

Article

Knitting Bacterial Cellulose Filaments Produced from Agro-Industrial By-Products

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Abstract

This research presents bacterial cellulose (BC) filaments knitted from agro-industrial by-products. The fermentation media came from pressed fruit (beetroot, ginger, grape), vegetable beverages, bagasse with different concentrations (1/2.5, 1/5, 1/7.5, and 1/10), and a control medium with unrefined sugar from sugarcane or panela. The BC filaments were obtained from a mixed culture of bacteria and yeast (SCOBY); functionalized using NaOH purification treatment and glycerol plasticizer; untwisted and twisted with 1-, 2-, and 4-ply; and characterized physically and mechanically by weight, diameter, tensile strength, Young's modulus, and elongation. The untwisted and 2-ply twisted BC filaments from the fruit medium 1/2.5 showed tensile strength of 272 MPa and 155 MPa, respectively. Finally, control panela filaments with 1-, 2-, and 4-ply and fruit filaments with 2- and 4-ply were knitted in wet states. This research demonstrates the use of by-products to produce BC filaments with knitting properties for textile applications.

Keywords: bacterial cellulose; bio-based material; agro-industrial by-products; filament; knitting; textile

1. Introduction

Bio-based fibers derived from living organisms such as bacteria, yeast, fungi and algae, represent a sustainable alternative to synthetic and artificial fibers due to their biological and biodegradable nature, which reduces the environmental impact of textile production [1–4]. In this context, biofabrication using microorganisms has enabled the development of novel and renewable materials, such as leather-like structures produced from bacterial cellulose (BC) [5–7]. BC can be obtained through the fermentation of a pure bacterial culture or from SCOBY (symbiotic culture of bacteria and yeast) consortia present in kombucha tea. Kombucha is a prebiotic beverage native to Asia that ferments for 1–14 days [8] at an optimal temperature of 27–34 °C [9,10].

BC is chemically equivalent to plant cellulose [11], but it exhibits a high degree of crystallinity and purity (free of lignin or hemicellulose), tensile strength, elasticity, durability, hydrophilicity, non-toxicity, biocompatibility, biodegradability [12,13], and moldability during its formation [14]. It is for these reasons that BC can be an alternative to plant-based fibers. Functionalization involves modifying a material to endow it with new properties. This functionalization can be performed within the BC culture (in situ) or outside of it, once the BC has been produced (ex situ); for example, through a purification and mercerization



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treatment with NaOH in order to remove bacterial cell debris and components of the culture medium [15], as well producing a change in the crystalline structure going from cellulose I to cellulose II [16]. By applying mercerization in BC, the mechanical properties of the material can be tuned [17]. When glycerol is applied ex situ, the BC increases its plasticity and elongation at break [18].

Several factors influence the growth of CB, such as the composition of the culture medium, temperature, pH, oxygen supply, growth period, and reactor type [9]. The medium must contain a carbon source (usually sugar) and a nitrogen source (usually tea). To reduce the environmental impact and production costs of BC, food substrates, such as fruit juices, sugarcane, and agro-industrial by-products like bagasse, peels, pulp, and overripe vegetables, can be reused [19]. In this context, a circular economy relationship is established between the textile and food sectors through the reuse of agricultural by-products as fermentation substrates to produce BC. In addressing this challenge, we are working toward Sustainable Development Goal (SDG) 12, “Responsible Consumption and Production,” which focuses on waste management, cleaner production, and ensuring that people have the information and awareness necessary for sustainable development and lifestyles in harmony with nature [20].

BC can be produced in film form during static incubation and in granule form during agitated incubation [21–23]. BC enables the production of materials with properties similar to leather, fabrics, and textile fibers [24–26]. In the leather and nonwoven sectors, BC has been widely used in various research studies and commercial applications, such as Malai, Modern Synthesis, and Polybion; however, BC fibers remain an under-explored area. The synthesis of BC fibers and filaments are primarily based on fiber regeneration processes via chemical dissolution, thereby wasting the mechanical strength inherent in the BC network [27–29]. There are also some procedures for producing BC fibers and filaments via static, chemical-free cultivation, such as: starting from a BC sheet [30] or introducing a mold into the culture medium [31,32]. In their research, Zhang et al. (2025) used a BC sheet cut into thin strips, which were subsequently wet-stretched, twisted, and dried at 105 °C, to produce BC yarns [30]. In contrast, Takagi et al. (2025) used a traditional Japanese method called “kami-ito,” which is employed to produce paper yarns by taking advantage of the alignment of the fibrils in the BC films [29]. On the other hand, the methods of Morrow et al. (2023) and Freixas et al. (2026) produced BC filaments by incorporating a spiral-shaped mold into the culture, defining the filament geometry at the air–liquid interface [31,32]. By adjusting the diameter of the spiral, BC filament production can be increased. Furthermore, by modifying the pitch of the spiral, the cross-sectional thickness of the BC filament can be modified. The production of BC fibers and filaments differs from that of BC nonwovens in aspects such as the form of the raw material, twisting, and the application of textile techniques, such as knitting, weaving, and braiding [33].

Based on the topics discussed, the main objective of this study is to reuse agricultural by-products to produce functionalized and twisted BC filaments with knitted fabric properties. In turn, the study aims to evaluate the effect of the culture medium, the mechanical properties of the functionalized BC filaments, and the textile properties of the BC-based knitted fabrics, as well as determine the potential for applying these filaments in the textile sector and the main challenges associated with processing the material for textile use.

2. Materials and Methods

2.1. Inoculum

A SCOBY obtained from kombucha production (Kefiralia, Mondragón, Spain) was used for BC production. The predominant bacteria were *Gluconacetobacter xylinus*, *Acetobacter xylinum*, and the yeasts *Saccharomyces cerevisiae*, *Brettanomyces bruxellensis*,

Candida stellate, *Schizosaccharomyces pombe*, and *Zygosaccharomyces bailii*. The study used the same SCOBY inoculum, stored at 30 °C, and fed every 14 days with 200 mL of infused distilled water, 0.4 g of green tea, and 40 g of control medium with unrefined sugar from sugarcane or panela (P).

2.2. Substrates Used

Different materials (Figure 1) were used as culture media for BC production (Table 1): “P” (Azucarera SL, Madrid, Spain); brewer spent grain bagasse (BSG) (Cerveseria Montseny SL, Seva, Spain); vegetable beverage waste (LV) (Liquats Vegetals SA, Viladrau, Spain); and pressed fruit comprising beetroot, ginger, and grape (F) (CoBeverage SL, Barcelona, Spain).

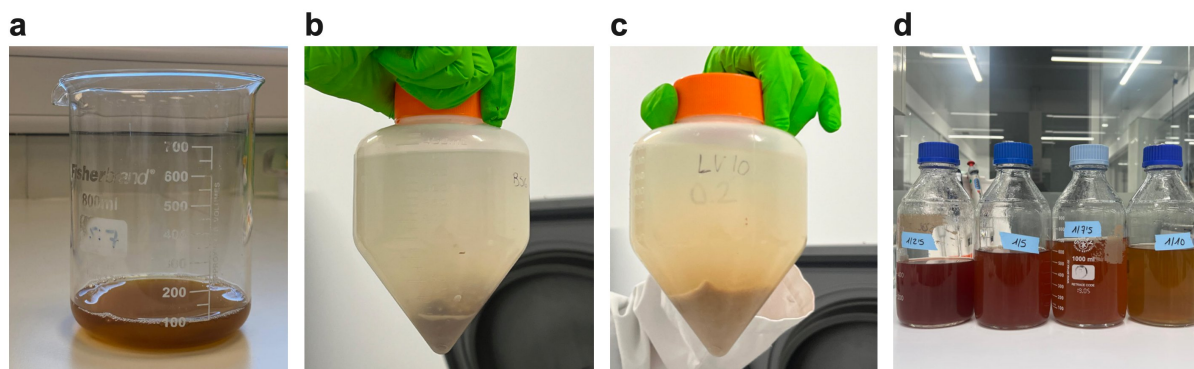


Figure 1. Green tea and panela (P) medium (a); brewer spent grain bagasse (BSG) medium (b); vegetable beverage (LV) medium (c); and fruit (F) medium in different concentrations: 1/2.5, 1/5, 1/7.5, and 1/10 (d).

Table 1. Characterization of the by-product substrates of fruit (F), vegetal beverage (LV), and brewer spent grain bagasse (BSG). Organic matter and elemental carbon were determined as independent parameters. Organic matter includes compounds present in the substrate, whereas carbon content corresponds only to the elemental carbon fraction.

Parameter	F	LV	BSG
Dry matter (%)	15.41 ± 0.61	21.44 ± 3.08	24.00 ± 1.50
Organic matter (%)	93.97 ± 1.26	86.57 ± 11.15	94.60 ± 0.60
pH	4.95 ± 0.24	4.23 ± 0.24	5.60 ± 0.10
Reducing sugars (g glucose/100 g DM)	24.07 ± 3.46	6.61 ± 1.59	3.00 ± 0.00
NKT (g N-NH ₄ /kg DM)	13.29 ± 1.48	55.89 ± 23.00	51.54 ± 3.50
N (%)	1.26 ± 0.19	5.24 ± 1.47	3.31 ± 0.35
C (%)	41.04 ± 1.27	45.65 ± 1.48	48.56 ± 0.32
C/N	33.51 ± 6.13	9.34 ± 2.51	19.20 ± 2.10

The control medium P and three media derived from agro-industrial by-products—BSG, LV, and F—were used. For medium P, 200 mL of distilled water infused with 0.4 g of green tea and 40 g of P sugar was used, to which 20 mL of SCOBY starter culture was added. Three replicates of the media were prepared and cultured at 30 °C in reactor boxes (SacO₂, Deinze, Belgium) for 14 days.

In the BSG, LV, and F media, the agro-industrial by-products were thawed and solid–liquid extracts were prepared at different concentrations (1/2.5, 1/5, 1/7.5, and 1/10, weight/volume) with distilled water, in triplicate, in 1 L glass containers, which were then shaken for 30 min at 110 RPM to extract the sugars from each residue in the liquid phase. The extracts were then filtered through a 0.17 mm mesh, sterilized in an autoclave for 30 min at 121 °C, and cooled to 30 °C. A volume of 200 mL of the different BSG, LV and F media were placed in reactor boxes (SacO₂, Deinze, Belgium) and 20 mL of SCOBY starter culture was added to each for 14 days.

2.3. Production System

The production method chosen for forming the BC filament was the spiral mold [31,32]. The mold has a diameter of 100 mm, a height of 20 mm, and contains a spiral-shaped cavity 2 mm wide that generates a filament 3.33 m long per mold. This mold was immersed in the reactor box containing the culture medium (Figure 2), where fermentation at the air–liquid interface led to the formation of a BC film within the mold’s cavities. The thickness of this film increased progressively during the fermentation process until the BC filament was formed.

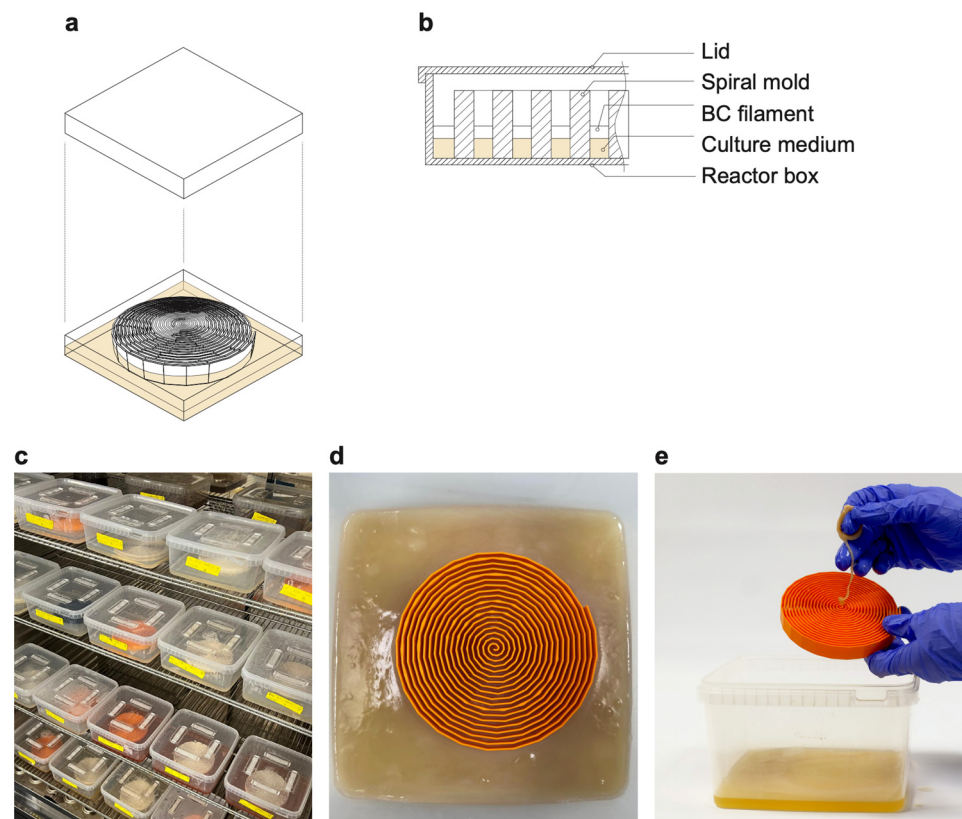


Figure 2. BC filament production method with a 3D-printed spiral mold in a reactor box with SCOBY (a); spiral section and BC filament formation inside the reactor box (b); reactor boxes with different by-products and control P medium (c); BC filament produced inside the cavities of the spiral mold in the air–liquid interface of the culture media (d); and BC filament extraction (e).

The production and post-processing of the BC filaments (functionalization, characterization, and suitability for knitting) are described in Figure 3. After selecting the type of by-product and its optimal concentration, BC filament production was scaled up using two 290 mm diameter spirals, which allowed filament production to be increased to 44 m in each fermentation system.

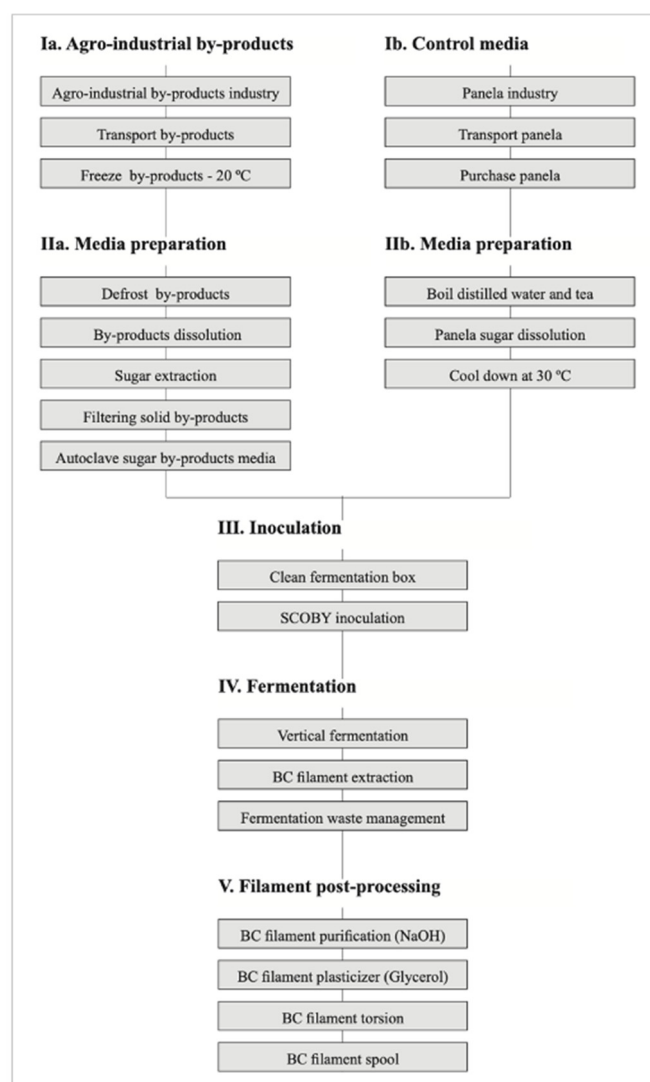


Figure 3. Control medium procedures and media with agro-industrial by-products for BC filament production.

2.4. Monitoring Fermentation and Scaling BC Production

The reduction in sugar concentration in the medium [34] was quantified by analyzing samples taken at the start and end of fermentation after 14 days. At the same time, the pH (Hanna Instruments, Limena Italy) was recorded at the start and end of fermentation after 14 days.

The level of production as a function of the culture medium was determined by measuring the thickness or height of the BC film on days 5, 7, 12, and 14 of the fermentation process in the incubator at 30 °C. Thickness was measured with a tape measure from the outside of the transparent reactor box (Figure 4a). The BC filament produced in the spiral mold was extracted manually (Figure 4b).

The by-products with the highest film thickness and control medium P were selected for the production scaling of BC filament. By increasing the size of the reactor box to 670 × 350 × 150 mm and placing two spiral-shaped molds with a diameter of 290 mm, the production of the BC filament was increased to 44 m (Figure 4c). A stainless-steel spool was used to wind the BC filament as it was removed from the spiral mold (Figure 4d).

The linear density of the filaments was determined after removing them from the different culture media and allowing them to dry at 22 °C on waxed baking paper (Figure 4e).

Once dry, after 24 h, their weight was measured using a balance (Ohaus Scout, NJ, USA), taking the average of three replicas of 240 mm sections (A, B, C).

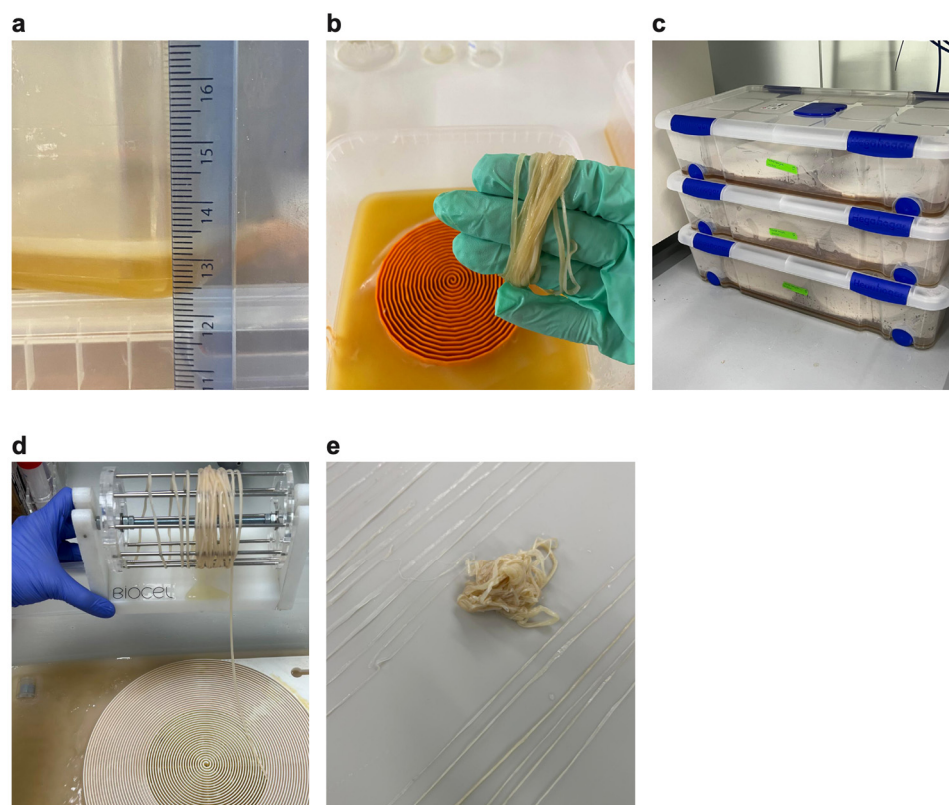


Figure 4. BC pellicle and filament thickness measurement (a); BC filament manual extraction (b); scaled production of BC filament from 3 m to 44 m by scaling the spiral mold and the reactor box dimension (c); BC filament extraction from the scaled spiral mold with a stainless-steel spool (d); and BC filament drying on waxed baking paper at 22 °C (e).

2.5. Functionalization

To improve the knittability of the BC filaments, four functionalization treatments were applied for 24 h at 50 rpm and a temperature of 19.5 °C in a continuous agitated shaker (Labwit ZWY-1101C, Melbourne Australia): 20% NaOH and 10% glycerol; 20% NaOH and 5% glycerol; 10% NaOH and 10% glycerol; and 10% NaOH and 5% glycerol. Once the filaments were treated without tension, they were left to dry at 22 °C on waxed baking paper. Once dry, the different filaments were weighed using a balance (Ohaus Scout, NJ, USA).

The functionalization improvement was determined using a qualitative knot slippage test by holding both ends of the BC filament and tying a knot to observe how easily it bent and slid over itself; from this, the treatment that offered favorable flexibility and sliding properties without reaching fracture can be selected.

2.6. Mechanical Properties

The mechanical properties of the BC filaments were characterized using tensile tests in accordance with EN ISO 2062:2009 [35], using a ZwickRoell Model 500N Zwicki static testing machine (ZwickRoell Group, Ulm, Germany). The test was set up with a strain rate of 100 mm/min until break, applying a preload of 0.5 cN/Text and a gauge length of 200 mm.

Four replicas of 240 mm long test specimens were prepared from the four types of filaments studied: P; F1/2.5; lyocell yarn (LY); and raffia paper yarn (RA). The F1/2.5 and P filaments were tested under different conditions: untwisted monofilament, twisted

monofilament, 2-ply twisted filament, and 4-ply twisted filament. The filaments were twisted manually at 60 rotations/m in the Z direction to the right and then weighed to calculate the respective Tex values. Young's modulus was calculated using stress–strain curves, and the elongation of the samples was recorded.

2.7. Knittability

The samples knitted on a Silver Reed SK280 7gg handloom were produced by hand using BC filament. The filaments used for knitting require a high degree of flexibility and some elasticity to form loops and pass over the same filament, thereby creating the knitted structure. Several knitting tests were conducted to develop the protocols for the BC filament. The fabric was knitted with 10 needles set to stitch length position 6. A few initial rows were knitted with cotton yarn (Uppingham Yarns, Uppingham, UK). First, the dry P filament—purified with 10% NaOH and treated with 5% glycerol—was tested, but it was not possible to produce a stockinette stitch sample due to its fragility. Next, the P filament was tested by moistening it with distilled water for 1 min, and it was possible to knit it by manually moving the knitting machine needles and performing 10 passes. To finish the piece, cotton thread was inserted, and the P filament was allowed to dry. This procedure was repeated for the different types of P and F1/2.5 filaments, twisted into 1-, 2-, and 4-ply.

The evaluation of the resulting fabric was carried out by observing the samples under a compound microscope (Trinocular Euromex MicroBlue, Gelderland, The Netherlands) at 5× magnification. This analysis complemented the previously obtained mechanical strength results, providing information on the uniformity and the presence of possible defects in the fabric. Statistical significance analysis was not performed due to the exploratory nature of the study and the limited sample size.

3. Results and Discussion

3.1. Monitoring Fermentation and BC Production

In the initial experiments, the production of BC in media derived from agri-food by-products (1/5 and 1/10) was compared with the control medium P. First, the sugar concentration, pH, and thickness of the BC from the different fermentations were evaluated (Figure 5).

The initial sugar concentration (day 0) in the different media fell into three distinct ranges: >10 g/L (29.31 g/L for P and 15.17 g/L for F1/5); between 1 and 10 g/L (3.27 g/L for F1/10); and <1 g/L (between 0.77 and 0.25 g/L for the LV- and BSG-based media, respectively) (Figure 5). BC produced by kombucha showed the highest yield (66.7%) with a sugar concentration of 90 g/L, and an increasing concentration from 100 g/L to 250 g/L produced a gradual decrease in the BC yield [36]. On the other hand, BC produced by *Medusomyces gisevii* showed higher BC yields in media with sugar concentrations close to 10 g/L within the studied parameters from 4 g/L to 18 g/L [37]. Therefore, optimal sugar values vary depending on the microorganism's producers of BC [17], while higher sugar concentrations promote the formation of other metabolic components, such as acetic and gluconic acid, hindering BC synthesis [38].

In this study, most sugar concentrations decreased during fermentation, with the exception of the LV1/5 and F1/10 media, which showed a slight increase. The greatest reduction in sugar was recorded in the F1/5 medium, with a total consumption of 12.62 g/L during the process, compared to the P medium, which consumed a total of 4.74 g/L. In the other media, consumption was clearly lower, reaching a maximum of 0.23 g/L (LV1/10). However, the slight increase in sugar concentration in the LV1/5 and F1/10 media could be due to the hydrolysis of polysaccharides present in the vegetable or fruit matrix, releasing reducing sugars during fermentation. This phenomenon has

been observed in media rich in plant fiber, where the enzymatic activity of the SCOBY microbiota promotes the release of monosaccharides and disaccharides in the initial stages of fermentation [36,39].

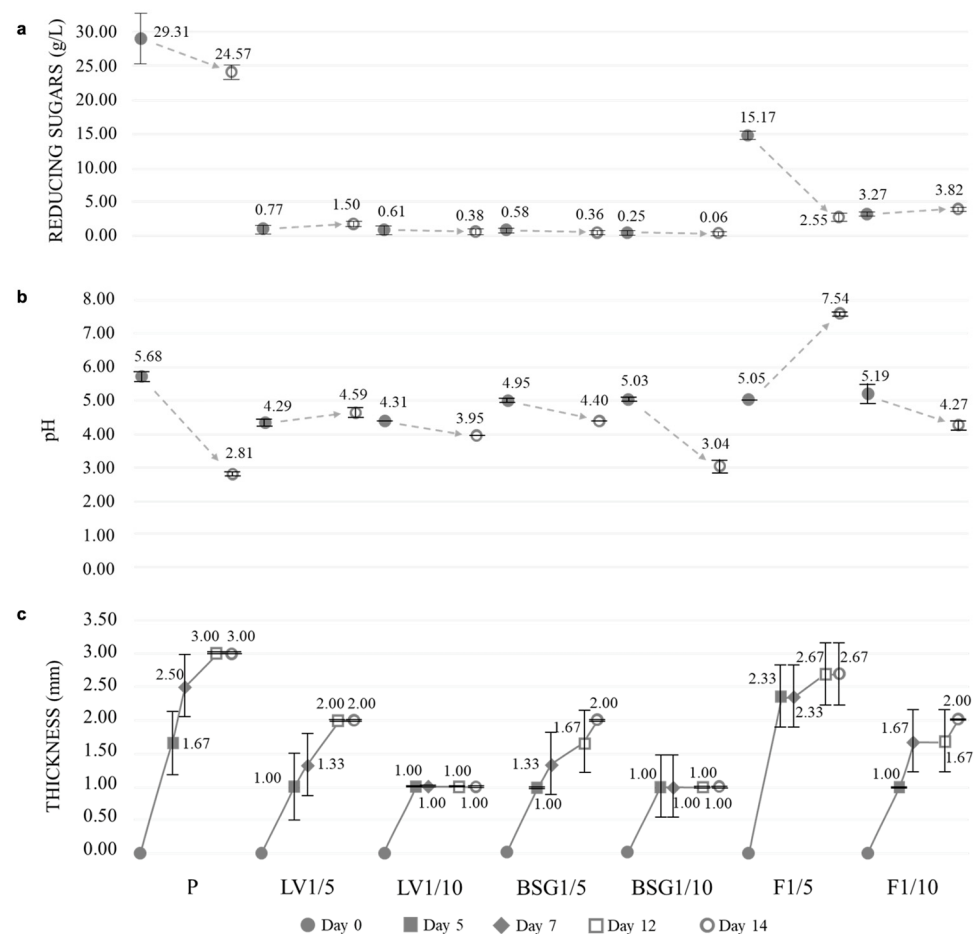


Figure 5. Quantification of sugar reduction on days 0 and 14 of fermentation for each type of medium: panela; vegetable beverage (LV) 1/5 and 1/10; brewer spent grain bagasse (BSG) 1/5 and 1/10; and fruit (F) 1/5 and 1/10 (a). Quantification of pH on days 0 and 14 of fermentation for each type of medium: panela; vegetable beverage (LV) 1/5 and 1/10; brewer spent grain bagasse (BSG) 1/5 and 1/10; and fruit (F) 1/5 and 1/10 (b). Thickness of the BC film inside the reactor box system (mm) on days 0, 5, 7, 12, and 14 for the media: panela; vegetable beverage (LV) 1/5 and 1/10; brewer spent grain bagasse (BSG) 1/5 and 1/10; and fruit (F) 1/5 and 1/10 (c).

The initial pH of the different media ranged from 5.68 (P) to 4.29 (LV1/5) (Figure 5). For favorable BC growth, the pH must be between 2.5 and 5 [9,40]. A decrease in pH can increase the amount of organic acid, and an increase in pH could reduce BC production yield [9]. Most media showed a decrease in pH during fermentation, with the exception of the LV1/5 and F1/5 media, which showed an increase. Medium P showed the most significant pH reduction, decreasing the medium's pH level by a total of 2.87—more than 50% of the initial value—reaching a final pH of 2.81, the lowest value obtained compared to the other media. In the case of the increase observed in medium F1/5, whose final pH reached 7.54, this could be due to the assimilation of organic acids present in the substrate, the re-assimilation of acetate in later stages of fermentation, and/or the release of alkaline compounds, among other reasons, consistent with what was described by Villarreal-Soto et al. (2018) [40].

Regarding the measurement of the thickness or height of the BC film within the system, the samples obtained from fermentation with agro-industrial by-products showed lower

values compared to P, which reached a maximum thickness of 3.00 mm. Figure 5 shows the four measurements taken during fermentation. The pressed fruit samples, F1/5 and F1/10, stand out with a maximum average growth of 2.67 and 2.00 mm, respectively, compared to the other two types of by-products, which exhibit significantly lower thicknesses (2.00 mm, LV1/5 and BSG1/5; and 1.00 mm, LV1/10 and BSG 1/10), as well as a weak and brittle structure when the BC filaments were extracted. In particular, the F1/5 medium exhibited very active fermentation, with growth concentrated in the first 5 days, thanks to access to easily fermentable sugars (fructose, glucose) while the pH was still within the optimal acidic ranges. Subsequently, the acids produced during fermentation are consumed by the microorganisms, which causes an increase in pH and, consequently, slows down and eventually halts BC growth. This behavior was described by Villarreal-Soto et al. (2018) and Nayak et al. (2024), who noted that the evolution of pH and sugar profiles depends largely on the nature of the substrate and fermentation conditions, and may deviate from the typical pattern of continuous acidification [9,40]. Finally, it was observed that BC growth was lower in all media containing agro-industrial by-products at a 1:10 ratio. This is attributed to the low sugar content, which, in the case of the LV and BSG samples, caused growth to stagnate starting on the fifth day.

Regarding the weight of the BC filaments once extracted from the various media and dried at 22 °C, it was observed that it ranged between averages of 45 Tex and 12 Tex. Table 2 shows the different weights of the three samples and the averages for the P, LV1/5, LV1/10, BSG1/5, BSG1/10, F1/5, and F1/10 media. The filaments with the highest average linear density were P (45 Tex) and F1/5 (40 Tex). The LV1/10 and BSG1/10 filaments were rejected due to their fragility, to the point of being impossible to work with.

Table 2. Linear density (Tex) of BC filament dried at 22 °C temperature. Vegetable beverage (LV) 1/10 and brewer spent grain bagasse (BSG) 1/10 were very fragile and could not be measured.

	P	LV1/5	LV1/10	BSG1/5	BSG1/10	F1/5	F1/10
A	38	36	ND	18	ND	42	39
B	60	33	ND	12	ND	33	24
C	38	33	ND	6	ND	45	15
Average	45	34	0	12	0	40	26
Deviation	13	2	0	6	0	6	12

The study presents limitations in the bacterial quantification and consortium stability across batches. The consistency of the study was maintained by using the same amount of SCOBY culture (20 mL) for each medium and batch.

3.2. Optimizing BC Production

Once the first production phase was completed, a second iteration of the medium containing fruit by-products was prepared given the positive results obtained, incorporating two additional concentrations into those already studied. The objective was to bring the sugar content closer to the levels of medium P and increase the thickness of the resulting BC. In the production optimization, two additional concentrations were prepared using fruit press residues, with three replicates per treatment of F1/2.5 and F1/7.5, in addition to those previously tested (Figure 6). The thickness of the BC film was measured on days 5 and 12 from the start of fermentation.

An increase in the initial thickness of the F1/2.5 medium was observed, equivalent to that obtained with the P samples (Figure 6). This was due to the high fermentative activity observed through color changes and suspended particles in the medium, which was attributed to the transformation of polyphenols and the activity of bacterial and yeast enzymes, as well as the release of biomass, CO₂, and the presence of suspended cells

during fermentation [41]. However, the final thickness reached 3 mm, just as in medium P, suggesting that most of the fermentation and BC growth occurred during the first few days of the process.

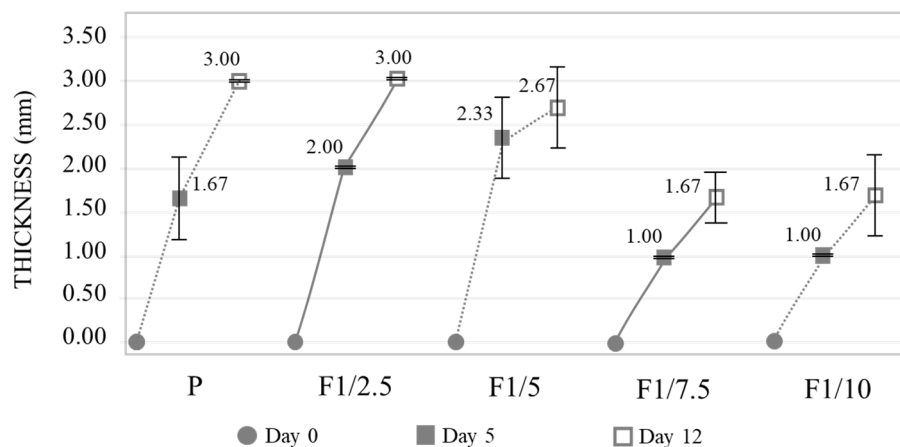


Figure 6. Average thickness of BC film within the reactor box system (mm) at concentrations of fruit (F) 1/2.5 and 1/7.5, added to those previous analyzed panela (P) and fruit (F) 1/5 and 1/10 (dotted line).

3.3. Functionalization

Functionalization treatments were initially applied to the BC filament using medium P. Treatment with 10% NaOH and 5% glycerol yielded the best results, demonstrating good flexibility in the knot slippage test, as well as lower chemical consumption. Applying 5% NaOH can increase the BC stiffness from 15 GPa to 30 GPa [40,42]. As such, glycerol acts as a plasticizer for the BC, improving its flexibility, mechanical properties [9,43], and processability [44]. Based on these results, 10% NaOH and 5% glycerol treatment was applied to the BC filament from medium F1/2.5, as this medium yielded the best fermentation results. The functionalized BC filaments from media F1/2.5 and P were dried at 22 °C and prepared for knitting in a single-ply format, untwisted (P_0 and F1/2.5_0) and twisted (P_1 and F1/2.5_1), as well as in twisted 2-ply configurations (P_2 and F1/2.5_2) and 4-ply twisted configurations (P_4 and F1/2.5_4). The weight of the BC filaments was measured. Table 3 shows the linear density and thickness of the different F1/2.5, P, LY, and RA filaments and yarns.

Table 3. Linear density and thickness of lyocell (LY) and raffia (RA) yarns and BC filaments of panela (P) and fruit (F) 1/2.5 of 1-ply with and without a twist and of 2 and 4-ply with a twist.

Sample	Configuration for Knitting	Average Linear Density of BC Filament (Tex)	Average Diameter of BC Filament (mm)
P_0	1-ply without twist	37 ± 7	0.17 ± 0.02
P_1	1-ply with twist	37 ± 13	0.23 ± 0.09
P_2	2-ply with twist	71 ± 10	0.32 ± 0.02
P_4	4-ply with twist	108 ± 27	0.44 ± 0.17
F1/2.5_0	1-ply without twist	29 ± 2	0.17 ± 0.04
F1/2.5_1	1-ply with twist	21 ± 5	0.22 ± 0.04
F1/2.5_2	2-ply with twist	50 ± 5	0.20 ± 0.03
F1/2.5_4	4-ply with twist	83 ± 2	0.28 ± 0.05
LY	100-ply with twist	26 ± 1	0.14 ± 0.01
RA	2-ply with twist	506 ± 10	0.98 ± 0.15

It was observed that the maximum average linear density corresponded to RA at 506 Tex, followed by, at a considerable distance, the 4-ply filaments of P_4 and F1/2.5_4, which recorded similar values of 108 Tex and 83 Tex, respectively. As for the average diameter, the highest value was also obtained for RA (0.98 mm), while the P_4 filament

reached 0.44 mm, followed by P_2 at 0.32 mm and F1/2.5_4 at 0.28 mm, all values similarly far from that recorded for the RA.

The study presents limitations in the knot slippage test [45] and the relation between mechanical performance, number of plies, braid angle, linear density, and average diameter that should be studied in future work.

3.4. Mechanical Properties

The tensile strength, elongation, and Young's modulus of the functionalized P and F1/2.5 filaments in 1-, 2-, and 4-ply configurations were analyzed and compared with those of LY and RA. Figure 7 shows the results for tensile strength, elongation, and Young's modulus obtained in the tensile test of the different filaments, according to the number of plies with and without twist.

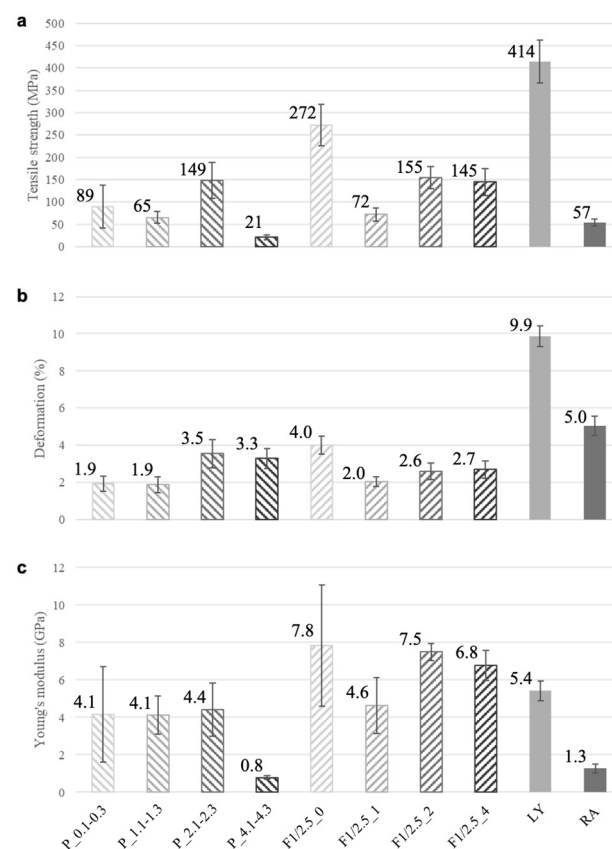


Figure 7. Tensile strength (a), deformation (b), and Young's modulus (c) graphs comparing the average of BC filaments in fruit (F) 1/2.5 and panela (P) media with the reference yarns lyocell (LY) and raffia (RA).

Regarding tensile strength (Figure 7), the LY yarns exhibited a higher average strength, reaching 414 MPa, compared to the other filaments. However, RA yarns and BC filaments of the P_4 medium recorded the lowest values, with average strengths of 57 and 21 MPa, respectively. Among the two types of BC filaments, considering the same number of plies and twists, the F1/2.5 medium showed a higher average strength (between 72 and 272 MPa) than the BC filaments from the P medium, whose values ranged from 21 to 149 MPa. This difference, compared to the BC filaments obtained in medium P, could be attributed to the greater compaction of the fibers related to the type of nutrient source (type of sugar) used for BC cultivation. The BC filaments from medium F1/2.5_0 reached the highest value, with a strength of 272 MPa. This result could indicate that the torsion induced in the BC filaments generates greater structural brittleness, an effect that is atten-

uated as the number of filament plies increases. This effect has been reported in twisted cellulose nanofiber yarns and plant-fiber yarn composites. The twist level affects tensile performance [46], while related excessive twist to fiber obliquity and misalignment with the tensile loading direction [47]. Therefore, the lower tensile strength observed after twisting may be associated with the helical reorientation of the BC fibrillar network, especially in single-ply filaments. Regarding deformation (Figure 7), the LY and RA filaments exhibited higher average resistance, reaching 9.9% and 5.0%, respectively, while the BC F1/2.5_0 filament showed the highest average deformation (4.0%) among all functionalized filaments. Regarding Young's modulus (Figure 7), the BC F1/2.5_0 filament exhibited the highest average value (7.8 GPa) compared to all analyzed filaments. In a study by Zhang et al. (2025), the results show that wet-stretching aligns the BC nanofibers, and applying heat (105 °C for 2 h to yarns twisted at 160 turns per 20 cm) fixes the structure, improving the yarn's stability and durability with a tensile strength of 751.56 MPa and an elongation of 11.56% [30]. In contrast, Takagi et al. (2025) developed a laminated and twisted BC yarn that had a tensile strength of 153 MPa [29]. This study observed the highest tensile strength in the BC F1/2.5_0 filament at 272 MPa without twisting, a result that falls between the tensile strength values reported by Zhang et al. and Takagi et al. Finally, both previous studies envision a biomedical suturing application, combining BC properties with high tensile strength and low friction [29,30]. Future work should study the relations between NaOH concentrations, mechanical properties, low friction, wet-stretching processing, and biomedical properties of BC filaments.

3.5. Knittability

Finally, 1-, 2-, and 4-ply P and F1/2.5 filament yarns were evaluated using textile technology. The tests demonstrated that the moisture content and number of plies clearly influence the processability of BC filaments. The results are shown in Table 4.

Table 4. Knitted fabric with two types of BC filaments: panela (P), with 1-, 2- and 4-ply twists, and fruit (F) 1/2.5, with 2- and 4-ply twists.

Sample	State	Number of Ply	Knitting Feasibility	Principal Observations
P	Dry	1, 2, 4	Not feasible	High filament stiffness and brittle failure during handling
P	Wet	1, 2, 4	Feasible	Increased elastic deformation and flexibility enabling stitch formation
F1/2.5	Dry	1, 2, 4	Not feasible	High filament stiffness and brittle fracture during handling
F1/2.5	Wet	1	Not feasible	Filament breakage preventing stable stitch formation
F1/2.5	Wet	2	Partially feasible	Localized structural failure at the junctions with the support yarn
F1/2.5	Wet	4	Feasible	Improved structural stability and higher filament cross-section regularity

The dry P filaments could not be knitted due to their high stiffness and brittleness, failing mainly by brittle fracture during handling and needle insertion, whereas in a wet

state they exhibited greater elasticity and flexibility, allowing for satisfactory knitting in 1-, 2-, and 4-ply configurations. In the study by Takagi et al. (2025), it was also emphasized that in order to produce BC yarns using the traditional kami-ito technique, BC must be moist to prevent the material from becoming stiff and breaking [29].

For the F1/2.5 filaments, the 1-ply configuration was not suitable for knitting due to tensile rupture during loop formation; the 2-ply configuration exhibited mechanical limitations, with breakage at the junctions with the support yarn in the final sample; and only the 4-ply configuration achieved performance comparable to that of P. Figure 8 shows examples of the knitted structures obtained in the knitting tests, corresponding to the results listed in Table 4. Visually, the 4-ply-twisted P sample has a similar appearance to the knitted samples made of raffia or ramie [48]. Finally, considerations of factors such as humidity, the relationship between torsion and number of plies, the friction coefficient with the metal needles of the knitting machine, and finishing coatings [45] should be investigated.

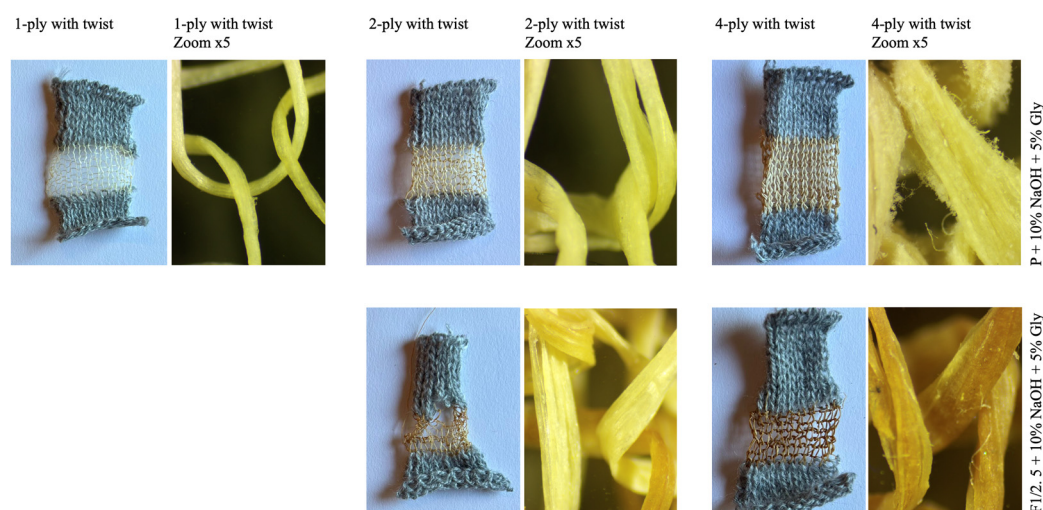


Figure 8. Samples knitted by hand with panela (P) and fruit (F) 1/2.5 filaments, treated with 10% NaOH and 5% Gly with 1-, 2-, and 4-ply twists. Each knitted sample was observed under a 5× magnifying microscope.

4. Conclusions

This study investigates the conversion of agricultural by-products to produce functionalized, twisted BC filaments with knitting properties. The results indicate that it is possible to produce BC filament using carbon and nitrogen sources recovered from the agro-industrial sector. Notably, the medium prepared with pressed fruit (F1/2.5_0) yielded good results, with a BC sheet thickness and linear density of the BC filament similar to that of the P_0 medium. Furthermore, the F1/2.5 medium showed a high sugar reduction (12.62 g/L), reflecting high fermentation activity despite a final pH of 7.54, which could be the cause of the slowdown in BC growth starting on the fifth day. The greater sugar consumption observed in the F1/5 medium may indicate a more favorable nutrient composition for bacterial metabolism, potentially related to the available carbon source and C/N balance. Since only total reducing sugars were quantified, the contribution of specific mono- and disaccharides could not be determined. Future work should evaluate the saccharide profile of agro-industrial substrates.

In this study, no direct relationship was observed between twists and the mechanical properties of the BC filament. The comparison of tensile strength showed a higher average strength for the LY yarns, which reached 414 MPa, followed by the BC filaments with the F1/2.5 medium without a twist and with two twisted plies (272 MPa and 155 MPa, respectively) and the BC filaments with the P medium with two twisted plies (149 MPa). In

contrast, BC filaments in the dry state could not be knitted due to their high stiffness and brittleness, whereas in the wet state they allowed for satisfactory knitting in configurations of 1-, 2-, and 4-ply for the P medium and 2- and 4-ply for the F1/2.5 medium. It has also been demonstrated that it is possible to scale up BC filament production by increasing the diameter of the spiral mold from 100 mm to 290 mm.

To scale up toward this, BC filament structural functionalization opens up critical areas of future research, such as optimizing mercerized BC filament properties by applying tension with wet-stretching processes and improving BC filament knitting in a dry state by using different coatings. Given the feasibility of producing knitted structures and the biocompatibility, BC filaments show promise for the development of textile applications and biomedical sutures with a low environmental impact.

5. Patents

Laura Freixas has issued patent #ES2954111B2 to assignee.

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Abbreviations

The following abbreviations are used in this manuscript:

BC	Bacterial cellulose
SCOBY	Symbiotic culture of bacteria and yeast
P	Control panela
BSG	Bagasse
LV	Vegetable beverage
F	Fruit
LY	Lyocell yarn
RA	Raffia paper yarn

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