3D Printing Bacterial Cellulose and Polyethylene Terephthalate Glycol to Reinforce Textiles for Material Longevity in Textile Circularity

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Abstract

In a circular textile economy, there is a requirement to reduce the consumption of new materials and encourage ways to keep materials and apparel in use for longer while utilising waste as a raw material. Repair and reinforcement of materials are circular practices that have been applied to extend the life cycle of apparel. The digitalisation of repair tools could facilitate how the repair is adopted at scale. 3D printing has been highlighted as an important technology for future manufacturing due to its ease, speed, and ability to be locally or globally produced. Although 3D printing is an accessible tool for at-home object printing of repair parts, this tool has not been investigated to extend the life cycle of a textile material through repair or reinforcement. In this paper, we present an interdisciplinary approach explored in the Textiles Circularity Centre to investigate how 3D printing a medium consisting of bacterial cellulose and polyethylene terephthalate glycol onto textiles can reinforce a material. We characterise the printed medium and discuss the use of 3D printing as a tool for advanced repair practices in a circular textile economy. The novelty of this approach is in the deposition of a cellulose-based filament onto a textile to facilitate material longevity, namely, reinforcement for repair and reuse.

Keywords Circular economy · Bacterial cellulose · 3D printing · Repair · Reuse · Circular design

Introduction

Reuse in a Circular Economy

A circular economy for textiles envisions a system in which materials are kept in use for as long as possible before transforming waste textiles into a feedstock for a new material life cycle (Ellen Macarthur Foundation 2017). Millward-Hopkins et al. (2023) discuss a series of scenarios that encourage how the extension of a material life cycle could take place: One of these scenarios shows the importance of building a relationship between how waste is used as a resource for textiles and how textiles already in use are reused, repaired, and resold, extending the life cycle of materials (Millward-Hopkins et al. 2023).

Repair, reinforcement, re-making, and reuse are highlighted as important practices for achieving a circular economy and extending the lifespan of materials (Zhang and Hale 2022). These practices are often rooted in tradition and passed down through craft knowledge, from skills such as darning, patching, or the practice of physically mending apparel (O'Neal 2023). This knowledge is often embodied through the physical interaction with a material (Heimer 2022). However, the modern relationship between motivation and 'mending frequency' is not equal (Diddi and Yan 2019). While consumers are very positive and driven to repair their items, their drive does not directly equate to the action of repairing (Diddi and Yan 2019). This suggests there is a willingness to repair clothing but also the need to help with the adoption of repair as a practice. Multiple studies show that this lack of adoption is due to factors such as time, ease, and education (Laitala and Klepp 2018; McQueen et al. 2023). Digitalisation and innovations

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in textile technologies could be one way of engaging with repair.

Apparel and textiles are at the forefront of digitalisation; however, many of the innovations are centred on facilitating ease in design, sales, and consumption (Akhtar et al. 2022). The focus on the digitalisation of circular approaches such as resale has been shown to increase the second-hand market (Charnley et al. 2022). Currently, there is a lack of digital tools or technologies that can aid repairing and reinforcing of textile materials at scale. Digitalised textile technologies could be used as a radical innovation to repair materials, hence extending the life of apparel already in use. This can be achieved through a tool such as additive manufacturing.

3D Printing in Additive Manufacturing

Additive manufacturing, referred to as 3D printing, is a manufacturing approach used for rapid prototyping or manufacturing to fabricate 3D structures directly from a computer-aided design (CAD) file (Gibson et al. 2010). There are several types of 3D printing with the main difference between them being the material deposition technique. Methods such as fused deposition modelling (FDM) melt or soften the material. Methods such as selective laser sintering (SLS) melt powdered materials together. Other methods such as stereolithography use photo-solidification where liquid materials are cured. The most mature and cheapest method of 3D printing is FDM. This method uses a plastic filament which is heated and pushed through a heated extrusion nozzle. Although FDM is an industrial form of additive manufacturing, FDM can be purchased and used by consumers within the home. The printing process is initiated by slicing the CAD file using a slicer software. FDM printing can be used as an alternative to other common textile technologies including screen printing, flexography, inkjet printing, and gravure (Melnikova et al. 2014). This aids the production of more complex, tailorable, and customised designs. It can be used to fabricate functional or smart textiles through the deposition of smart functional polymers or blends on textile fabrics (Hashemi Sanatgar et al. 2017). The deposited patterns are directly printed without using any masks or etching process, ensuring the simplicity and sustainability of the process.

Consumers now have access to low-grade additive manufacturing technologies such as 3D printing to create small solid objects and forms within a home (Jain and Jain 2020). This presents an opportunity for customers to have autonomy over hyperlocalised home reinforcement or repair to advance the design of their own objects (Rayna and Striukova 2016). This approach could be translatable and socially scalable to other areas of consumer goods including textiles, which would allow consumers to take an integral part in mending processes, a concept that is highlighted as an important factor in building relationships with textiles (Hernandez et al. 2024). If effective, 3D printing repair and reinforcement can be used to keep textiles and apparel in use for longer. 3D printing would not only become a key tool to reinforce materials but would also encourage consumers to engage with repair by utilising alternative technologies. As an advanced and novel technology for consumers, it is important to explore how additive manufacturing can be used to facilitate new circular practices. This approach would transition manufacturing in a circular economy towards a pathway in which there is less reliance on creating more new materials and shift consumers towards maintaining their materials to reduce consumption.

3D Printing for Textiles and Apparel

3D printing for textiles and apparel focuses on experimental forms due to its range of textural possibilities. Designers such as Julia Koerner show this by printing fully formed apparel (Koerner 2017). Materials and textiles can also be created in structures similar to knitted and woven materials (Lussenburg et al. 2014; Beecroft 2016). However, the quality, drape, and texture of these materials produced by 3D printing are difficult to compare to traditional textiles (Xiao and Kan 2022). This contributes to why designs remain experimental and why 3D-printed materials have not been fully adopted as a manufacturing technique for textiles (Xiao and Kan 2022).

The printing of polymers onto textiles as embellishments has been largely explored within two categories: functional support and creative application. Functional research into 3D printing onto textiles focuses on the direct printing of apparel fastenings such as claps, zips, and buttons, as well as for heat conductive or performance applications (Varis et al. 2018), while creative applications focus on aesthetics, shapes, colour, and pattern (Pei et al. 2015). Literature does not point to 3D printing being used as a way to increase the lifespan of a textile material already in use. Instead, it is used as a way to decorate or add function to new textile-based products (Pei et al. 2015, Čuk et al. 2020). Further, these applications mainly rely on petrochemical filaments and do not use renewable sources. Although plastic-based filaments for 3D printing are widely developed and allow ease of creativity, when it comes to the end of life, synthetic deposition has strong adhesive properties (Gorlachova and Mahltig 2021). While adherence to synthetic polymers is beneficial for the longevity of a print design, it means that the deposited material is difficult to separate from the textile substrate when it comes to end-of-life recycling. This context highlights the need for a renewable material for the 3D-printed deposition onto textiles that matches the adhesion qualities of synthetic materials and that can enter into a circular textiles recycling system.

Cellulosics and 3D Printing

Regenerated cellulose obtained from post-consumer textiles in chemical recycling has been used for 3D printing functional textiles, as well as for screen printing textiles for modification of their properties in functional and aesthetic finishes (Ribiul 2023). Bacterial cellulose (BC) is a novel bio-assembled material that is produced through fermentation. The material can be produced using glucose from bio-waste sources. Although the production of cellulose for 3D printing has been explored for textile modification and functionalisation, the use of 3D printing with bacterial cellulose has not been explored as a medium to reinforce textiles to extend their life in a circular textile economy (Kataja and Kääriäinen, 2018). The Textile Circularity Centre investigates how bio-based waste can be utilised in the production of bacterial cellulose (BC) to transform this into high-value textiles. Within this paper, BC is combined with PETG for the purpose of 3D printing onto and reinforcing cellulose-based textile materials already in use within the apparel system. A WA Prusa 3D printer was used with the aim to enable future consumer-led repairs, as this is similar to ones suitable for home use. Structural designs were developed to deposit the medium onto textiles, and the results of the mechanical properties were characterised. The novelty of this work highlights how 3D printing technologies can be implemented into circular practices enabling material longevity such as repair and reinforcement techniques while utilising a cellulosic filament obtained from bio-waste sources.

Materials and Method

Bacterial cellulose forms as a natural nonwoven at the surface of nutrient and sugared liquid with access to oxygen. This nonwoven is formed of nanofibrils and ribbons that are tangled together at the stage of growth. Polyethylene terephthalate glycol (PETG) was provided by RS Components (RS International, RS Components Ltd., Corby, UK) in white filament form with a 1.75 mm diameter. Organic cotton textiles were bought from MerchantandMills™ in twill weave, a common textile weave structure identified by its diagonal weave pattern and used commonly within apparel.

Bacterial Cellulose

Bacterial cellulose (BC) was produced using *Gluconacetobacter xylinus* strain ATCC 53524, a published strain obtained from the American Type Culture Collection (ATCC). The strain was cultured using 50 g/L bacterial peptone, 50 g/L yeast extract, 27 g/L disodium phosphate, and 15 g/L citric acid monohydrate in the presence of 2% glucose (Hestrin Schramm medium) (Nguyen et al. 2022). The solution was placed inside cell culture flasks and incubated at 30 °C for 6 days under static conditions (fermentation incubation). Then, cellulose pellicles were harvested, incubated at 80 °C for 4 h, using sodium hydroxide (NaOH) (0.1 M) and dried at 30 °C after extensive washing with deionised water. Finally, dried cellulose pellicles were milled into powder using a ball mill at a frequency of 30 1/s for 1 min (TissueLyserII, Qiagen).

Filament Production

PETG/BC (w/w:80/20) filaments were produced using the following procedure. First, PETG filaments were pelletised into 4-mm pellets using Process 16 Pelletiser (Thermo Fisher Scientific, Altrincham, UK). Then, BC and PETG pellets are simultaneously fed into two separate twin Screw Brabender feeders (Kubota Brabender Technologie GmbH, Duisburg, Germany), which are connected to a Haake Polylab with Rheomex Twin Screw Extruder (Thermo Fisher Scientific, Altrincham, UK). The BC and PETG are homogeneously blended at 190 °C and extruded into a water bath. The extruded blend is then pelletised into 4-mm pellets. The following equations were used to obtain an accurate and homogeneous mixing of the materials:

$$VF = Q\rho \tag{1}$$

$$GF = mt \tag{2}$$

where VF is the volumetric flow rate, Q is the feed rate, ρ is the density of the polymer, GF is the gravimetric flow rate, m is the mass of the polymer and t is the time period of the flow (Lee et al. 2015). VF and GF results of the different material concentrations are presented in Table 1 (Fig. 1). Following the mixing and pelletisation process, the pellets were dried using an oven at 50 °C for 48 h to dry and remove the water absorbed. Finally, the pellets were extruded using the 3devo filament maker (3devo, Utrecht, Netherlands) at 190 °C producing 1.75-mm PETG/BC filaments ((w/w) 80/20); process flow is presented in Fig. 1.

Table 1 Volumetric and gravimetric flow rate results of different material concentrations

Materials	Volumetric flow rate (kg/hr)	Gravimetric flow rate (kg/hr)
PETG/cellulose (80/20 wt%)	0.972	0.243

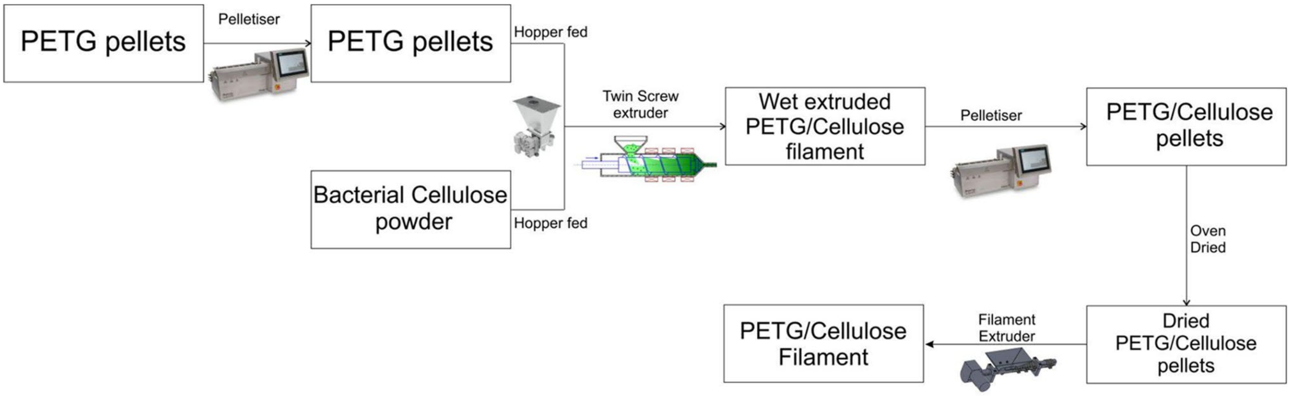

Fig. 1 PETG/cellulose mixing process flowchart

Filament Digestion Back to Glucose

The filament created was further tested to see if it could be returned to the bio-recycling process, creating a closed-loop system. The filaments were tested to investigate if an enzymatic process was able to convert the bacterial cellulose component of the filaments into glucose. The filaments were cut into 2–3 cm pieces, and half the material was pretreated with 0.8 M NaOH at 80 °C for 6 h. The samples were then washed until the pH was back to neutral and dried at 30 °C. Five grammes of the original sample and 5 g pretreated filament sample (in triplicate) were mixed with 0.063 g cellulase enzyme cocktail (gift from Novozymes) and MES buffer pH 5.5 before incubation at 50 °C for 7 days. Glucose concentration was measured using a glucose assay kit (Megazyme Ltd.). Filaments produced by 3D printing were digested using enzymes with or without pretreatment. Analysis of glucose levels at the end of the digestion showed that pretreatment was necessary for significant digestion. Glucose concentration reached 8 g/L, which meant that 40% of the cellulose could be converted back into glucose.

Pattern Design and Fabrication

The objective of the design and deposition was to reinforce the textile at a material level of apparel products. Truss structure theory is used to distribute the points of stress within architectural builds (Yu et al. 2022). This occurs by creating triangular connections which helps in shifting the forces, ultimately reducing the stress, leading to better structural integrity. The circle is considered to have high structural strength as points of stress are dispersed across the arch and is a geometric shape that has been tested for tension points in application in textile materials for aircraft and automotive industries (Sugiyama et al. 2018). The patterns were designed to use a combination of triangular lines and circular shapes at different densities and scales to combine these two methods of strength and stress dispersion. Truss patterns were used to guide points of stress, and circular patterns were used to disperse points of stress.

Firstly, curves were maximised in pattern one (Fig. 2), mainly consisting of intersecting circular patterns. Points of contact were designed to distribute the point of stress by adding circular shapes. Pattern two reduced the connection points between the circular structures, and to lower potential points of failure, a vertical and horizontal line was added to create more triangular shapes with curved edges. Pattern three was created following truss theory with force directed towards the circular shape to which it is dispersed. This predominantly created triangular connections which helps in shifting the stress to the points where the lines meet: this stress was dispersed with circles combining both methods in a simple way ultimately leading to a better structural integrity of the design which is optimal for reinforcement.

The effect of pattern density on the reinforcement performance was assessed through having varied repeats of patterns. Each pattern investigates these geometric points of stress at a scale of 1 repeat, 4 repeats and 16 repeats (Fig. 1). All patterns were printed onto a cotton twill woven material. Twill was chosen for its high tensile strength. The woven pattern is often found in textiles and apparel.

Solidworks (Dassault Systems, Waltham, MA, USA) was used to produce the 3D models of the designed patterns. The designed patterns were saved in Standard Tessellation Language (STL) format, and a Prusa slicer was used to slice the files. Prusa i3 MK3S (Prusa Research, Prague, Czech Republic) were used to print the patterns on the fabrics using the following procedure. First, the fabrics were cut into 250 × 190 mm ($L \times W$) rectangles. Then, the fabric cut-out is fitted on the Prusa print bed and secured using clamps. Finally, the patterns are deposited on the fabrics using the parameters in Table 2.

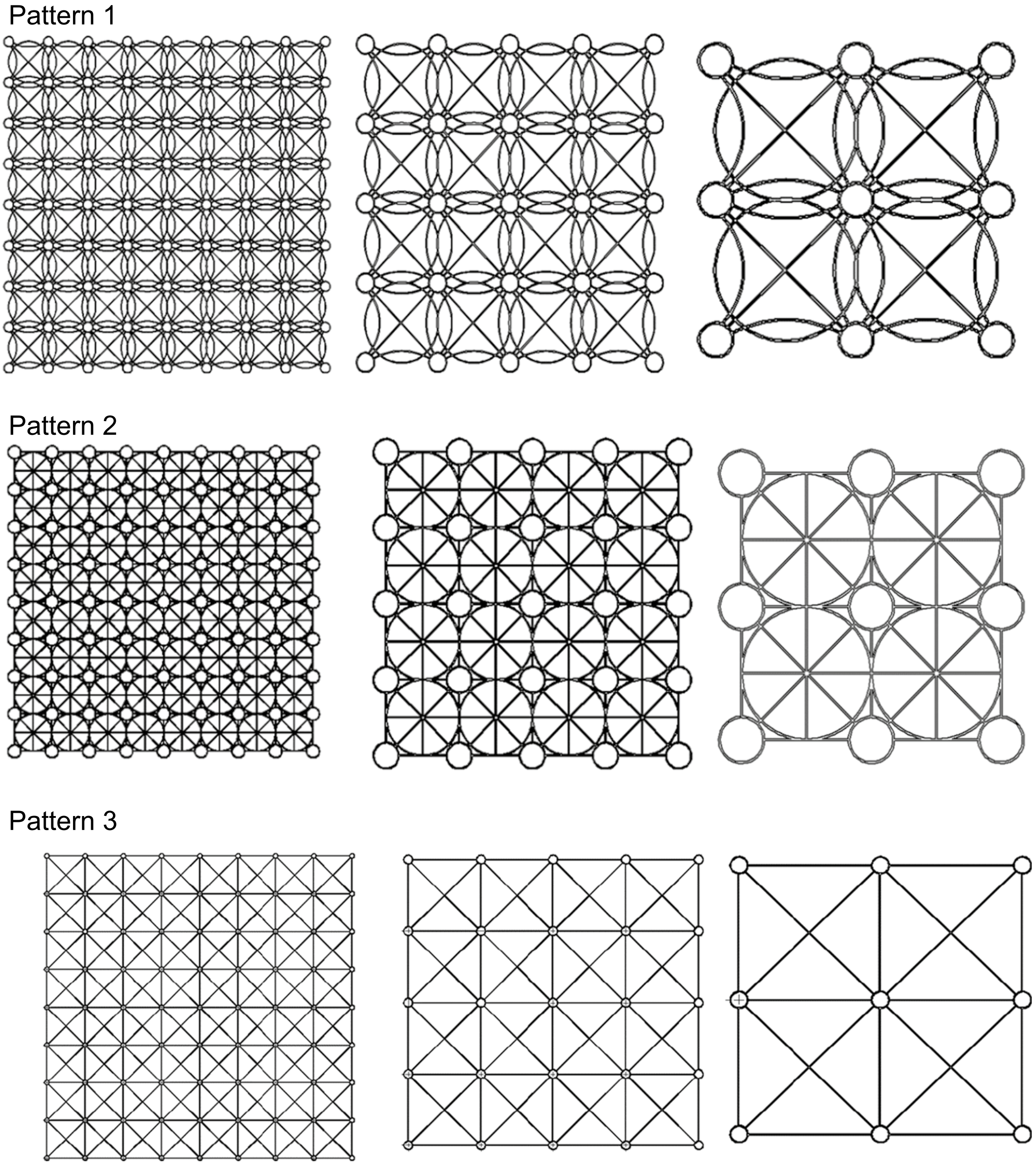

Fig. 2 Designed patterns for textile reinforcement

Mechanical Testing

Table 2 **3D** printing parameters

Parameters	Value
Layer height (mm)	0.3
Filament diameter (mm)	1.75
Printing temperature (°C)	220
Bed temperature (°C)	50
Printing speed (mm/s)	60

Our objectives were to investigate, through mechanical testing, whether 3D printing BC and PTGE using our designed patterns add reinforcement to the fabric. The first objective was to test the strength of the material, and the second objective was to understand how the deposited material bonds to the fabric.

Tensile D5034-21

The mechanical properties of the reinforced fabric (control, pattern 1, pattern 2 and pattern 3) were investigated using

Instron 3344 and Bluehill software (Instron, Norwood, MA, USA) using a 2 KN load cell following ASTM D5034-21. Reinforced fabrics ($n=3$) were cut into 150 × 100 mm (~ 0.57 mm thick) and clamped at an initial grip separation of 75 mm. The reinforced fabrics were elongated at a rate of 300 mm/min until breakage. Young's modulus was calculated using the stress–strain curve slope in the initial linear portion.

Bonding Adhesion Testing

The filament (PETG/cellulose, 80/20) bonding adhesion to the fabric was investigated using the shear tensile strength test proposed by Malengier et al. (2018) based on the EN 1373:2015 standard. The test was carried out by placing the fabric substrate in the tensile machine with the lower clamp holding the textile and the upper clamp holding the printed surface. The initial clamp separation is 100 mm. The fabric substrate is elongated at a rate of 50 mm/min until break.

Abrasion of 3D Printed Fabric

Consistent rubbing of fabrics, particularly in the case of apparel, results in wear of the fibrous structure, ranging from change in appearance, pilling, and material loss and subsequently leading to a total breakdown. This behaviour can be simulated using abrasion testing methods where the test material is assessed visually and incrementally over a given number of rub cycles.

To test the durability of the 3D-printed polymer on the woven fabric, the ISO 12947 test method has been adopted. This method has been standardised for assessing the abrasion resistance of fabrics using the Martindale testing apparatus. As shown in Fig. 3, the method involves placing the fabric in a specimen holder that allows the face of the test specimen to be placed against the face of a standard abrasive cloth under a constant pressure of 12 kPa acting down on the spindle. The Martindale abrasive (SM25) cloth is a highly durable woven worsted wool fabric which is clamped on the static abrasion table. The abrasive cloth is cushioned from underneath and clamped to ensure a consistently taut surface area. For this set of tests, pattern 2 was chosen, as it has the largest amount of deposited material within the surface area of the fabric.

The test specimen is rubbed against the abrasive fabric in a Lissajous pattern (Fig. 4) that provides even wear across the surface area of the test specimen. This pattern is generated with the help of two simultaneous motions that allow a circular pattern to transition into ellipses and then into a straight line, thereafter reversing in a diagonally opposite direction to complete the repeat pattern.

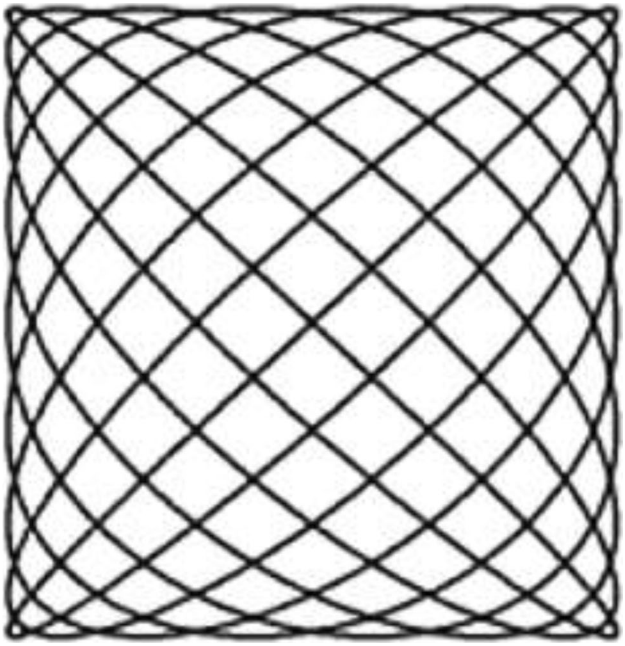

Fig. 4 Lissajous pattern

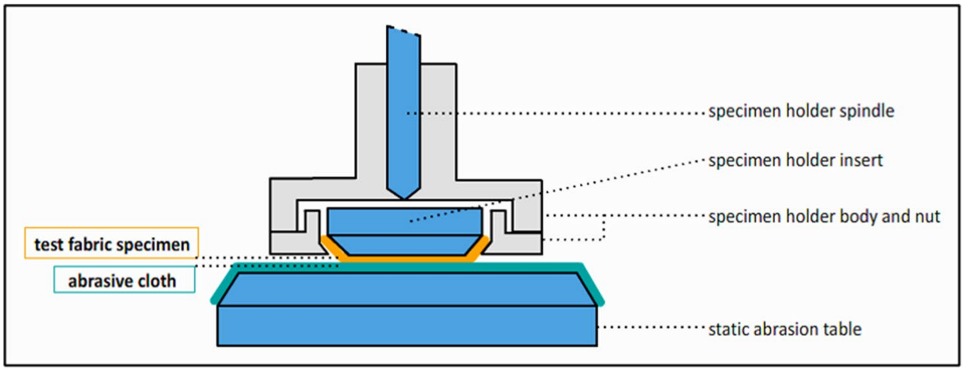

Fig. 3 Martindale fabric abrasion test setup

Table 3 Shear tensile strength test results

Bonding test	Force (N)	Standard deviation
1	581.3	30.19
2	507.07	6.93
3	474.41	23.26
Average	520.93	20.12

Results

Adhesion/Bonding

Bonding between the printed fibres and the fabrics is assessed using a shear tensile strength test. The tensile stress–strain curve and Table 3 present the bonding results with an average of 2.72 GPa which is good compared to other materials, such as TPU and PLA, that were previously investigated by Goncu-Berk (Goncu-Berk 2019). This indicates that the printing parameters and materials are suitable for the reinforcement of fabrics to increase the mechanical properties. The bonding can be attributed to the polymer binding with the fabric yarn on a microlevel. The heat from the printing head liquefies the material, and pressure from the printing head forces it between the fabric yarns, increasing the bonding.

Abrasion

Figure 5 compares the surface of the abraded test specimen following 25 k cycles with the non-tested 3D-printed woven fabric. At this stage the sample has not reached breakdown; however, the base woven fabric structure undergoes minor loss of fibres from the surface. The 3D-printed regions remain intact with the fabric surface but appear polished down, yielding a smooth finish as a result of the mechanical rubbing action during testing. The abrasion behaviour of the material can be correlated to the bonding behaviour. As the material exhibits a strong bonding to the fabric caused by being embedded between the yarns, it makes it harder to remove from the surface, and the mechanical rubbing during the test causes excess unbonded materials to be removed.

Tensile

Tensile stress–strain curves were plotted and used to assess the mechanical properties of the reinforced fibres. The curves demonstrate an increase in the tensile strength of the fibres directly proportional to the increase in the BC fibres deposition (Fig. 6a–d). The tensile properties increase as the size of the pattern increases from small to medium and large (Fig. 6). Furthermore, pattern 3 has the highest tensile strength (4.47 GPa), and pattern 1 has the lowest tensile strength (3.18 GPa) which is still higher than the control fabric tensile strength (2.77 GPa).

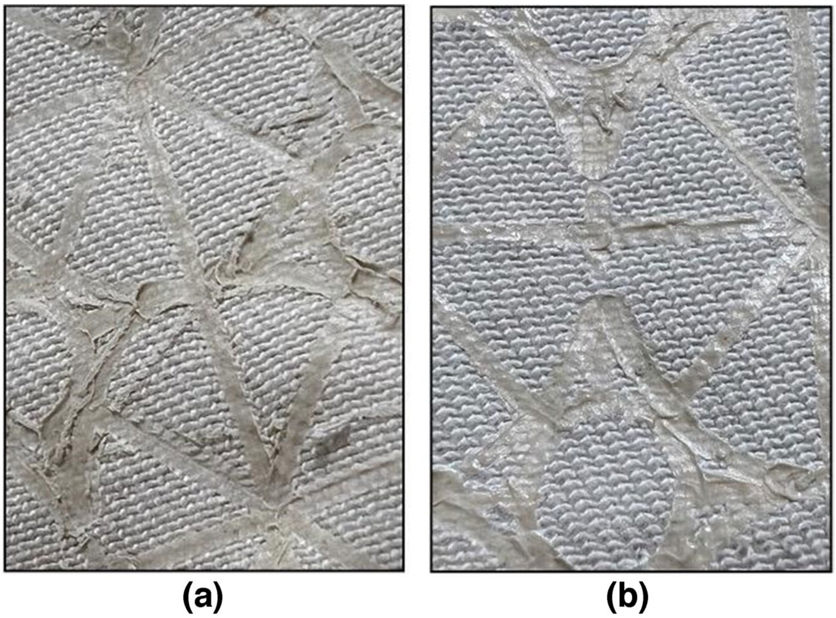

Fig. 5 3D-printed woven fabric; **a** before and **b** after abrasion testing up to 25 k rub cycles

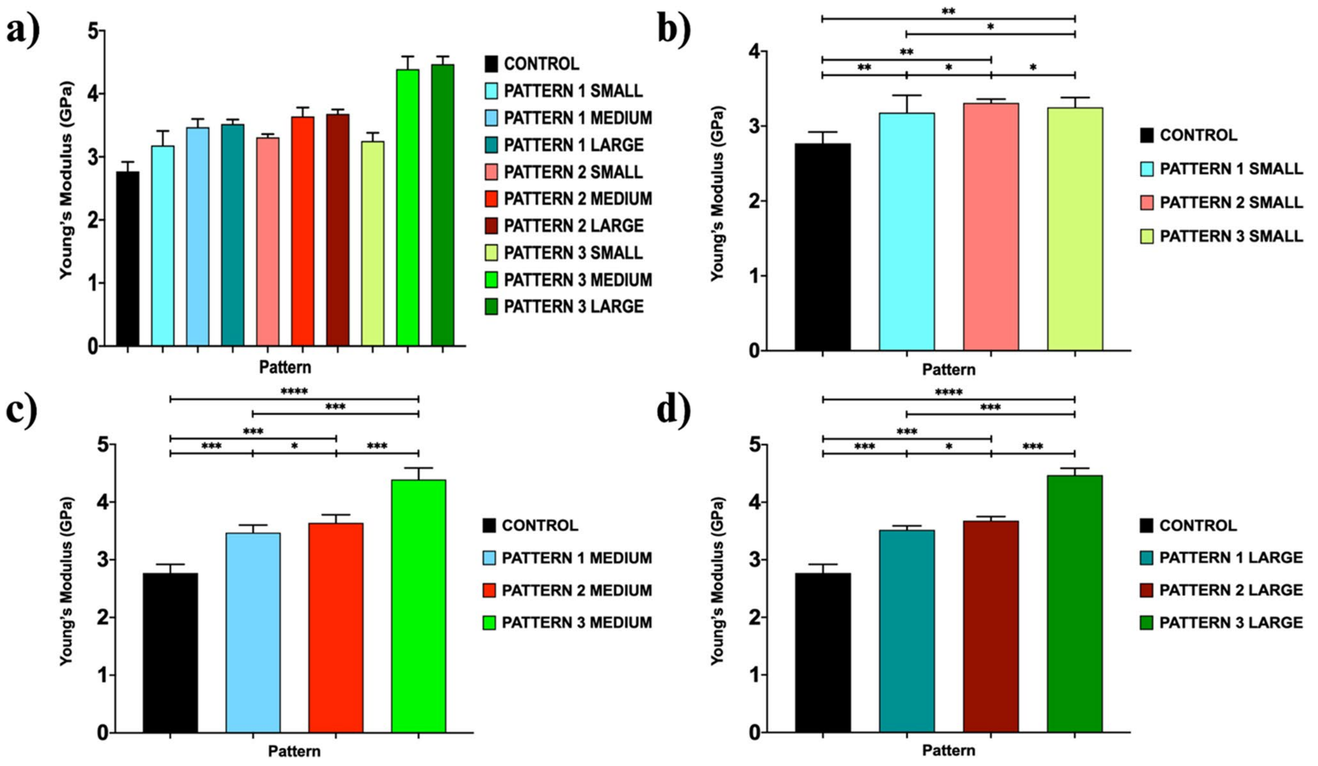

Fig. 6 Mechanical properties of the patterns printed, **a** Youngs' modulus results for all patterns, **b** Youngs' modulus results for all small patterns, **c** Youngs' modulus results for all medium patterns, and **d** Youngs' modulus results for all large patterns. Results were presented as mean * SD. Statistical analysis was conducted using one-way analysis of variance (ANOVA) with Tukey's post hoc test. Significant differences were considered at $*p<0.05$, $**p<0.01$, $***p<0.001$, and $****p<0.0001$

Discussion

The aim of the study was to investigate the effect of 3D-printed PETG/BC (20%) filament reinforcement behaviour on cotton-based textiles, as well as the effects of different patterns on this reinforcement. Three patterns at three different scales (small, medium and large) were used in the study. The performance of the patterns was assessed through tensile testing. Pattern 3 'large' had the highest Young's modulus (4.47 GPa) compared to the other patterns. This can be attributed to the design where a truss-like structure was created to help with shifting the forces around the design until failure. Furthermore, the number of repeats in a pattern was investigated concluding that the lower the number of repeats and the larger the pattern size, the higher the Young's modulus. This directly reflects the amount of material deposited onto the fabric. This means that the pattern size and Young's modulus are directly proportional to the pattern size and amount of deposition. From this, we can understand that the pattern design and dimension can determine the force of the tensile strength.

The bonding of the 3D-printed filaments on the fabrics is a crucial aspect of the use of 3D printing to reinforce fabrics; hence, this was investigated using shear tensile testing. The printing nozzle offset distance is an important factor to consider throughout the process: if the distance between the nozzle and the fabric is too small, the nozzle would catch or displace the fabric during the printing process. Hence, an appropriate distance is required to apply pressure and heat to the textile. The average bonding force of the PETG/BC filament on the fabric was 520 N and Young's modulus of 2.72 GPa. The average bonding force for TPU with Neoprene fabric was investigated by Goncu-Berk and was found to be 178 N, which is lower than the bonding force of PETG/BC filament on the cotton fabric. Therefore, the force is enough to ensure the bonding of patterns to the surface of the textile, therefore reinforcing it.

Conclusion

The aim of this research was to investigate how additive manufacturing technology, namely, 3D printing, can aid the circularity of textiles by reinforcing a woven cotton twill. The two scenarios discussed by Millward-Hopkins—firstly utilising waste as a raw material and, secondly, making sure materials are kept in use for as long as possible—are combined in this approach (Millward-Hopkins et al. 2023). In the Textiles Circularity Centre, we propose that bacterial cellulose is derived from bio-waste and used for both the production of circular textiles and the extension of their life. In this paper, we demonstrate how it can be deposited onto textiles to facilitate material longevity.

One objective was to test the strength of the textile once the pattern has been 3D printed using the cellulose material, which was conducted by testing the tensile strength. The results show that all patterns 3D printed onto the woven twill implemented an improved strength of the textile. In addition, the specific pattern design had a direct effect on the strength. Pattern 3 proved to provide the highest added strength. This was due to the pattern's truss-like shape with strain dispersing through circular points, even though patterns 1 and 2 had a larger amount of material deposited. Another objective was to test the abrasion of the material. The test results showed that the mechanical action only minutely affected the finish of the material, giving the 3D-printed polymer a polished surface as a result of cyclic rubbing. Most importantly, the 3D-printed material remained completely adhering to the fabric surface, suggesting that it can withstand the abrasion that a textile product undergoes typically. These results are true to testing on a cotton twill fabric and may show different results when investigating different material types, fabric structures and fibre choices.

In the context of textile circularity, this approach demonstrates several opportunities. Firstly, the bacterial cellulose that is used for 3D printing can be derived from bio-waste, and secondly, the deposited material can be used to extend the life of materials already in use. As all materials within this study are cellulosic, they can be recycled and reused in a new life cycle. Future areas of research could include reinforcing apparel through 3D printing, which could localise the material deposition to specific, customised areas that need reinforcement. Further research could investigate pattern optimisation, as well as characterisation through wash testing and longitudinal wear studies with consumers.

This paper highlights the need to reduce textile waste by innovating advanced technologies such as additive manufacturing to allow materials to stay in use for longer and demonstrates the need for innovations within circular repair practices for textiles and apparel. 3D printing is a novel application that is becoming more accessible across a wide scale of consumers including for use at home. In this paper, we demonstrated that 3D printing can enable material longevity. This work can underpin future research to encourage users to keep materials in use for as long as possible. This paper demonstrates a first step for investigating the application of advanced manufacturing technologies such as 3D printing in additive manufacturing for application in circular material life extension practices to aid a transition towards a truly circular textiles economy.

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Data Availability The data supporting this study are openly available via The University of Manchester online data repository with the identifier https://doi.org/10.48420/25721871.v1.

Declarations

Competing Interests The authors declare no competing interests.

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