
Supplementary information

Large-scale fabrication of structurally coloured cellulose nanocrystal films and effect pigments

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Large-scale fabrication of structurally coloured cellulose nanocrystal films and effect pigments

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Table of contents

S1 – General consideration on the sustainability of CNC microparticles vs. commercial alternatives ...	2
S2 – Optimisation of the surface properties of the web and wetting for R2R processing.....	3
S3 – Additional optical analysis and modelling	4
S4 – Suspension properties – Phase diagram	7
S5 – Composite CNC films	7
S6 – Effect of drying at elevated temperature.....	8
S7 – Peeling and grinding of R2R-cast CNC films.....	11
S8 – Optical properties of photonic CNC microparticles.....	12
S9 – Heat treatment of R2R-cast CNC films	13
S10 – Swelling properties of the produced CNC microparticles	15
S11 – Angular response of the CNC microparticles.....	16
S12 – Method-related additional information.....	18

S1 – General consideration on the sustainability of CNC microparticles vs. commercial alternatives

Most polymer-based glitters available on the market today are obtained using web-casting as part of a roll-to-roll process¹. These particles, often larger than 100 µm, are rarely collected after use and therefore, accumulate as land waste and marine litter along with other microplastics².

While biodegradable alternatives have been developed to meet current biodegradability standards, by replacing the bulk synthetic polymer matrix by degradable alternatives, so called “bioglitter” may still contain a fraction that remains non-biodegradable that can still trigger a detrimental response once released in the environment³.

Additionally, many inorganic effect pigments are prepared from mica¹, a non-renewable resource primarily extracted in developing countries that often lack the legal structure to prevent child labour⁴. Finally, even products that do not contain mica may still contain titanium dioxide, which has recently been listed as a potential carcinogen in France, casting doubt onto other widely used nano-minerals^{5–7}.

The composition of example products that our photonic CNC particles could substitute are given below with values taken from Technical Data Sheets, when available.

Plastic glitter – e.g. Glitterex Poly*Flake range ($\varnothing > 50$ or 100 µm):

Polyethylene terephthalate	[95.4 – 97.0] %
Aluminium	0.1 %
Polyurethane	[2.5 – 3.2] %
Dyes	[0 – 1.4] %

Partially biodegradable glitter – e.g. Colorlord Bio-glitter® Sparkle / Pure ranges ($\varnothing > 100$ or 150 µm):

Modified regenerated cellulose	ca. 71 %
Glycerin	ca. 11 %
Aqua	ca. 6 %
Urea	ca. 3 %
Styrene/acrylate copolymer or Shellac	ca. 4 %
Dyes (such as Tartrazine, Blue 1 lake and/or Pigment Red 57:1), Inorganic minerals and Metals (such as Titania, Mica, Tin oxide, Iron oxide, Silica, Ferric ammonium ferrocyanide and/or Aluminium powder)	ca. < 5 %

Mineral effect pigment – e.g. BASF Timica® range ($\varnothing > 10$ µm):

Mica	[48 – 59] %
Titania	[41 – 52] %

Borosilicate effect pigment – e.g. Merck Xirona® range ($\varnothing > 20$ µm):

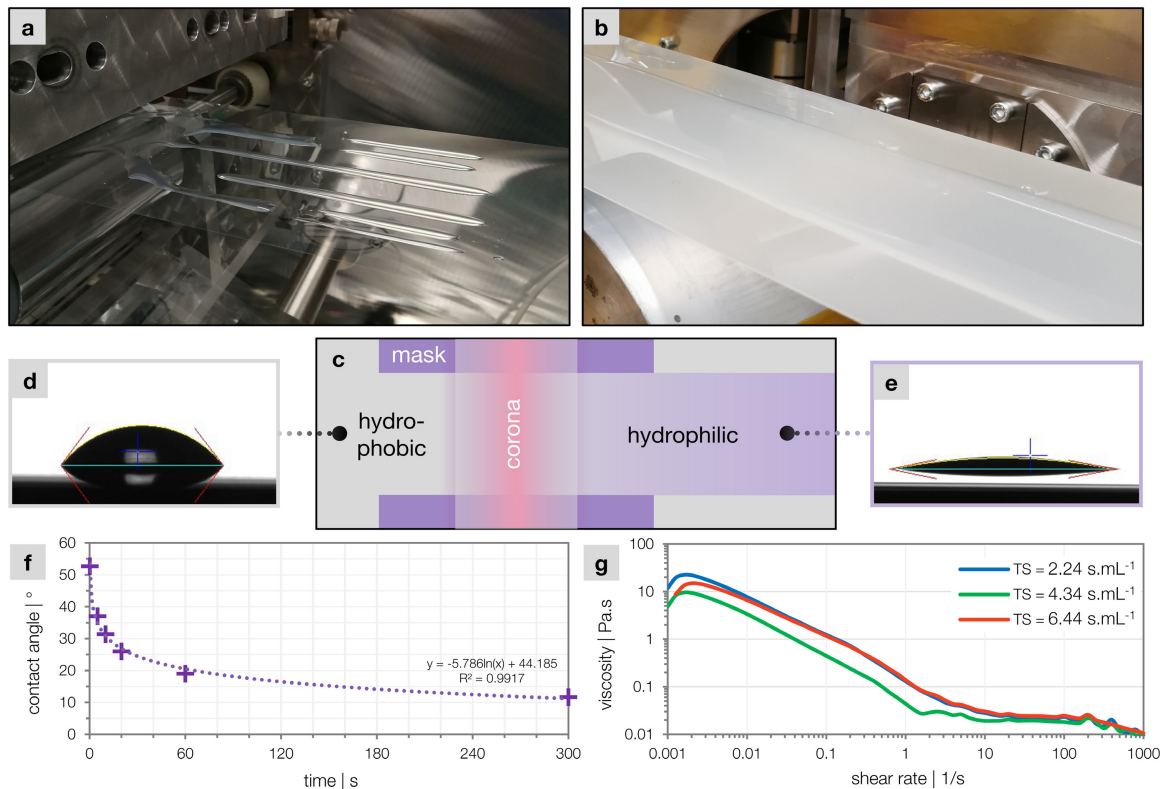
Calcium aluminium borosilicate	[52 – 72] %
Silica	[15 – 23] %
Titania	[13 – 23] %
Tin oxide	<2 %

In our system the produced photonic CNC microparticles are formed from cellulose nanocrystals, *i.e.*, the composition is almost purely cellulose and as such we do not expect their degradation to differ impactfully from natural raw cellulose fibres. Furthermore, it has been reported that cellulose nanocrystals are more biodegradable than microcrystalline cellulose, which is the standard used for testing biodegradability against for ISO 14851 Fresh Water Biodegradation⁸. More information on Life Cycle Assessment (LCA) for nanocelluloses is reported by Li *et al.*⁹

S2 – Optimisation of the surface properties of the web and wetting for R2R processing

Corona discharge is applied to the central part of the hydrophobic polyethylene terephthalate (PET) web, in order to increase its surface energy and facilitate the deposition and wetting of the low-viscosity aqueous CNC suspension. **Supplementary Fig. 1** shows the effect of corona discharge surface activation and the viscosity of the CNC suspension used in the experiment.

Supplementary Video 1 and **Supplementary Video 2** show how unwanted flow of the CNC suspension can be prevented by using a thicker web that inhibits stress-induced web warping.



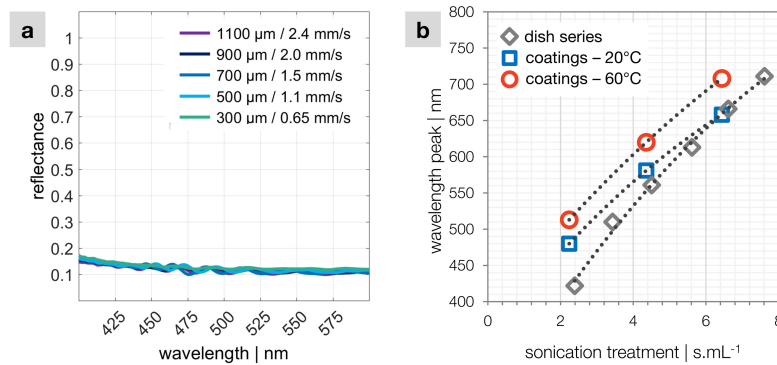
Supplementary Fig. 1 – Optimization of the surface properties of the web. **a**, Deposition of CNC suspension at the head of the web through the slot-die of the R2R machine on a pristine 125 μm thick PET web, showing immediate dewetting. **b**, Deposition of CNC suspension on a corona-etched 500 μm -thick PET web, showing good wetting. **c**, Schematic (top view) of the corona etching process showing the masking of the edges of the web with tape (deep purple) for selective corona treatment (pink), resulting in the hydrophilic property of the central part of the web (light purple). **d**, Sessile drop of water on PET before etching and **e**, after a 5 min treatment. **f**, Contact angle of a sessile water drop on the PET substrate with increasing plasma-etching time (dotted line showing best fit). **g**, Sweep rheological measurements of the CNC suspension used to produce the red, green and blue films shown in Fig. 3.

S3 – Additional optical analysis and modelling

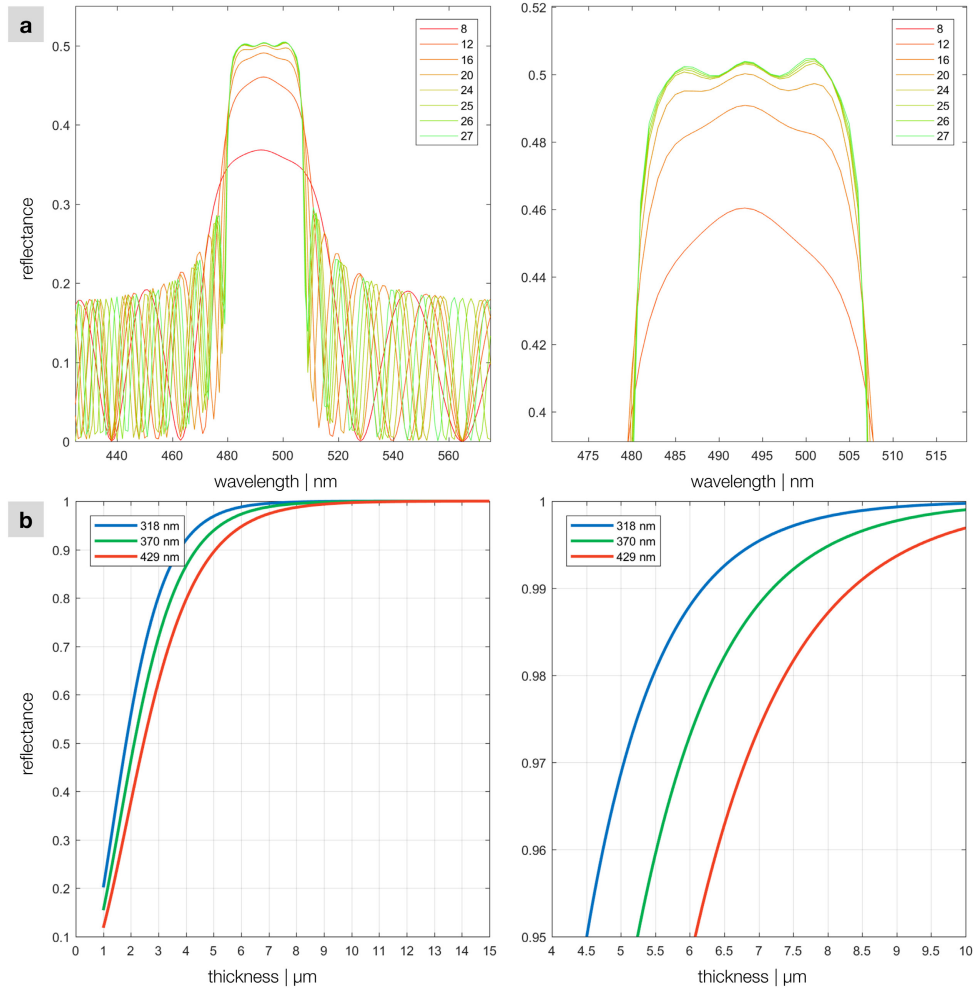
All CNC films reflect primarily in the left-circular polarisation (LCP) channel. In right-circular polarisation (RCP), only thin film interference is visible, see **Supplementary Fig. 2a**.

Sonication and evaporation under different thermal treatments result in a peak shift of the reflected wavelength, see **Supplementary Fig. 2b** and a widening of the peak along with a decrease of the peak maximum reflectivity as shown in **Fig. 3a–b**.

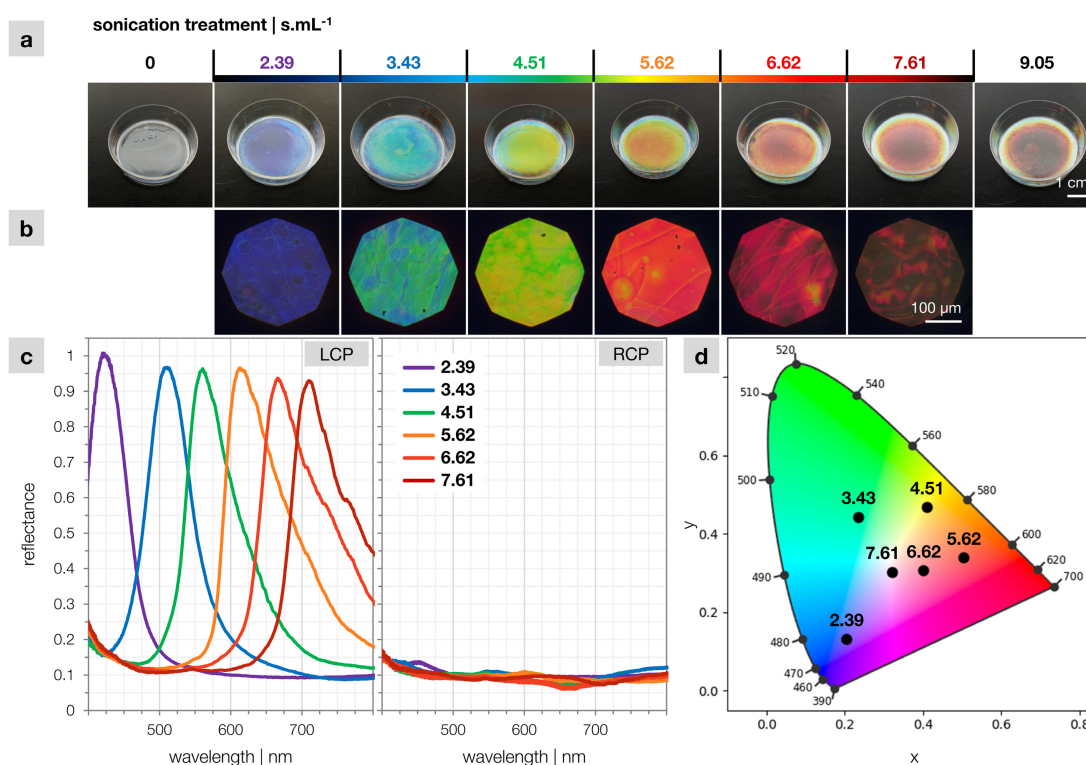
These behaviours are consistent with previous studies on similar systems^{10,11} and are both the result of increasing pitch p with longer sonication treatment as **Supplementary Fig. 3** shows: a larger pitch leads to an increase of the band gap $\Delta\lambda$ as $\Delta\lambda = p\Delta n$, whereby Δn is the birefringence (taken as the difference of refractive index locally defined parallel and perpendicular to the average direction of the CNC long axis) and therefore to the widening of the reflectance peak; whereas the decrease of the peak reflectivity for the more sonicated sample can be explained by the decrease of the number N of repetitive units (p) diffracting light for a given thickness D ($N = D/p$)¹². For a larger pitch (corresponding to longer reflected wavelengths) N decreases and a thicker film is needed to reach the maximum reflectance from the cholesteric structure.



Supplementary Fig. 2 – Supplementary optical data. **a**, RCP reflectance spectra of the blade-cast CNC films reported in Fig. 2 of the manuscript. Each spectrum is an average taken over 10+ locations. **b**, Sonication time vs. the peak wavelength extracted from the plots in Fig. 3 and compared to those in Supplementary Fig. 4. Dotted lines are a guide for the eye.

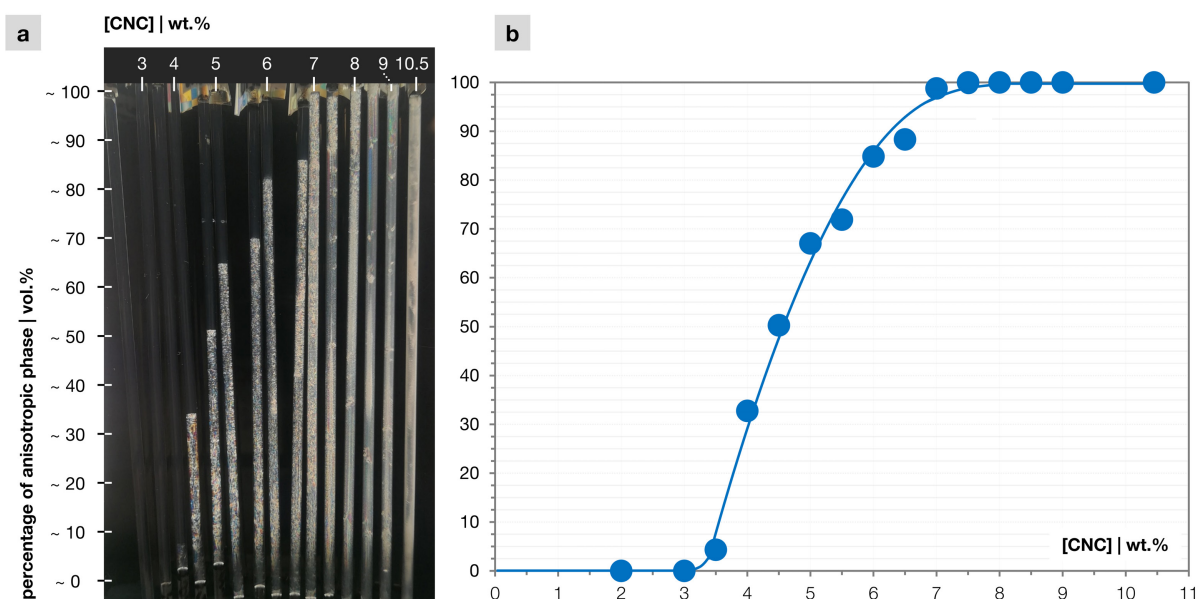


Supplementary Fig. 3 – Computed reflectance vs. film thickness, assuming refractive indices $n_o = 1.514$ and $n_e = 1.590$. **a**, Calculated spectra of a cholesteric structure of incremental thickness expressed as multiple N of the pitch p (taking pitch $p = 318$ nm) using a numerical model (Berreman 4x4 matrix method¹³). The plot on the right is an expansion of the reflected peak, showing saturation beyond $N = 24$, corresponding to a film thickness $Np = 7.6$ μm . **b**, Predicted maximal reflectance peak from three cholesteric structures made of a pitch $p = 318$, 370 and 429 nm (corresponding to the peak wavelength of the blue, green, and red films displayed in Fig 3. of the manuscript) vs. film thickness, using an analytical model (de Vries formula). Reflectance $> 99.5\%$ is reached for film thicknesses greater than 6.9, 8.1 and 9.3 μm for $p = 318$, 370 and 429 nm, respectively.



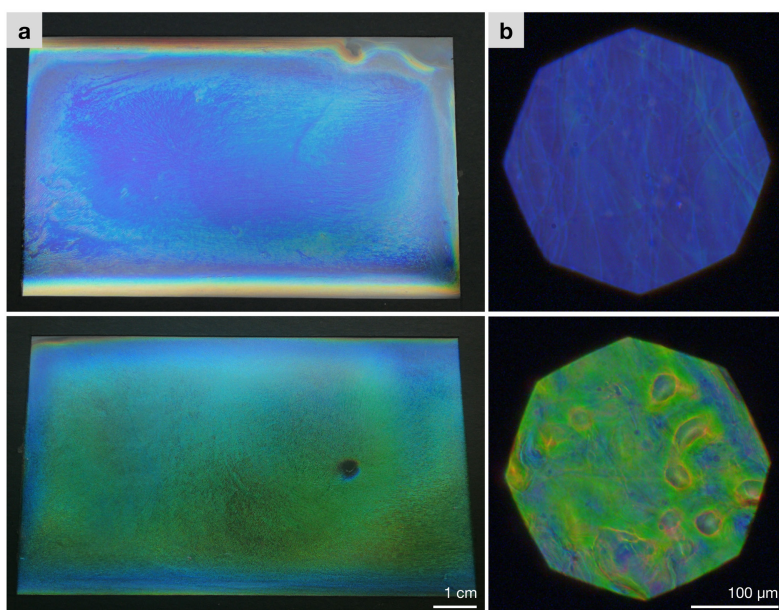
Supplementary Fig. 4 – Effect of tip sonication on the visual appearance of CNC films prepared from a 6 wt.% biphasic suspension. **a**, Macroscopic photographs of the CNC films, **b**, corresponding micrographs through a left-circularly polarised (LCP) filter, **c**, corresponding reflection spectra through LCP (left) and RCP (right) filters averaged over 10+ locations and **d**, corresponding CIE 1931 colour space chromaticity diagram calculated from the Python ‘Colour v0.3.16’ package¹⁴. The CIE [x ; y] coordinates are (from blue to red): [0.20 ; 0.13], [0.32 ; 0.30], [0.40 ; 0.31], [0.50 ; 0.34], [0.42 ; 0.47] and [0.23 ; 0.44]. The CNC suspension was diluted with ultrapure water to 6 wt.% in a 50 mL tube (Corning Falcon with conical bottom). A starting volume of 40 mL was sonicated in an ice bath and aliquots successively pipetted out. Drop-cast cellulose nanocrystal films were obtained by casting 1.0 g of the CNC suspension into polystyrene Petri dishes (Corning, diameter = 3.5 mm).

S4 – Suspension properties – Phase diagram



Supplementary Fig. 5 – Phase diagram of the CNC suspension prior to tip sonication. *a*, Photograph of glass capillaries filled with CNC suspension of increasing concentration and viewed between crossed polarisers. *b*, Volumetric ratio of anisotropic phase vs. CNC concentration extracted from (a).

S5 – Composite CNC films



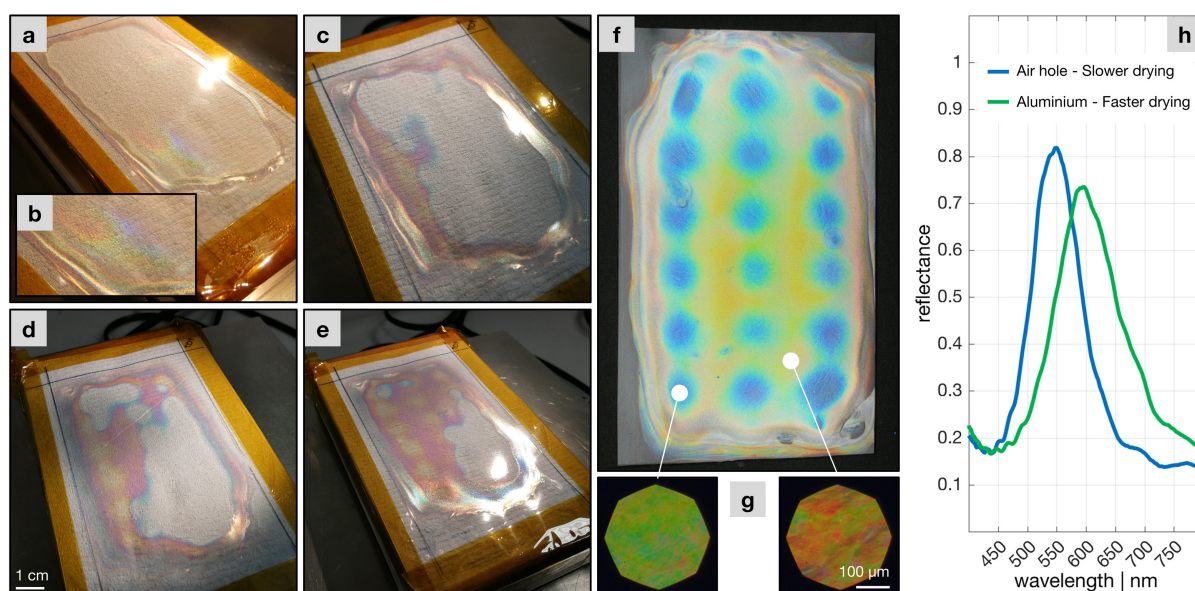
Supplementary Fig. 6 – Impact of adding a polysaccharide (hydroxypropyl cellulose) to 6 wt.% blade-cast CNC suspension. *a*, Photograph of two blade-cast CNC films prepared using $g_c = 900 \mu\text{m}$ and $v_c = 1.5 \text{ mm.s}^{-1}$. The sample at the top corresponds to the CNC film shown in Fig. 2 (sonicated for 2.24 s.mL^{-1}) while the sample at the bottom was prepared from the same suspension to which hydroxypropyl

cellulose was added prior to casting (40 wt.% with respect to the dry CNC mass). **b**, Microscope images of the central part of the films shown in (a).

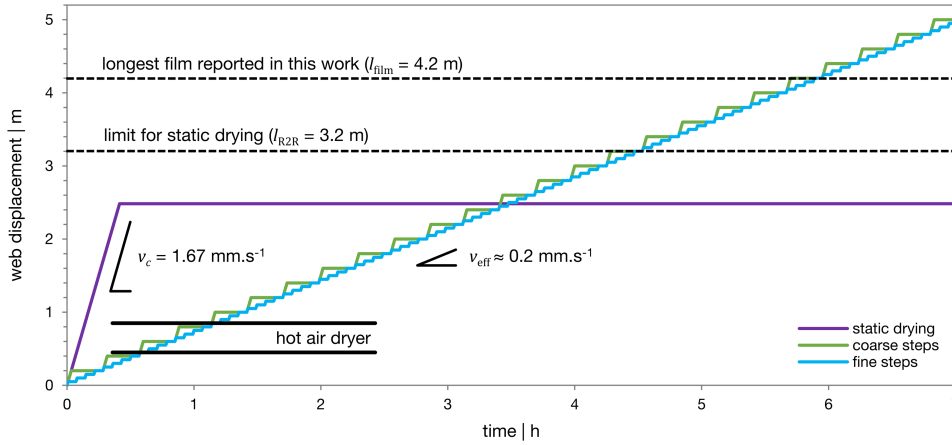
S6 – Effect of drying at elevated temperature

Reducing the time available for self-assembly time affects the optical properties of the obtained film. This effect is apparent, as shown in the example of **Supplementary Fig. 7**, when a CNC suspension is evaporated over a perforated aluminium board placed over a 60 °C hot plate.

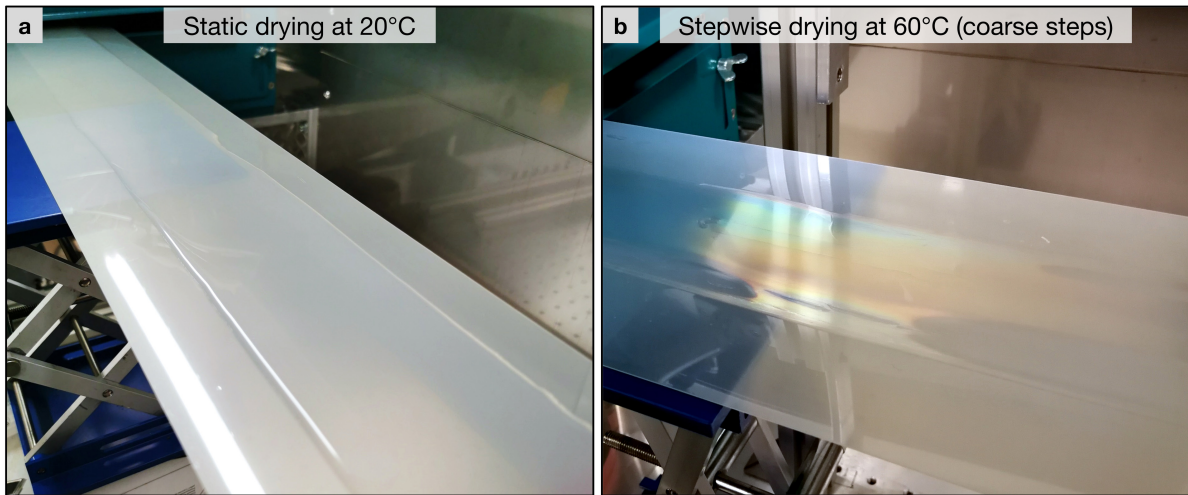
Supplementary Fig. 8 shows the web displacement vs. time for each deposition method used for R2R deposition. **Supplementary Fig. 9, 10 and 11** show typical effects of drying at elevated temperature with hot air dryer on the R2R machine.



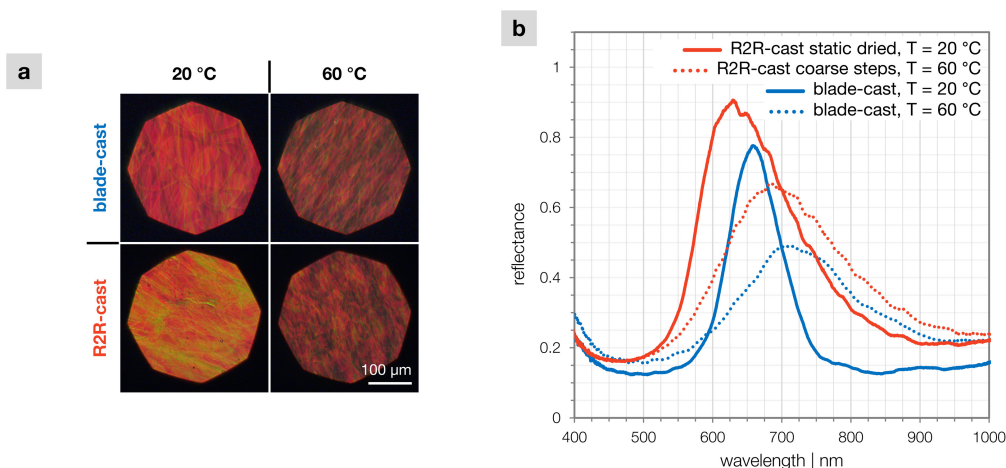
Supplementary Fig. 7 – CNC film dried over a perforated hot plate. a–e, Photographs of a blade-cast CNC suspension ($g_c = 700 \mu\text{m}$ and $v_c = 1.5 \text{ mm.s}^{-1}$), taken during drying over a perforated aluminium board placed on top of a hot plate at 60°C. The temperature gradient between the aluminium board and the circular holes created a drying rate gradient across the suspension. **b**, Close-up view of (a), where iridescent, self-organised domains are clearly visible in the still wet CNC film. **f**, The resulting patterned CNC film and **g**, LCP micrographs of the two areas dried at different rates. **h**, Corresponding LCP reflectance spectra of the two areas, with each spectrum averaged over 3+ locations.



Supplementary Fig. 8 – Plot of the web displacement vs. time for each deposition method used for R2R deposition. For static drying, considering the limit of the web pathway of the specific pilot-scale R2R machine used in this study, the web was typically translated by 2.5 m during coating in a single step ($v_c = 1.67 \text{ mm.s}^{-1}$), prior to drying without motion over several hours. For step-wise experiments, the translation of the web was divided into multiple steps interrupted by stationary rest periods. For both coarse (green line) and fine steps (blue line) the effective translation speed was $v_{\text{eff}} \approx 0.2 \text{ mm.s}^{-1}$, approximating to a continuous deposition process. The inclusion of an in-line hot air dryer allowed for the evaporation of the CNC suspension to be accelerated, such that the film could be dry before reaching the end of the web pathway ($l_{\text{R2R}} = 3.2 \text{ m}$), allowing for this limitation to be overcome.



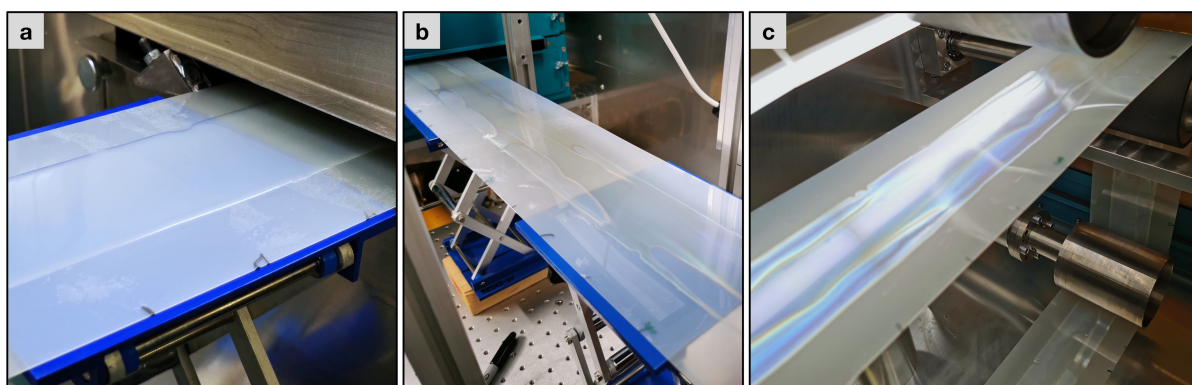
Supplementary Fig. 9 – Drying of CNC films on the R2R web. Expanded view **a**, of the photograph shown in Fig. 1d and **b**, of the photograph shown in Fig. 1e. Photographs were taken at similar location along the R2R pathway. For reference, the width of the web is 14 cm.



Supplementary Fig. 10 – Effect of the deposition method and drying conditions on the visual appearance of red CNC films. *a*, LCP optical micrographs of films prepared from CNC suspensions sonicated for 6.44 s.mL^{-1} and dried either at $20 \text{ }^{\circ}\text{C}$ (left) or $60 \text{ }^{\circ}\text{C}$ (right). The top row shows blade-cast films ($g_c = 700 \text{ } \mu\text{m}$, $v_c = 1.5 \text{ mm.s}^{-1}$) while the bottom row shows R2R-cast films (static at $T = 20 \text{ }^{\circ}\text{C}$, coarse steps at $T = 60 \text{ }^{\circ}\text{C}$). *b*, Corresponding LCP reflectance spectra, averaged over 15+ locations.

Deposition	Blade-cast static dried	R2R-cast static dried	R2R-cast coarse steps
Thickness (μm)	10.7 ± 1.2	45.6 ± 4.1	25.1 ± 3.2

Supplementary Table 1 – Thickness measurements of the different films presented in Supplementary Fig. 10.



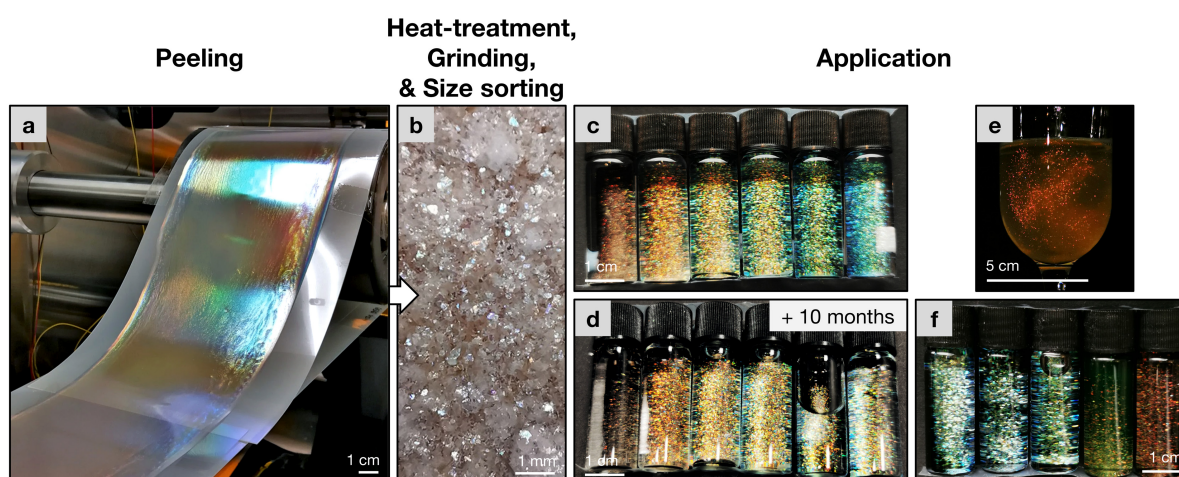
Supplementary Fig. 11 – Photographs taken at three key locations along the web pathway showing continuous drying for coarse stepwise deposition. *a*, Photograph of the still wet suspension before it enters the oven. *b*, Photograph of the partially dried suspension as it exists the hot air dryer ($T = 60 \text{ }^{\circ}\text{C}$). *c*, Photograph showing complete drying of the CNC film (with directed illumination added above the CNC film to better decipher the film colour) before it reaches the rewinding roll and showing the dry CNC film bending over several rolls prior to web rewinding. For reference, the width of the web is 14 cm.

R2R deposition	Static dried	Fine steps with hot air dryer		
Drying temperature	20 °C	20 °C	40 °C	60 °C
Drying time (h)	> 9	9	6.5	3.25
Thickness (μm)	4.6 ± 2.1	13.1 ± 2.8	13.1 ± 1.4	12.5 ± 3.1

Supplementary Table 2 – Drying time and thickness of the films for the different deposition methods and drying conditions presented in Fig. 4.

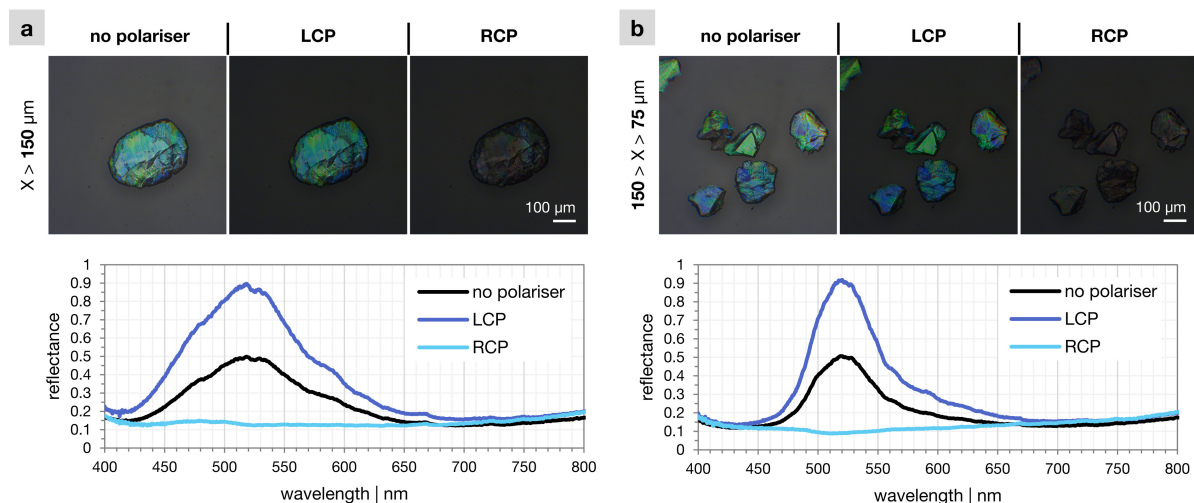
S7 – Peeling and grinding of R2R-cast CNC films

Once dry, the CNC film can be processed further, as shown in **Supplementary Fig. 12a–b**. Note that peeling can be more problematic once additives are included in the formulation, as they can increase adhesion to the substrate (see **Supplementary Fig. 6**).

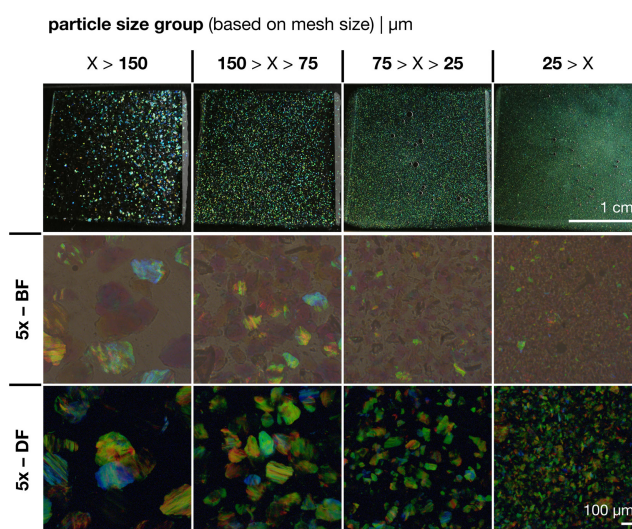


Supplementary Fig. 12 – From R2R-cast CNC film to photonic microparticles. **a**, In-line detachment of the dried CNC film from the PET web using a plastic blade (125 μm-thick). The CNC film was carried by the moving web (as it was still attached on one side) while detaching without breaking and gliding over another motionless web for collection. **b**, Photonic microparticles obtained from grinding a heat treated R2R-cast CNC film. **c**, Photonic CNC microparticles (size group: 150 > X > 75 μm) immersed in water/ethanol mixtures of various mass ratios (from left to right: 1:0, 95:5, 85:15, 70:30, 1:1, 0:1). **d**, The same samples as in (c) photographed ten months later (did not evolve further over additional six months). **e**, Example application of photonic CNC microparticles as a visual enhancer in a sparkling beverage. **f**, Photonic CNC microparticles dispersed in a wide range of solvents of various polarity and ionic strength, from left to right: diethyl ether, hexane, sunflower oil, water/soap (Premiere Products, Savona D2, 6:1 wt. ratio), 1 mM NaCl aqueous solution.

S8 – Optical properties of photonic CNC microparticles



Supplementary Fig. 13 – Optical properties of heat-treated CNC microparticles. *a*, Microscopic pictures of a typical photonic particle and corresponding spectra under different polarisation configurations. *b*, Microscopic picture of a photonic CNC particle with a flat interface (at the centre of the image) where the measurement was collected. This particle may have broken away from one of the two interfaces of the CNC film (CNC film/air or CNC film/substrate). These microscopic images and the corresponding reflection spectra were collected either without a polariser, through a LCP filter and through a RCP filter. For LCP and RCP, the reference was also collected through the corresponding polarisation filter.



Supplementary Fig. 14 – Macroscopic visual appearance of photonic CNC microparticles embedded in a transparent epoxy resin. Photographs (top row) under diffuse illumination show that the larger particles give a pixelated appearance to the coating while the smaller particles give a much more uniform effect. Observing under the microscope with a 5x objective (Zeiss, EC Epiplan Neofluar, $NA = 0.13$) in brightfield and darkfield modes (BF and DF, second and third rows respectively), it appears that the larger particles tend to remain aligned along the glass substrate while the smaller particles are more randomly oriented. The loading of photonic CNC particles was approximately 10 wt.% (i.e., 15 mg

in 150 mg of Norland Optical Adhesive 81), giving a coverage of approximately 3.1 mg/cm². The mixture was applied on a glass slide and covered with a cover slip.

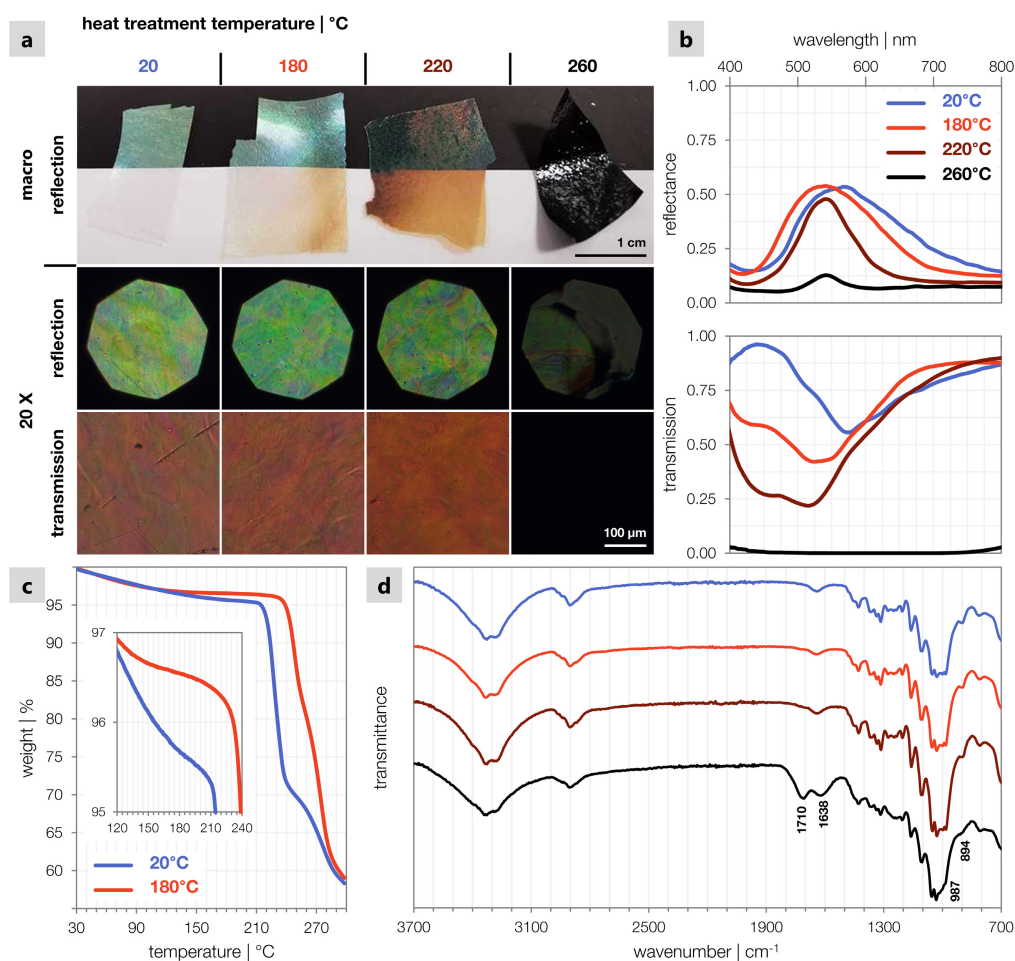
S9 – Heat treatment of R2R-cast CNC films

From **Supplementary Fig. 15a–b**, it can be observed that the spectra of the film made from pH-neutralised CNCs treated for 30 min at 180 °C have a similar shape as the pristine film, the reflection peak being only slightly shifted as a result of a shrinkage of the cholesteric domains as water evaporates. While the maximum of the reflection peak is unaffected, the overall transmittance decreases, and the film in transmission has a slight gold tint, improving contrast in reflection. When heat treatment is performed at 220 °C, the blackening of some parts of the film becomes clearly visible, while the intensity of the reflection peak decreases. At 260 °C, the film appears carbonised and the cholesteric structure has been significantly altered.

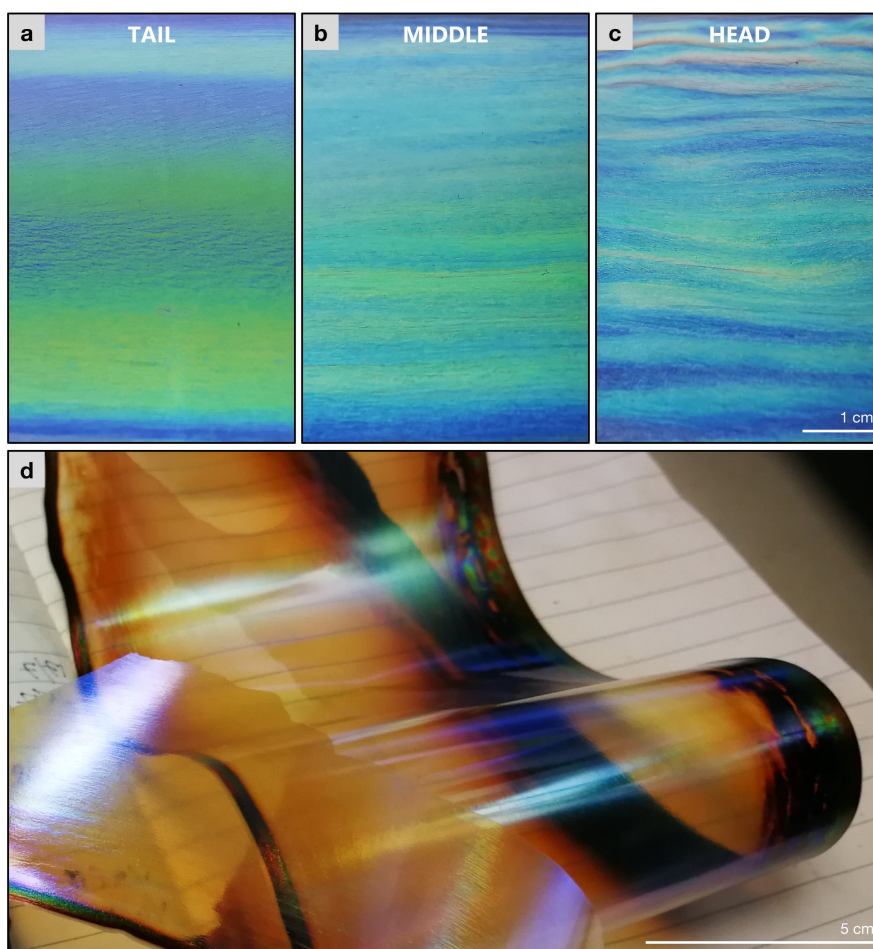
In contrast to films made from pH-neutralized CNCs, where blackening occurs near the degradation point of cellulose (at about 210-220 °C)^{15–18}, acidic CNCs are known to display a strong blackening after a heat exposure to much lower temperatures, associated to a much earlier TGA degradation¹⁷. We ascribe this to the heat-activated auto-catalysed acidic desulfation of the CNCs, whereby the sulfate half-ester groups of the H-CNC surface detach and release sulfuric acidic moieties (following the equilibrium: $\text{CNC-O-SO}_3^- + \text{H}^+ + \text{H}_2\text{O} \rightleftharpoons \text{CNC-OH} + \text{SO}_4^{2-} + 2\text{H}^+$)¹⁹, leading to sulfuric acid-mediated degradation of the cellulose macromolecules²⁰.

FT-IR spectroscopy and TGA data of **Supplementary Fig. 15c–d** also suggest little degradation of the nanocrystals for heat treatment at temperatures below 220 °C. Looking more specifically at the FT-IR spectra, physico-chemical modifications of the nanocrystals appear obvious for films heat-treated at 260 °C for 30 min.

The sample displayed on **Supplementary Fig. 16a–c** was produced on a misaligned web and shows that the accumulation of wet CNC suspension on one end of the web (view C) leads to wavy patterns in the dry state across the width of the film. The material can also accumulate across the width (**Supplementary Fig. 16d**), as a result of the faster drying happening at the pinned edge of the film (folded part on the left) or a small misbalance of the R2R web across the width (folded part on the right). Areas with more deposited CNC suspension tend to show wavy patterns that are likely to blacken strongly and first upon heat treatment.

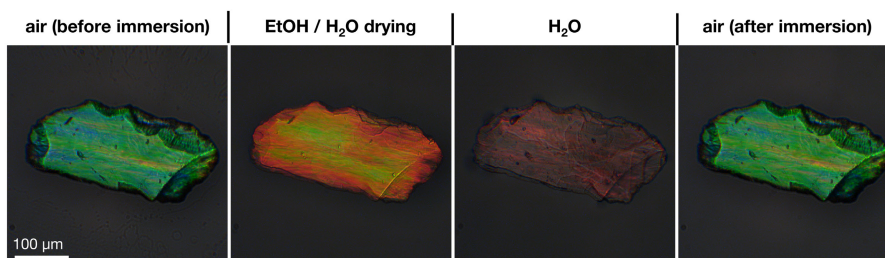


Supplementary Fig. 15 – Optimization of the heat treatment. **a**, Effect of the applied temperature during heat treatment ($t = 30$ min) on the macroscopic and microscopic visual appearance of free-standing sections cut from a R2R-cast film. **b**, Corresponding spectra in reflection and transmission. Measurements were taken using a 20x objective (Nikon T plan SLWD, $NA = 0.3$) with a 200 μm -cored optical fibre (Thorlabs FC-UV200-2-SR), smoothed and averaged over up to 3 locations. In reflection, the reference was collected without a polariser. **c**, Thermogravimetric analysis (TGA) plot of a pristine CNC film and a heat-treated film (180 °C for 30 min) obtained from the same casting. **d**, FT-IR spectra of the CNC samples displayed in (a).



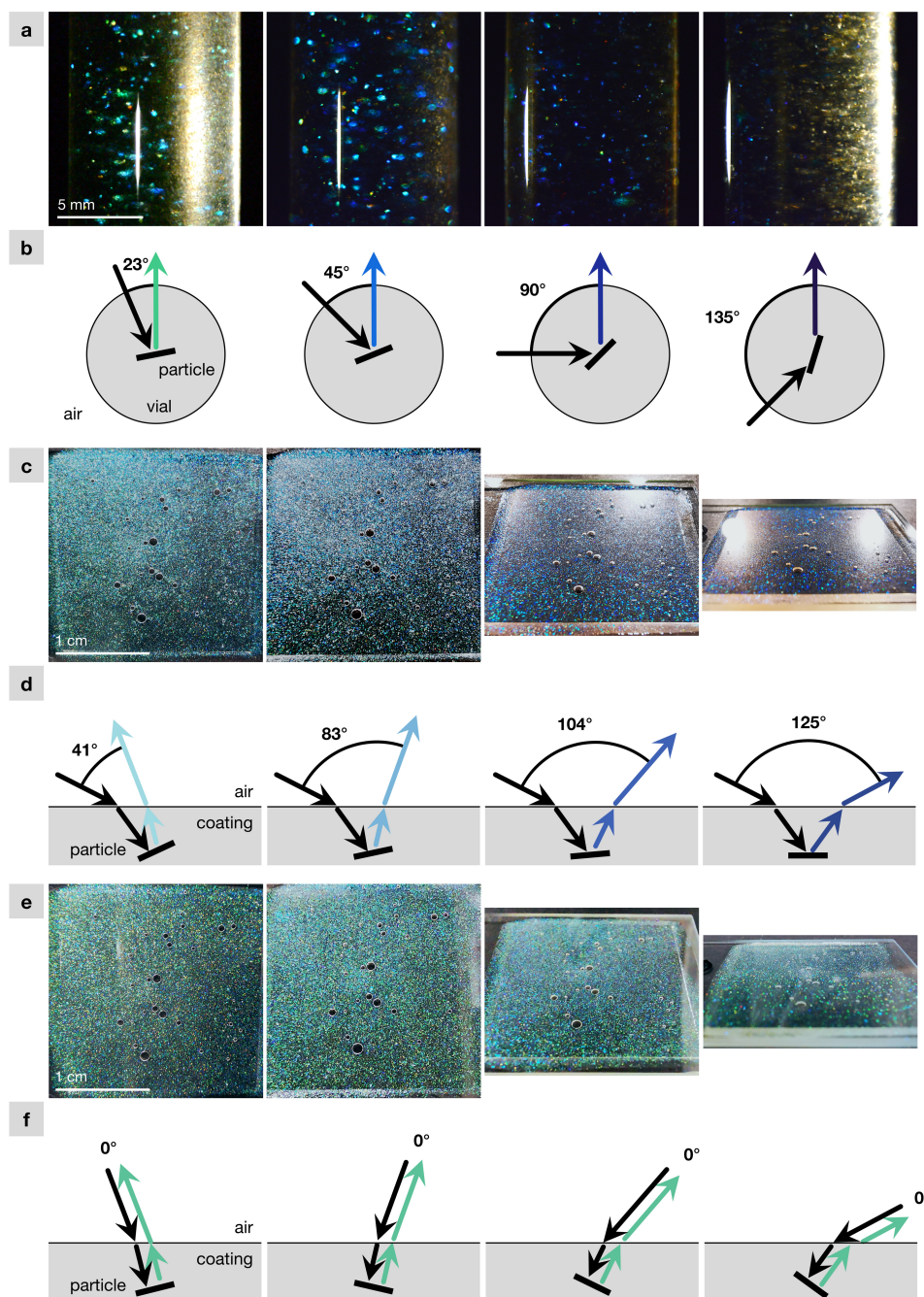
Supplementary Fig. 16 – Effect of flow during drying on the homogeneity of the structural colour of a static dried R2R-cast film. **a–c**, Three different parts of the same R2R-cast film produced on a misaligned web showing the accumulation of material on the head end of the web (c). **d**, A folded piece of a R2R-cast CNC film after heat treatment, showing the blackened edges.

S10 – Swelling properties of the produced CNC microparticles



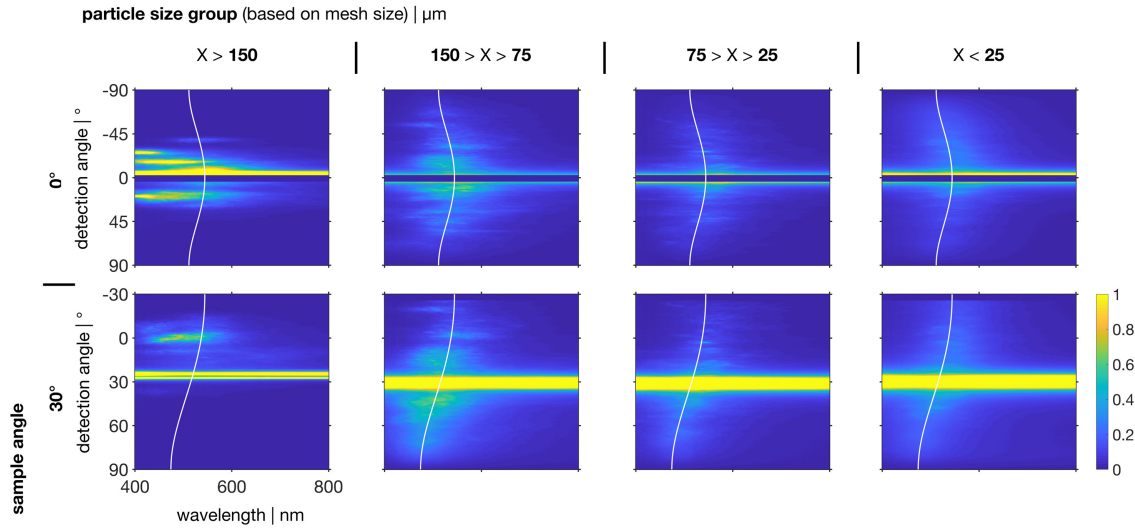
Supplementary Fig. 17 – Reversible colour change upon swelling a photonic CNC microparticle. Microscope snapshots (extracted from **Supplementary Video 5**) of a single photonic CNC particle placed in a mixture of water and ethanol. From left to right: initial particle in air, particle in an evaporating mixture of ethanol and water, particle in water (ethanol evaporated and water condensation taking place) and particle back in air (i.e., after complete water evaporation).

S11 – Angular response of the CNC microparticles

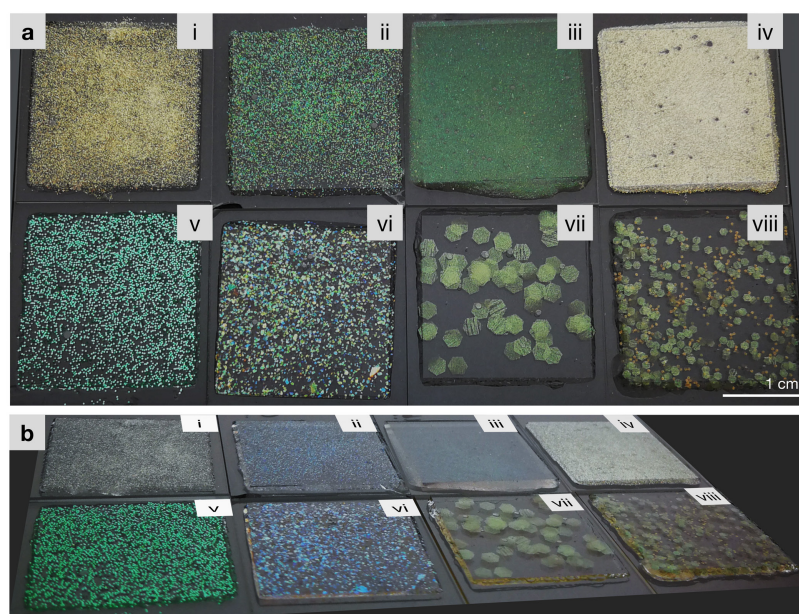


Supplementary Fig. 18 – Iridescence of dispersed photonic CNC microparticles. **a**, Snapshots, taken at increasing illumination angles of green photonic CNC microparticles (size: $150 > X > 75 \mu\text{m}$) dispersed in glycerol (particles prepared from a CNC suspension tip-sonicated for 4.36 s.mL^{-1} , loading of particles in the vial is approximately 5.5 mg/mL). From left to right, the angle of illumination increases and results in a strong apparent blueshift, from green to blue and eventually beyond the visible spectrum. **b**, Schematic of the resulting reflection from samples displayed in (a). The orientation of the contributing particles is depicted in black. **c**, Photonic CNC microparticles (size: $75 > X > 25 \mu\text{m}$, as displayed in **Supplementary Fig. 14**) embedded in transparent epoxy resin covering a glass slide and under directed illumination. From left to right, the angle of illumination increases and results in a reduced apparent

blueshift, from green to deep blue. **d**, Schematic of the resulting reflection from samples displayed in (c), highlighting the key role of Snell's law correction at the air/coating interface to reduce the blueshift. **e**, Same sample as in (c), but under diffuse illumination. **f**, Schematic of the resulting reflection from samples displayed in (e). The combination of diffuse illumination and Snell's law correction at the air/coating interface results in suppression of most of the blueshift, leading to an almost non-iridescent coating.

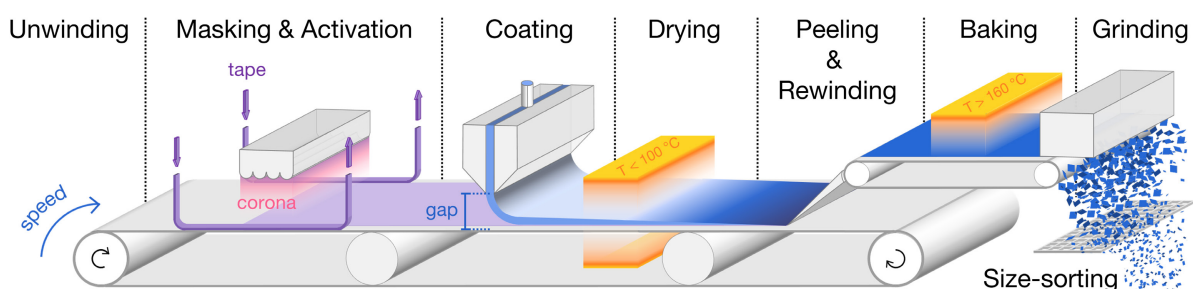


Supplementary Fig. 19 – Scattering measurement of photonic CNC microparticles embedded in a transparent epoxy resin (same samples as in Supplementary Fig. 14). Samples are illuminated at $\theta_{\text{in}} = 0^\circ$ (normal incidence, top row) or at $\theta_{\text{in}} = 30^\circ$ (bottom row). As the size of the particles decrease, the scattered signal becomes smoother and more continuous to the point where it fits the signal of a randomized distribution of diffracting domains of identical pitch (white curves). This scattering signal is less iridescent than the equivalent scattering signal of a typical CNC film²¹.

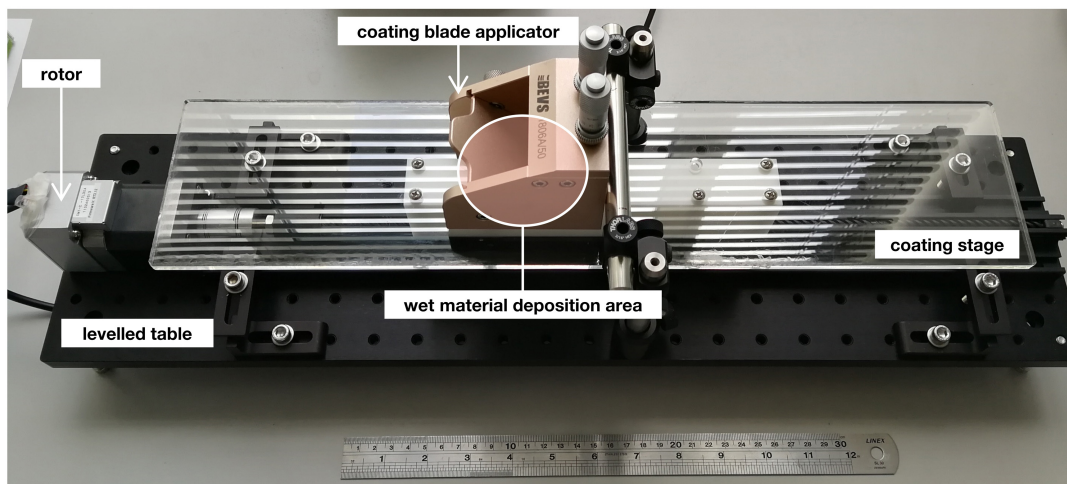


Supplementary Fig. 20 – Benchmarking of photonic CNC microparticles (ii, iii and vi) vs. commercial effect pigments and glitters. **a**, Photograph taken under directed illumination at near normal angle of observation. **b**, Photograph taken under directed illumination at ca. 110° from the light source highlighting the angle-dependant visual response of the photonic CNC microparticles. Sample list: **i**. Merck Xirona® (Moonlight Sparks, size: 20 – 150 μm , 1 wt.%). **ii**. Photonic CNC microparticles (size group: $150 > X > 75 \mu\text{m}$). **iii**. Photonic CNC microparticles (size group: $X < 25 \mu\text{m}$). **iv**. Merck Xirona® (Moonlight Sparks, size: 20 – 150 μm , 10 wt.%). **v**. Bio-glitter® Sparkle (Spring green, size: 8 mil $\approx 200 \mu\text{m}$). **vi**. Photonic CNC microparticles (size group: $X > 150 \mu\text{m}$). **vii**. Bio-glitter® Pure (Sea green, size: 94 mil $\approx 2.4 \text{ mm}$). **viii**. Bio-glitter® Pure (Sea green, size: 40 mil $\approx 1 \text{ mm}$ and Light gold, size: 15 mil $\approx 380 \mu\text{m}$) The loading was approximately 10 wt.% for all samples, except for sample (i) where the loading was reduced to 1 wt.% to avoid excessive scattering that results in a white appearance (as sample (iv) shows).

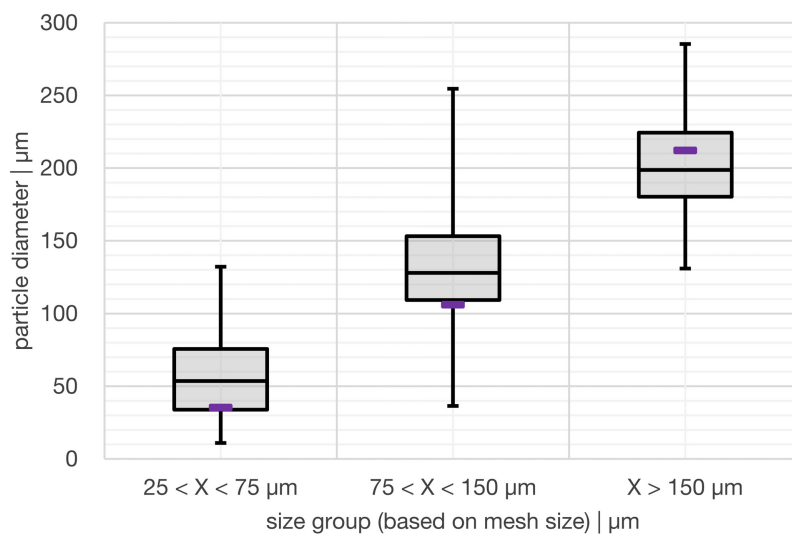
S12 – Method-related additional information



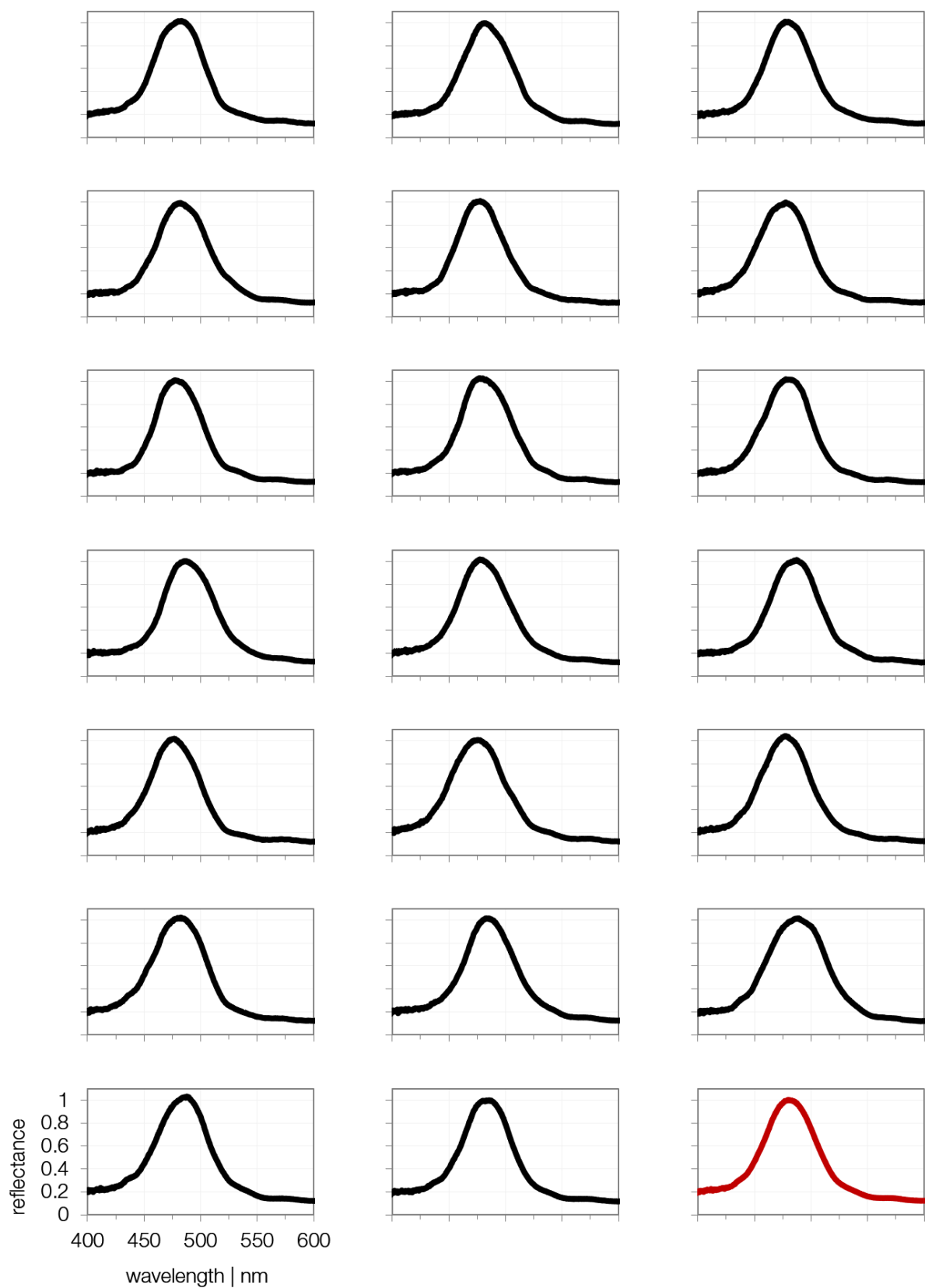
Supplementary Fig. 21 – Schematic of a feasible in-line industrial implementation of the different processing steps required to prepare photonic CNC microparticles. Notably, as the R2R-cast CNC films detach from the web without damaging it or leaving any residue (**Supplementary Video 4**), this also offers the possibility to implement a closed-loop rolling web, where the PET web can be reused.



Supplementary Fig. 22 – Photograph of the set-up used for preparing laboratory scale blade-cast CNC films.



Supplementary Fig. 23 – Box plot of the size distribution of the sequentially size-sorted photonic CNC microparticles vs. the mesh size of the sieves used. The purple line indicates the maximal opening of the mesh considering the diagonal of one square of the mesh grid, below which a round particle of the corresponding diameter should pass through the mesh of the sieve. From these values, a median particle diameter (assuming perfectly circular particles) for each size group can be retrieved and equates to 54, 128 and 199 μm respectively.



Supplementary Fig. 24 – LCP reflectance spectra of the same CNC film recorded at 20 different locations (see Fig. 2, sample C: $v_c = 1.5 \text{ mm.s}^{-1}$ and $g_c = 700 \text{ }\mu\text{m}$) with contribution from the PET substrate, and its average response (bottom right, in red).

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