-PLA was evaluated according to the ASTM D570-81. Each sample was cut into 1 × 1 cm dimension and preconditioned at 60 ± 5 °C in an oven for 24 h and weighed (X_0). After immersing in distilled water for 24 h, the fabric and biocomposite samples were dried with tissue paper to remove excess water from the surface and weighed (X_1). Then, X_1-X_0 was calculated to determine total weight gain of samples which represent the amount of water absorbed. An average value from five measurements was reported. The water uptake percentage was calculated as follows.

$$\textit{Water uptake}\ (\%) = \frac{X_1 - X_0}{X_0} \times 100$$

Here.

X_0 = Weight of the fabric/biocomposite samples.
X_1 = Weight of fabric/biocomposite samples after immersion in water for 24 h.

2.8. Antimicrobial activity

Inoculums of *Escherichia coli* DH5α was prepared by inoculating a loop of *E. coli* cells into 10 mL LB broth followed by incubation at 37 °C for overnight in an incubator shaker at 220 rpm 100 µL of the inoculum was spreaded over four LB agar (2% LB + 1.5% agar) plates in sterilized condition to avoid contamination. Strips (1 × 1 cm dimension) of each fabric sample (Natural fibre (N), UFF, MFF, UFF-PLA and MFF-PLA) were put on the surface of LB agar in two quadrants of the plate. As a control, one drop of PLA and one 1 × 1 cm strip of neat fabric were also put in the remaining two quadrants of the plate. After incubation at 37 °C for overnight, all the plates were observed for zone of inhibition around the sample that will indicate antimicrobial activity. Plates were further incubated at 37 °C for 1 week and were visually monitored every day for the decrement in zone of inhibition due to overgrowth of *E. coli* cells. This is important to evaluate the extent of antimicrobial activity of samples.

2.9. Characterization

Optical microscope study was done at 10X magnification to analyse the surface morphology of UFF, MFF, UFF-PLA and MFF-PLA. It was important to demonstrate the appearance of BC on modified fabric surface. The infrared spectroscopy of the all the fabric samples were recorded with FT-IR spectrophotometer from PerkinElmer, USA. The FT-IR spectra of the solid biocomposite samples were taken at room temperature. The samples were scanned from 4000 to 400 cm^{-1} with a resolution of 4 cm^{-1}. All spectra were reported after an average of 32 scans.

The tensile strength, elongation at break, and Young's modulus values of the fabric and biocomposites were measured according to ASTM D882 on a Universal Tensile Testing machine from Zwick, Germany. ASTM D882 is used to determine mechanical properties of thin plastic samples and since resultant biocomposites is thin plastic sample so we have used this standard method for fabric and biocomposites. The tensile specimens with dimension of 80 mm × 10 mm with thickness of ~0.2 mm were prepared by casting. The tensile strength, elongation at break and Young's modulus values of the UFF, MFF, UFF-PLA and MFF-PLA were carried out. The tensile tests were carried at a cross head speed of 10 mm/min. Three test samples of three replicate were tested and the average values were reported.

3. Result and discussion

3.1. Modification of flax fabric

3.1.1. Growth curve of G. liquefaciens producing BC on flax fabric

Pommet et al. reported the production of BC in the stationary phase after fermentation by *Gluconacetobacter xylinus* BPR2001 for a week (Pommet et al., 2008). In this work, we have aimed to determine the time at which the bacterium enters the stationary phase. *G. liquefaciens* was inoculated in the fermentation medium and allowed to grow at 30 °C for 1 week in agitated condition (220 rpm). Then optical density (OD) of the cell mass was observed at 600 nm at an interval of 24 h till 7 days and the graph was plotted as a function of time (h) vs. Cell mass OD (600 nm) as depicted in Fig. 2. The lag phase and stationary phase of *G. liquefaciens* was observed in Fig. 2 and it was found that the bacterium entered the stationary phase at the end of the second day of fermentation.

In the second set of the experiment, actual growth pattern in the lag phase of *G. liquefaciens* was studied. For this purpose, the previous experiment was performed again at same conditions. The OD of cell

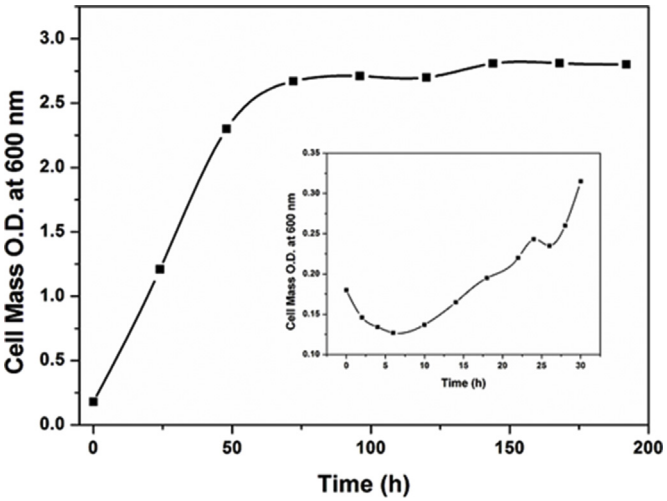

Fig. 2. Growth pattern of *G. liquefaciens* on the surface of flax fabric fermented in the fermentation medium.

Table 2
Weight change of unmodified flax fabric after removing moisture content and subjecting to sterilization process.

Sample subjected to various conditions	UFF (Fabric 1)	UFF (Fabric 2)
Weight of neat fabric (mg)	702.61	697.28
Weight after removing moisture at 60 °C for 24 h (mg)	688.53	686.27
Weight after sterilization at 121 °C for 20 min (mg)	Not subjected to this step	677.78
Weight change (%)	−2.00	−2.79

mass (600 nm) was observed for 2 day at different time intervals. Then the graph was plotted between time (h) and cell mass OD (600 nm) and the nature of lag phase was determined and is presented in inset of Fig. 2. It was observed in Fig. 2 that after 10–15 h of lag phase, the exponential growth phase of the *G. liquefaciens* started.

3.1.2. Surface modification of flax fabric through fermentation

Table 2 shows the moisture content of ~2.00% for flax fabric and the weight loss of ~2.79% for flax fabric subjected to sterilization by autoclaving at 121 °C for 20 min. The weight loss at high temperature during autoclaving process was due to removal of components present on the fabric in addition to removal of moisture content.

To evaluate the quantity of BC deposited on the surface of MFF, fabric weight before and after each individual treatment was recorded and is given in Table 3. From Table 3, it was clear that the total percentage weight loss of UFF (control) was 12.29% after sterilization by autoclaving at 121 °C for 20 min followed by NaOH extraction. However, the total percentage weight loss of MFF (first set) and MFF (second set) was recorded to be 2.38% and 3.34%, respectively after same treatment. Weight loss occurred was mainly due to the leaching of impurities like hemicelluloses and removal of media, microbes etc. Therefore, the total quantity of BC deposited on the surface of MFF (first set) and MFF (second set) was measured to be 9.91% and 8.95%, respectively. It has been reported by Pommet et al. in their studies that about 5–6% BC got adhered to the sisal and flax fibres (Pommet et al., 2008). Flax fabric is of hydrophilic nature and it can easily interact through hydrogen bonding with the hydroxyl groups found in BC hence we could easily see in this study that flax fabric acted as a support for the growth of BC similar to as reported by Pommet et al. (2008).

3.2. Comparative properties of unmodified and modified flax fabric

3.2.1. Morphology

The photograph of the flax fabric surface, alkali treated flax fabric surface before and after modification with BC taken from the compound micrograph is shown in Fig. 3a to Fig. 3d. There are clear spaces between two threads of the neat and alkali treated flax fabric (Fig. 3a and b). Fig. 3c and d clearly revealed the presence of BC in case of modified fabric as the gap between two threads of the flax fabric comparatively decreased and the fabric looked denser in comparison to unmodified fabric as shown in Fig. 3a and b.

The compound micrograph of flax fabric-PLA biocomposites is shown in Fig. 4a to Fig. 4d. Compound micrograph of the surface of flax fabric-PLA biocomposites before (Fig. 4a and b) and after compression molding (Fig. 4c and d) revealed that PLA was uniformly distributed over the fabric surface in both unmodified and modified biocomposites after compression (Fig. 4c and d). The uniform distribution of PLA over the fabric surface diminished all the gaps between threads of modified biocomposites when compared with the unmodified one (Fig. 4b and d). It was also observed that the threads of flax fabric were breached after compression due to high pressure (Fig. 4c and d). However, the biocomposite structure was maintained because of strong interfacial interaction between the flax fabric and the PLA matrix.

3.2.2. FT-IR analysis

The absorbance peaks in case of UFF and MFF at 3355 cm^{-1} and 1644 cm^{-1} are attributed to –OH and C = O stretching bands (Fig. 5). Absorbance peaks in the range of 1000–1550 cm^{-1} represented the lignin and hemicelluloses contents of UFF (Gea et al., 2011). After the deposition of BC on flax fabric there were no changes in the MFF peaks and this may be attributed to structural similarity of BC with the cellulose present in the flax fabric. The results obtained by Pommet et al. also revealed that characteristic vibrational modes of BC produced were almost same in the typical fingerprint regions as in commercial cellulose (Pommet et al., 2008).

The FT-IR spectra of UFF and MFF based PLA biocomposites is shown in Fig. 6. Hydroxyl (–OH of alcoholic and carboxylic) and –C=O bands are represented at 3302 cm^{-1} and 1760 cm^{-1}, respectively. The band at 1456 cm^{-1} represented C–H bending vibrations in PLA. So, with the incorporation of PLA there was appearance of ester bond at 1760 cm^{-1} and there was also a significant decrease in the intensity of –OH band which signified the hydrophobic nature of PLA based flax fabric biocomposites (Kumar et al., 2010b).

3.2.3. Mechanical properties

Fig. 7a shows the mechanical properties of UFF and MFF. The tensile strength, tensile modulus and elongation at break of the UFF were about 26.66 ± 1.15 MPa, 74.93 ± 6.16 MPa and 39.09 ± 1.09%, respectively. After the growth of BC on flax fabric with bacteria, the tensile strength, tensile modulus and elongation at break decreased. The tensile strength and tensile modulus of MFF decreased to 23.82 ± 0.272 and 62.79 ± 2.76 MPa respectively, while the elongation at break was observed to be 35.83 ± 1.637% similar to what has been reported by Pommet et al. (2008). The decrease in tensile strength, tensile modulus may be attributed to decrease in the cohesiveness of the fabric as reported for hemp or sisal fibre in a previous literature. Fig. 7b shows the mechanical properties of UFF and MFF based PLA biocomposites. The tensile strength, modulus and elongation at break of the UFF-PLA were about 27.29 ± 1.21 MPa, 71.464 ± 3.75 MPa and 34.38 ± 0.24%, respectively. After the growth of BC on flax fabric with bacteria, the tensile strength and modulus of MFF-PLA increased to 28.01 ± 0.16 MPa and 82.93 ± 4.10 MPa. However, the elongation at break of MFF-PLA got decreased to 37.10 ± 2.1%. The increase in tensile strength and modulus of MFF-PLA implied better interaction of modified flax fabric with PLA.

Table 3
Measured weight of modified and unmodified fabric after each individual treatment.

Samples subjected to different conditions	UFF (control)	MFF (first set)	MFF (second set)
Weight (mg) of fabric	709.13	730.14	703.54
Weight (mg) of fabric after removing moisture at 60 °C for 24 h	692.88	720.52	692.20
Weight (mg) after sterilization at 121 °C for 20 min	691.91	698.76	685.06
Weight (mg) after sterilization at 121 °C for 20 min and after 0.1 M NaOH extraction at 80 °C	606.84	–	–
Weight (mg) after sterilization at 121 °C for 20 min, fermentation with bacteria and after 0.1 M NaOH extraction at 80 °C	–	682.12	662.16
Weight change (%) after 0.1 M NaOH extraction at 80 °C	−12.29	−2.38	−3.34

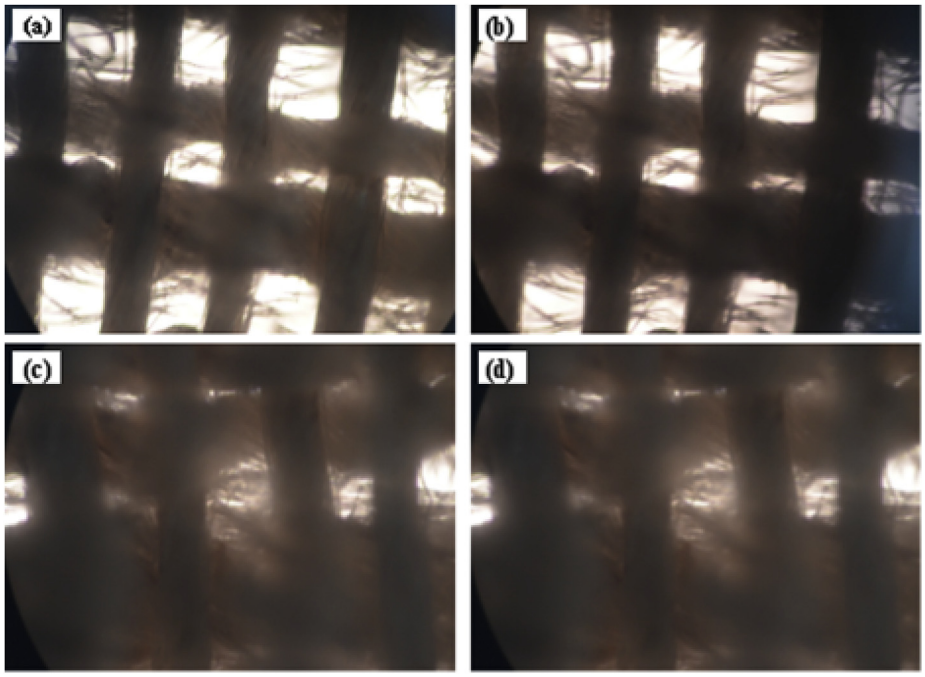

Fig. 3. Compound microscope photo of flax fabric surface: unmodified fabric (a), 0.1 M NaOH treated fabric (b), bacterial cellulose deposited on unmodified fabric (c), and bacterial cellulose deposited on 0.1 M NaOH treated fabric (d).

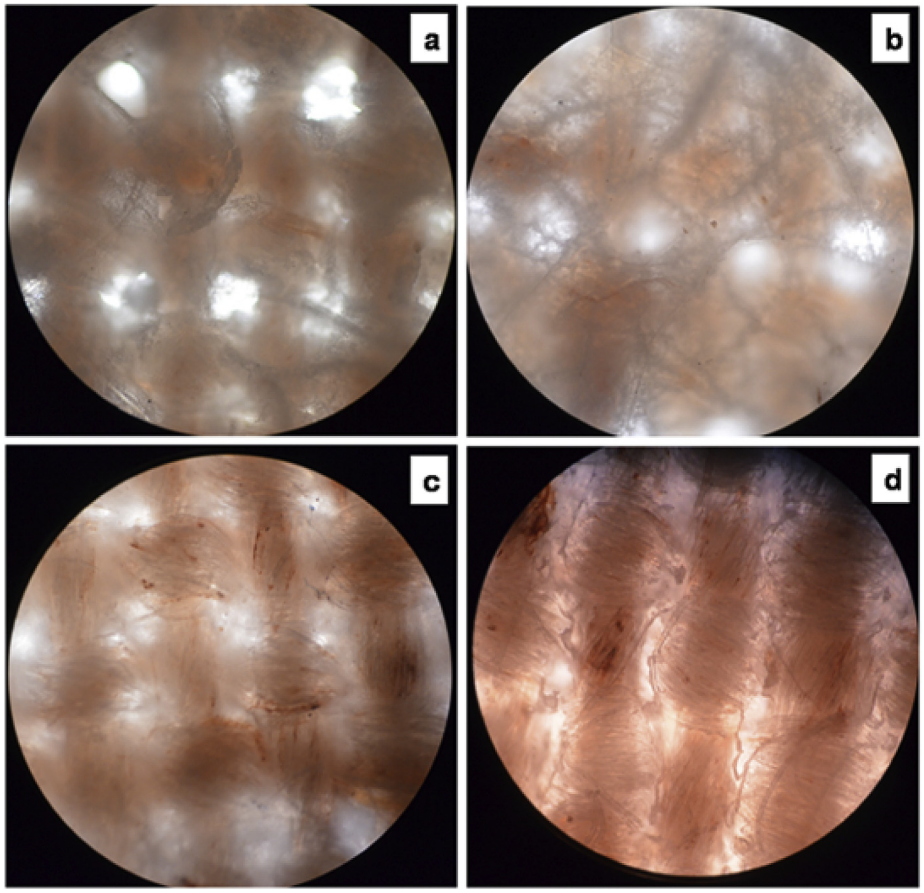

Fig. 4. Compound microscope photograph of flax fabric-PLA biocomposites surface: (a) UFF-PLAS and (b) MFF-PLAS i.e., before compression molding; (c) UFF-PLA and (d) MFF-PLA i.e., after compression molding.

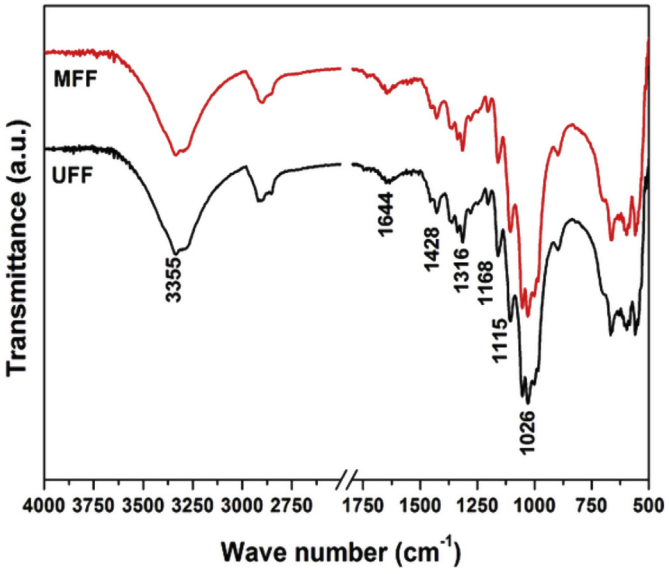

Fig. 5. FT-IR spectra of UFF and MFF.

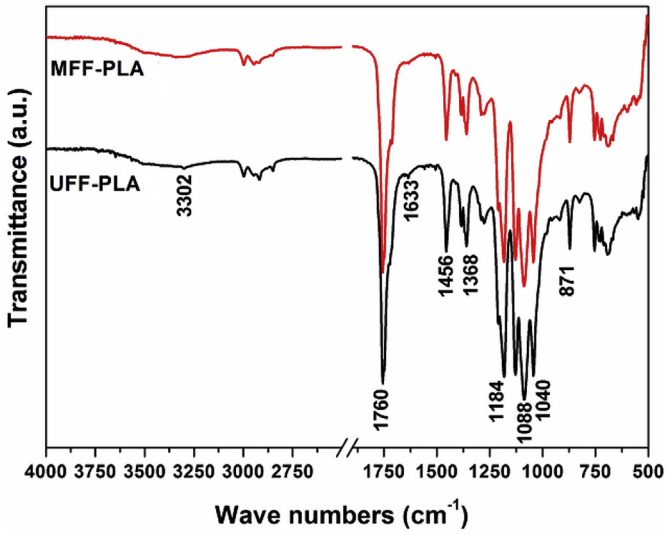

Fig. 6. FT-IR spectra of UFF-PLA and MFF-PLA.

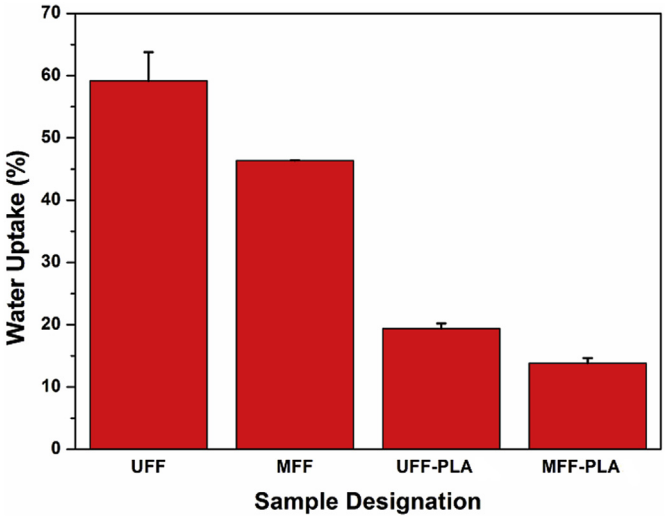

Fig. 8. Water uptake properties of unmodified and modified flax fabric as well as unmodified and modified flax fabric-PLA biocomposites.

3.2.4. *Water uptake*

The modified flax fabric shows low water uptake (%) due to the presence of BC pellicles on the flax fabric (Fig. 8). The MFF-PLA biocomposites showed lowest water uptake (13.40 ± 0.83%) (Fig. 8). UFF showed highest water uptake (59.19 ± 4.60%). The lowest water uptake property of MFF-PLA biocomposite was mainly due to the presence of incorporated PLA which is almost hydrophobic with ~2% water uptake as reported in the previous work (Kumar et al., 2014).

3.2.5. *Antimicrobial properties*

There was no antibacterial property contributed by UFF and MFF while the UFF-PLA and MFF-PLA biocomposites showed antibacterial property as no growth of *E. coli* was observed around them forming the zone of inhibition after the incubation of 24 h (Fig. 9). When we compared the four quadrant of a plate containing neat fabric, PLA, UFF-PLA and MFF-PLA, there was no zone of inhibition observed around neat fabric while a large zone of inhibition was observed around PLA, confirming that the antibacterial property of UFF-PLA and MFF-PLA was due to the presence of PLA. The experiment was performed in doublets to enhance the reproducibility. All the plates were continuously monitored for one week to observe the decrement in zone of inhibition. At the 5th day of incubation zone of inhibition was

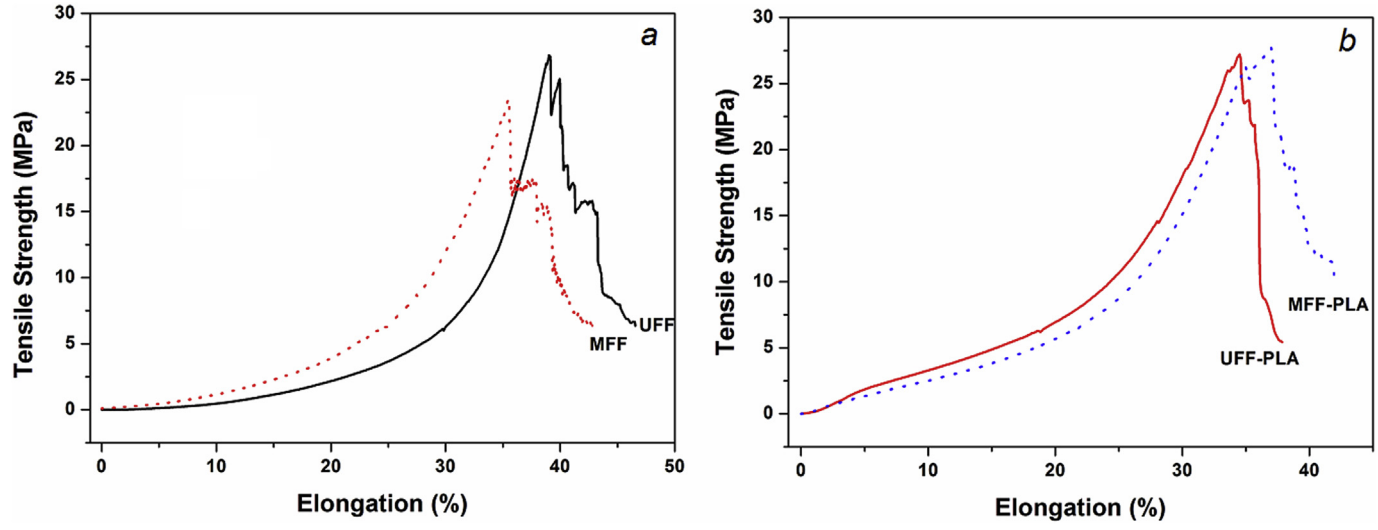

Fig. 7. Stress-strain curves of (a) UFF and MFF (b) UFF-PLA and MFF-PLA.

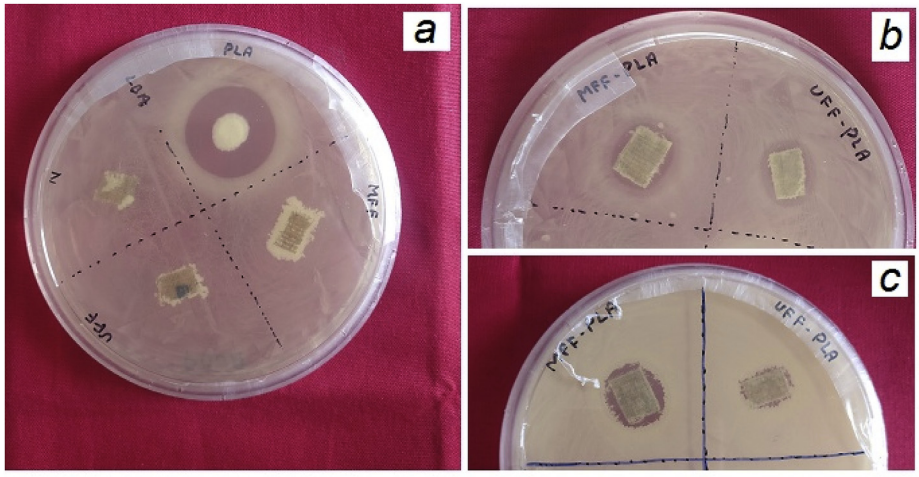

Fig. 9. LB plates showing antibacterial studies of (a) Natural fabric i.e., N as negative control, UFF, MFF, PLA as positive control (b) UFF-PLA and MFF-PLA after 24 h (c) UFF-PLA and MFF-PLA after 5 days against *E. coli*.

decreased to some extent indicating that the antimicrobial activity decreased with time.

4. Conclusions

About 10% of BC was successfully grown on the surface of flax fabric by microbes through one-week fermentation. The modified flax fabric showed low water uptake and high density of the flax fabric as observed photographically. However, tensile strength of modified flax fabric decreased significantly. Further the biocomposites with around 50% PLA incorporated in UFF and MFF were successfully prepared. FT-IR results indicated that the PLA was successfully incorporated into the modified flax fabric as the peak of ester group present in PLA was observed at 1760 cm^{-1}. Modified flax fabric-reinforced PLA biocomposites showed better mechanical properties compared to the neat and unmodified flax fabric. Tensile strength and modulus increased and elongation at break decreased that signified its stiffness property. Lowest water uptake (13.40 ± 0.83%) was observed in case of MFF-PLA which signified its use in major industrial applications as hydrophobic membranes from renewable resources. Morphological analysis of MFF-PLA showed the breaking of the individual threads as individual fibres were clearly observed in the modified biocomposites. However, the mechanical strength of the biocomposites increased even though. UFF-PLA and MFF-PLA both indicated antimicrobial activity against *E. coli* as confirmed by the appearance of zone of inhibition.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bcab.2019.101277.

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