Bicomponent regenerated cellulose fibres: retaining the colour from waste cotton textiles

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Abstract Bicomponent regenerated cellulose fibres (bRCF) have been created in a core–shell configuration from waste textiles. Textile dyeing and colouration is known to be a major contributor to the environmental impact of producing textiles and this needs to be addressed for textiles to become more sustainable. Coloration of the bRCF here was achieved by utilizing coloured textile waste in the shell component whilst using white cotton waste in the core. The shell and core extrusion speed and thus shell and core diameter were varied and optimised for colour strength. The optimised bRCF was made up of 49.6% dyed material yet was able to achieve the same colour strength as the single component regenerated cellulose fibre (RCF). The potential benefit of this approach is the reduced amount of coloured material required to colour these recycled fibres without any sacrifice in colour intensity. The mechanical properties of the bRCF were similar to the single component RCF with tensile strengths of 115–116 MPa and maximum elongations of 15.2–17.5%. The morphology of the bRCF was similar to single component regenerated cellulose fibres, while optical micrographs showed the discrete coloured core–shell structure of the bRCF. This manuscript details the fibre properties, dye savings and spinning approach.

Keywords Textile coloration · Waste cotton · Wet spinning · Recycling · Ionic liquid · Dyes

Abbreviations
bRCF Bicomponent regenerated cellulose fibre
CED Bis(ethylenediamine)copper(II) hydroxide solution
C/S Core/shell
DMSO Dimethyl sulfoxide
DP Degree of polymerisation
DR Draw ratio (fibre take-up velocity divided by fibre extrusion velocity)
DSLR Digital single-lens reflex
IL Ionic liquid
RCF Regenerated cellulose fibre
SEM Scanning electron microscopy

Introduction

Dyeing and wet processing is known to be the most polluting stage of the textiles manufacturing process (Esteve-Turrillas and de la Guardia 2017; Moazzem et al. 2018). The textile industry is said to be second in the world in terms of water pollution (Hussain and Wahab 2018) and is considered one of the largest water consuming industries (Yuan et al. 2012; Samanta et al. 2019), meaning this industry...
has far-reaching impacts on the global environment. During the typical cotton dyeing process an estimated 20–50% of dye will be found in the effluent along with other auxiliary chemicals (Khattab et al. 2015), making for a toxic effluent which is difficult to clean (Haslinger et al. 2019; Khattab et al. 2020). Other environmental impacts of textile production such as global warming potential, eutrophication potential, and acidification potential are also contributed to significantly by the dyeing process. An environmental impact assessment study published by Esteve-Turrillas and de la Guardia found that the global warming potential of the dyeing process for cotton was almost an order of magnitude higher than the impact of cultivation (Esteve-Turrillas and de la Guardia 2017). The same study showed significant reductions in eutrophication and acidification impacts when dyeing was excluded from the process (Esteve-Turrillas and de la Guardia 2017). Synthetic dyes are common in the current industrial setting, however the use of natural dyes for textile colouration is a re-emerging topic (Yilmaz 2020). Using natural dyes instead of synthetic dyes is generally thought to reduce the environmental impact of the dyeing process. This is achieved through reducing the toxicity of the dyestuff (Khattab et al. 2020) and the inherent non-carcinogenic and biodegradable characteristics of natural dyes (Mirjalili et al. 2011; İşmal 2017). An environmental analysis by Costa et al. found that natural dyeing of cotton had approximately half the impact of synthetic dyeing for freshwater ecotoxicity and less than half the impact for human carcinogenic toxicity (Costa et al. 2021). However, natural dyes often still require synthetic chemicals and heavy metals to attach the dyes, use large amounts of water, and have lower colour fastness and colour reproducibility compared to synthetic dyes (Khattab et al. 2020; Kumar and Gunasundari 2018). Reducing the amount of dye required, or eliminating the use of dyes, would have the largest positive impact on the sustainability of textile fibres. While eliminating the use of dyes is not a viable solution, one potential avenue to reduce the amount of dye used in textiles is to create bicomponent fibres where only the exterior component of the fibre contains coloured material, this approach is reported here.

Bicomponent fibres have existed for decades, however due to recent developments in manufacturing technology these fibres are becoming more widespread and commercially available (Mukhopadhyay 2014; Naeimirad et al. 2018). Bicomponent fibre production involves coextrusion of two distinct polymers to form a fibre with a variety of configurations such as side-by-side, island-in-the-sea, and core–shell, with the latter being the most common (Naeimirad et al. 2018; Mukhopadhyay 2014). The distinction between polymers may be physical or chemical (Hufenus et al. 2020). Commonly, bicomponent fibres are produced via melt spinning using synthetic polymers (Hufenus et al. 2020). The environmental challenges in society today are leading us to transition away from fossil-based materials, such as oil-derived polymers, and towards renewable and bio-based polymers (Haider et al. 2019; Kim and Jang 2013). Cotton is currently the most utilized natural fibre for textiles (Textile Exchange 2020). However, the predicted future ‘cellulose gap’ which refers to an increase in demand for cotton fibres that will not be met by an increase in supply, indicates that alternative fibres with properties similar to cotton are needed. Regenerated cellulose fibres are expected to play a significant role in addressing the cellulose gap and the demand for regenerated cellulose fibres (RCF) is increasing (El Seoud et al. 2020). The reliance of RCF on a raw material that is both annually renewable and biodegradable, and the increasing development of these fibres may result in RCF being an attractive alternative to synthetic fibres in the future.

Commercial RCF are made via the wet-spinning or the dry-jet wet-spinning process from dissolving-grade wood pulp. In these processes, cellulose is dissolved and extruded into a wet bath where it coagulates to form fibres. The two most commercially useful RCF production techniques are the viscosose process and the lyocell process. There are also many developmental RCF processes in literature. The aims of creating these alternative fibres range from improving the mechanical behaviour of the fibres (Sixta et al. 2015), using alternative cellulose sources (Ma et al. 2020, 2019a; Björquist et al. 2018), using different
Recent advances in the production of cellulose solvents (Chen et al. 2015), and creating functional fibres (Al-Maqdasi et al. 2021; Tian et al. 2014). Recently our group demonstrated the ability to chemically recycle dyed waste cotton into regenerated cellulose fibres whilst retaining the original fabric colour in the regenerated fibres (Ma et al. 2019a). The produced fibres had bright colours with a colour strength similar to the original waste fabric. These results have since been expanded on by Haslinger et al. who demonstrated chemical recycling of cotton containing various dye types (Haslinger et al. 2019). Their study also found the wash and rubbing fastness of the recycled fabrics outperformed the dyed waste fabrics, thought to be a result of constant dye distribution across the thickness of the fibres (Haslinger et al. 2019). A few recent reports exist detailing the use of regenerated cellulose as one of the components in wet spun bicomponent fibres. Orelma et al. created fibres with a regenerated cellulose core and cellulose acetate shell targeting optical fibre and watersensor applications (Orelma et al. 2020). Reyes et al. produced bicomponent fibres with a nanocellulose hydrogel as the core solution and regenerated cellulose as the shell component (Reyes et al. 2020). The regenerated cellulose shell was used to support the nanocellulose hydrogel and increase the overall spinability. Regenerated cellulose was also used as either the core or shell in technical textile fibres created by Liu et al. (Liu et al. 2022). The functional fibres produced by Liu et al. used graphene oxide/MXene mixtures as one component and regenerated cellulose as the other component in core–shell fibres made for thermal energy conversion and electromagnetic interference shielding applications. All three of these studies referenced the environmental benefits of regenerated cellulose as the motivation for its use within the bicomponent fibres (Orelma et al. 2020; Reyes et al. 2020; Liu et al. 2022).

Many different approaches to producing RCF exist in literature, largely different by solvent choices and cellulose type, and bicomponent fibres with one component comprising regenerated cellulose have recently been reported. However, to the authors knowledge there have been no reports on bicomponent cellulose fibres where both components consist of regenerated cellulose. In this study, we report on the production of coloured regenerated cellulose fibres using bicomponent spinning, termed bRCF. The core and shell spinning solutions are both prepared from the dissolution of waste cotton textile where the core solution comprises white cotton, and the shell comprises dyed cotton in a single, solid colour (Fig. 1). These fibres are characterized here for morphology, colour properties, and mechanical properties and compared to a standard RCF spun from waste cotton.

**Experimental section**

**Materials**

The waste cotton was in the form of pre-consumer off-cuts of ‘Prima Homespun 100% cotton fabric’. All fabrics were shredded to 0.2 mm in a cutting mill (Pulverisette 19, Fritsch) and pre-treated before dissolution. The 100% cotton fabrics were single, solid...
colours in white, blue, and red and no information on the dye history of the fabric is known. The ionic liquid (1-butyl-3-methylimidazolium acetate) was purchased from Iolitec and the dimethyl sulfoxide (DMSO) was purchased from Merck. Both were used as received. The sulphuric acid was laboratory grade, 98% purity, and was diluted with deionised water to the suitable concentration before use.

Cotton pre-treatment

The pre-treatment of cotton aims to lower the degree of polymerisation (DP) of the cellulose to a value that is suited to dissolution and wet spinning. This was achieved using hydrolysis in sulphuric acid aqueous solutions. The concentration of sulphuric acid varied from 0.5 to 4 wt% depending on the required final DP. The temperature and duration of the pre-treatment also varied from 70–90 °C and 0.5–1 h, respectively. The cotton concentration in solution was 1 wt% and the solutions were stirred at 250 RPM using a magnetic stirrer. The solution was filtered, and the pre-treated cotton was washed in deionized water until a neutral pH was measured. After pre-treatment the cotton was dried, and the DP was determined. To quantify the DP, intrinsic viscosity of the cellulose was determined by dissolving the samples in bis(ethylenediamine)copper(II) hydroxide solution (CED) and measuring the outflow time of the solution using a glass, capillary-type viscometer. The DP could then be calculated from intrinsic viscosity. The method complied with the standard ASTM D1795–13.

Cellulose dissolution

Cotton was dissolved in 80/20 (w/w) dimethyl sulfoxide (DMSO)/ionic liquid (IL) at a cotton concentration of 6 wt%. DMSO was first added to the cotton and stirred manually to swell the cellulose. Next IL was added and stirred manually for 2 min. The solution was then mixed and deaerated in a conditioning mixer (Thinky Mixer) for 30 min, reaching temperatures around 70 °C. Cellulose solutions were left overnight before use.

Wet spinning

The fibres were wet spun using a wet spinning line (Dissol Large Wet Spinning Line, Korea). The polymer solutions were pumped into the spinneret using gear pumps. The spinneret used was a pre-built co-axial needle (Ramé-hart instrument co., USA). The inner needle of the spinneret had an inner diameter of 0.406 mm and an outer diameter of 0.711 mm. The outer needle had an inner diameter of 0.84 mm and an outer diameter of 1.24 mm. Engineering drawings for the spinneret can be found at the supplier’s website. The polymer solutions were extruded from the spinneret into a water coagulation bath at room temperature, after which they travelled through a water wash bath at 60 °C before being wound up on metal rollers. After washing in warm water for 30 min, the fibres were transferred onto cardboard bobbins for drying and storage. As controls single-component regenerated cellulose fibres were also produced using the same method and were extruded through a 18G blunt needle (inner diameter – 0.84 mm, outer diameter

Table 1  Sample labels, descriptions, and characterization technique used for all samples reported

| Sample           | Description                                                                 | Characterisation                                      |
|------------------|-----------------------------------------------------------------------------|-------------------------------------------------------|
| RCF low DP       | Single component RCF made from cellulose with DP of 274                      | Colour strength, mechanical properties, morphology    |
| RCF high DP      | Single component RCF made from cellulose with DP of 644                      | Mechanical properties, morphology                      |
| bRCF1–bRCF5      | Dyed blue cotton solution in shell, white cotton solution in core. Various shell extrusion rates | Colour strength, morphology                           |
| bRCF(S) and bRCF(C) | Dyed blue cotton solution in shell, white cotton solution in core. Fibres had high shell extrusion rate [bRCF(S)] or high core extrusion rate [bRCF(C)] | Mechanical properties                                 |
| bRCF(O1) and bRCF(O2) | White cotton solution in shell, dyed red cotton solution in core. Fibres had slow core extrusion rate [bRCF(O1)] or fast core extrusion rate [bRCF(O2)] | Optical microscopy                                     |
- 1.27 mm). Table 1 details the labels and descriptions of samples reported in this work.

Characterisation

**Scanning electron microscopy (SEM)**

The cross-sectional morphology was imaged using a Jeol Neoscope Scanning Electron Microscope (SEM). To ensure a neat fracture the fibres were submerged in water which was then treated with liquid nitrogen to encase the fibres in ice. The ice containing the fibres was fractured by hand. Once dry, the fibres were loaded onto the exterior of aluminium stubs using carbon tape and coated with 3 nm of gold and palladium (Au/Pd). The SEM was operated under high vacuum at an accelerating voltage of 5 kV.

**Spectrophotometry for colour strength**

The colour strength of the bicomponent fibres and the single component regenerated cellulose fibres were measured using a Datacolor 600 spectrophotometer with a light source D65. The fibres were cut into 10 mm lengths and aligned using tape. At least three layers of aligned fibres were stacked in layers until no light could penetrate the samples. The colour strength (K/S) at the wavelength of maximum absorbance was measured. For each sample, at least five regions were selected for the measurement to obtain a mean value. The colour strength (K/S) was automatically calculated from the reflectance % (R) measured by the instrument using Eq. 1 below. The mean value for each sample was reported as well as the standard deviation.

\[
K/S = \frac{(1 - R)^2}{2R}
\]  

where R is the reflectance % as a decimal, K is the absorbance and S is the scattering (Kopacz 2012).

**Mechanical tests**

The force–displacement data for the fibres were measured using a universal load frame (Instron, USA). A 50 N load cell was used with a gauge length of 20 mm, a strain rate of 5 mm/minute, and a pretension of 1.1 cN. The force and displacement data for 8 fibres from each sample were collected and assessed. Due to the irregular shape of some fibres the diameter could not be measured using traditional methods such as digital calliper. To measure the cross-sectional area open-source image processing software (Web Plot Digitizer, Ankit Rohatgi) was used to analyse the SEM images. Using the scale bar as a reference, cross-sectional areas were calculated from 3 to 5 images for each sample and these areas were used in the analysis of mechanical data. The properties reported were the maximum stress, the maximum elongation, and the elastic modulus measured between 0.5 and 0.6% elongation.

**Optical microscopy**

A Nikon 80i Eclipse polarized light microscope was used to capture images of the bicomponent fibres. A magnification of 10× was used. The fibres were positioned on a glass slide where software was used to capture images. For these images, the core–shell fibres were prepared with a coloured core and clear/transparent shell, which was the inverse core–shell composition compared to the main fibres studied here. The extrusion speeds for these fibres were varied to achieve a minimal core diameter (slow core extrusion speed) for sample bRCF(O1) and a moderate core diameter similar to those seen in the coloured shell fibres (high core extrusion speed) for sample bRCF(O2). This technique allowed for the demonstration of the discrete components in the fibre using the differences in colour. This was not possible for the coloured shell fibres here as the colour contained in the shell impeded light passing through to the core component.

**Results and discussion**

**Colour strength**

Spectrophotometry measurements were taken for the bicomponent regenerated cellulose fibres (bRCF) whereby the blue waste fabric was utilized in the shell component. The shell-to-core mass ratio (m_{shell}/m_{core}) was varied by increasing the shell extrusion speed whilst the core extrusion speed remained constant. The ratio between shell and core was varied.
from approximately 0.46 for a shell extrusion speed of 0.5 m/min to 0.98 for an extrusion speed of 1.5 m/min. The mass of each component in the fibres was calculated using the mass of each cellulose solution used, the mass of losses, and the mass of each fibre set. It was assumed that the mass of shell material in each fibre set increased linearly with extrusion speed. This assumption is based on the steady, incompressible flow behaviour of the cellulose solution at constant temperature. The equation for volumetric flow rate for steady incompressible flows (Eq. 2), shows that the volumetric flow is equal to the product of the cross-sectional area and the flow velocity. If flow velocity is increased and the cross-sectional area is unchanged, the volumetric flow rate will increase.

\[
\dot{\nu} = VA
\]

(2)

where \(\dot{\nu}\) is the volumetric flow rate \((m^3/s)\), \(V\) is the flow velocity \((m/s)\) and \(A\) is the cross-sectional area \((m^2)\) (Çengel and Boles 2011).

The mass of the shell component, and thus the thickness of the shell component, plotted with the fibre colour strength is displayed in Fig. 2. For these fibres, the colour strength increased approximately linearly with shell mass from a colour strength of 13.56 ± 1.44 at 31.67% shell mass to a colour strength of 23.05 ± 1.39 at 49.61% shell. For reference a single component fibre (RCF) produced from the shell polymer solution was included as 100% shell mass.

![Fig. 2 Colour strength versus shell mass percentage for bicomponent cellulose fibres (bRCF) where the shell was blue dyed cellulose, and the core was white cellulose. For comparison, a single component fibre (RCF) produced from the shell polymer solution was included as 100% shell mass](image)

Table 2 Shell extrusion speed, shell-to-core ratio, and colour strength data for the five variations of bicomponent cellulose fibres

| Fibre | Shell extrusion speed (m/min) | \(m_{\text{shell}}/m_{\text{core}}\) ratio | Colour strength (K/S) |
|-------|-----------------------------|---------------------------------|-------------------|
| bRCF1 | 0.5                         | 0.463                           | 13.56 ± 1.44      |
| bRCF2 | 0.7                         | 0.560                           | 16.23 ± 1.84      |
| bRCF3 | 0.9                         | 0.736                           | 18.18 ± 0.75      |
| bRCF4 | 1.2                         | 0.920                           | 20.13 ± 2.72      |
| bRCF5 | 1.5                         | 0.984                           | 23.05 ± 1.39      |

entirely from coloured cellulose material. It has previously been shown by our team and others that regenerated cellulose fibres from waste textiles can be produced and the colour of the original waste textile is retained to almost the same intensity as the original waste garment (Liu et al. 2019; Ma et al. 2019a, b; Nasr-Nasrabadi et al. 2020; Haslinger et al. 2019). These studies have also shown that recycled regenerated cellulose fibres were able to achieve wash and rubbing fastness similar or even superior to that of the
original waste fabric, possibly because the fibre contains coloured material throughout the entire cross-section (Nasri-Nasrabadi et al. 2020; Haslinger et al. 2019). In this current approach less coloured waste is required. As an example, previously the production of 1 kg of coloured RCF would require 1 kg of dyed waste cotton in a theoretical system with no losses (Ma et al. 2019b). Using the bicomponent spinning technique described here, only 0.496 kg of dyed waste cotton is required to produce 1 kg of coloured bRCF whilst achieving the same colour intensity when compared to a traditional single component RCF. The wash and rubbing fastness of the fibres produced here were not tested, however as the studies above show, coloured material being present deep into the cross-section of the recycled fibre likely helps to maintain colour fastness. The dye history of the fabric used here was unknown, however it was assumed to be a reactive dye due to this being the most common form of dye for cotton textiles (Wakelyn et al. 2006). Haslinger et al. have investigated colour retention on RCFs in a similar recycling process for various vat and reactive dyes and found that while the dyes containing anthraquinone units performed best in terms of retaining the colour properties, most dye types resulted in recycled fibres with vibrant colours (Haslinger et al. 2019).

Mechanical properties

Fibers were produced with a low DP (DP ~ 274) cellulose in the shell component and a high DP (DP ~ 644) in the core component. Using a low DP (~ 274) cellulose for the shell component helped to reduce the viscosity of the cellulose solution which resulted in more controllable increases of the shell extrusion speed. To ensure there were no adverse effects on the mechanical performance of the bRCF caused by the differing DP of the cellulose, tensile tests were conducted. Low DP cellulose is representative of the post-consumer waste cotton material available to be recycled, with the DP of cotton decreasing throughout its use phase due to sun damage, abrasion and laundering (Haslinger et al. 2019). To compare bicomponent cellulose fibres with a large amount of core material to fibres with a large amount of shell material two fibre types were tested. The bRCF with more shell material were termed ‘bRCF(S)’ and had a shell extrusion rate 1.9× faster than the core extrusion rate, whilst the bRCF with more core material were termed ‘bRCF(C)’ and had a core extrusion rate 1.9× faster than the shell extrusion rate. Single component fibres were also extruded for the high and low DP (DP values 644 and 274 respectively) cellulose solutions for comparison. Figure 3a shows the stress-elongation data for the low DP single component, high DP single component, bRCF(S), and bRCF(C), whilst Fig. 3b

![Figure 3](image-url) Stress-elongation curves for low DP RCF, high DP RCF, bRCF(S) with faster shell extrusion speed, and bRCF(C) with faster core extrusion speed (a) for entire data range and (b) for the elastic range

| Sample | Degree of Polymerization (DP) | Maximum stress (MPa) | Elongation at break (%) | Young’s Modulus (GPa) |
|--------|-------------------------------|----------------------|-------------------------|-----------------------|
| Low DP | 274                           | 117.4 ± 3.7          | 17.8 ± 1.4              | 6.08 ± 0.27           |
| High DP| 644                           | 109.3 ± 2.6          | 13.5 ± 1.5              | 5.78 ± 0.26           |
| bRCF(S)| 644/274 (C/S)*                | 115.0 ± 4.5          | 15.2 ± 1.3              | 6.88 ± 0.26           |
| bRCF(C)| 644/274 (C/S)*                | 116.1 ± 2.8          | 17.5 ± 1.5              | 6.59 ± 0.16           |

*C/S: Core/shell
shows the elastic region for the same fibres. Table 3 includes the mechanical properties of the fibres displayed as average (mean) ± standard deviation of the sample.

It is generally accepted that as the degree of polymerization (DP) of the cellulose source used in regenerated cellulose fibres increases, so too does the strength of the fibre, until an optimal DP is reached (Sixta et al. 2015; De Silva and Byrne 2017; Kim and Jang 2013; Ma et al. 2019a). Some literature reports increases in elongation for increased DP (Kim and Jang 2013), whilst others report decreases in elongation as DP increases (Ma et al. 2020). These disparities arise from the drawing of fibres (Ma et al. 2020) and other wet spinning parameters. Drawing the fibre significantly reduces the fibres’ ability to elongate further (Kim and Jang 2013). For the single component fibres spun here the low DP sample showed higher maximum stress and higher elongation compared to the high DP fibre. This was likely a result of the lack of draw applied to the fibres, and the relatively large length and diameter of the spinneret hole. Regardless, the bicomponent fibres showed promising properties. The elongation of the bicomponent fibres was between the elongation seen for the high and low DP single component fibres, with the bRCF(C) having almost the same elongation at break as the low DP fibres. The maximum stress of both bicomponent fibre samples was only slightly less than the maximum stress achieved by the low DP fibre, with the bRCF(C) having higher max. stress than the bRCF(S). The elastic part of the curve displayed in Fig. 3b demonstrates the higher stiffness of both bicomponent fibres compared to the single component fibres, displayed by the steeper gradient of the linear part of the curve. The bRCF(S) appeared to show a similar shaped curve to the low DP fibres whilst the bRCF(C) showed a similar shape to the high DP fibres. This agrees with the fact that the bRCF(S) had a higher shell extrusion rate and thus an expected higher amount of low DP material. The same can be said for the bRCF(C) and high DP fibres. It was expected that the bRCF(S) fibres would also show higher elongation than the bRCF(C) fibres however this was not the case. This may have been due to the extruded volume of each polymer being impacted by the different viscosities, or it may be due to the load-sharing behaviour of bicomponent fibres. A previous study showed that in core–shell fibres, the stress was concentrated on an individual component of the fibre during different stages of loading (Shi et al. 2006). This load-sharing behaviour may also explain the increase in stiffness of these fibres. As the mechanical properties of the bicomponent fibres here are similar to those of the single component fibres, we have demonstrated that utilizing a dyed low DP cellulose shell and white high DP cellulose core fibre for dye-saving applications will not have significant negative effects on the mechanical performance of regenerated cellulose fibres.

Morphology and core–shell structure

Figure 4 contains SEM images showing the surface and cross-section morphology of the bRCF1 fibres with no draw and a draw ratio of 1.25. During spinning, the fibres showed distinct core–shell structure where the translucent blue shell encapsulated the transparent core. Upon complete coagulation and drying, the fibres exhibited a solid colour, with no core–shell structure observed from the fibre surface. As seen below, the SEM images of the fibres also showed no distinct cross-sectional core–shell morphology, demonstrated by the lack of a visible interface between the two components. This was expected since both components are the same polymer and colour differences are not observable in SEM images. A study by Tang et al. on all-silicone core–shell fibres with a functional filler in the core displayed similar SEM results regarding the lack of an observable interface between the two components made from
the same polymer (Tang et al. 2018). To confirm that mixing had not occurred between the core and shell components in the bicomponent fibres optical micrographs were used, and the configuration of the fibres was changed to use coloured waste as the core. These fibres were spun manually varying the extrusion speed for both the shell and core. Figure 5a shows an example where the core extrusion speed is significantly slower than the shell, the colour was retained exclusively in the core component showing that the core and shell components remain discrete along the fibre axis. Figure 5b is more representative of a fibre whereby the shell to core ratio is 1:1, again the shell and core components remain discrete along the fibre’s axis.

The morphology of both the undrawn and drawn fibres was homogenous along the cross-section and showed a dense structure free from micro-voids. This rough morphology is typical of regenerated cellulose fibres made using ionic liquid as the solvent and using cryofracture as the fracturing technique (Lee et al. 2019; Chen et al. 2015; Li et al. 2014) and is similar to the morphology of the single component cellulose fibres displayed in Fig. 6. The undrawn bRCF in Fig. 4 had a circular shaped cross-section and smooth surface however drawing of the fibre caused striations to occur on the fibre surface similar to those seen in fibres produced via the viscose process (Chen 2015). Regenerated cellulose fibres made via wet spinning ionic liquid-DMSO cosolvent systems are expected to exhibit this cross-sectional structure, with the striations becoming more pronounced as draw ratio (DR) increases (Ma et al. 2020). The striations are caused by a pressure difference between the water coagulation bath and the core of the fibre. As the fibre is drawn at higher speeds the pressure difference is increased, causing the exterior of the fibre to collapse (Ma et al. 2020). Interestingly, here the cross-section of the drawn fibre is very serrated whilst only having a low draw ratio (DR=1.25). It is probable that the design of the lab-scale bicomponent coaxial needle used here played a major role in causing the
During extrusion and immediately before coagulation, the core and shell cellulose solutions are separated by the wall of the spinnerets inner needle. With no draw applied, less pressure is applied on the exterior of the fibre, and it does not rush to fill this void as quickly. As draw is applied, the pressure on the fibre surface from the coagulation bath increases, and the fibres exterior collapses to fill the void. The pronounced striations seen here were therefore likely due to a combination of draw and the void left between the core and shell components by the thickness of the coaxial spinnerets inner needle.

**Conclusions**

We have demonstrated the production of bicomponent cellulose fibres in a core–shell configuration with coloured waste cotton used only in the shell component and white waste cotton used in the core. The bicomponent fibres were produced with similar tensile properties to traditional regenerated cellulose fibres requiring approximately 50% less coloured material to achieve the same colour strength. The mechanical properties of the bicomponent fibres were analysed for different extrusion speeds of the core and shell components and these were compared to single component cellulose fibres made from high and low DP cellulose. The maximum stress and elongation of the bicomponent fibres were between those of the single component fibres, whilst the stiffness of the bicomponent fibres was higher. The morphology revealed no core–shell structure in the fibre cross-section. This was due to the chemical similarities of the two components and indicates excellent interfacial adhesion. The drawn fibres showed a highly striated cross-sectional shape thought to result from the pressure caused by applying draw and the void left between the core and shell upon extrusion. A discrete core and shell structure was observed in the optical micrographs of coloured core bicomponent fibres, showing no adverse mixing between the components. The article demonstrates the first all-regenerated cellulose bicomponent fibre. Here, the discrete components of the fibre allow for high colour strength and prove that functionalisation of one component can be achieved without a negative impact on morphology and mechanical properties.
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Declarations

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