‘Supporting information

Mechanochemical Modification of Cellulose Nanocrystals by Tosylation and Nucleophilic Substitution

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Abstract:
Cellulose nanomaterials are derived from the most abundant biopolymer on earth, and are gaining importance in the shift from oil-based materials to sustainable alternatives. To facilitate this, sustainable methods to modify these renewable nanostructured materials must be explored, as surface modifications are prerequisite for many nanocellulose applications. Here, we present a solvent-free method for the surface modification of cellulose nanocrystals, encompassing mechanochemistry to convert uncharged or charged CNCs to tosylated CNCs, and for the subsequent versatile nucleophilic substitution with amines and esters. Systematic screening of the reaction parameters revealed key variables – milling time, base type and amount, for tosylation to take place during 60 minutes of ball-milling without major changes to CNC morphology and crystallinity. Both step-wise and one-step *in-situ* nucleophilic substitution of the tosyl CNCs was successful with amine and ester modification. Our results demonstrate how fine-tuning the parameters of solvent-free methods can lead to fast and environmentally benign reactions on cellulose nanomaterials while retaining their structure on the nanoscale.

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1 Materials and Equipment

All chemicals but the cellulosic starting materials were bought from commercial suppliers and used without further purification: *p*-toluenesulfonyl chloride (Sigma-Aldrich), pyridine (Sigma-Aldrich), potassium carbonate – anhydrous (Sigma-Aldrich), N,N-Diisopropylethylamine (Sigma-Aldrich), 1,8-diazabicyclo(5.4.0)undec-7-ene (Sigma-Aldrich), *N*-methyl-2-pyridone (Sigma-Aldrich), Triethylamine (Sigma-Aldrich), dodecylamine (Sigma-Aldrich), aniline (Sigma-Aldrich), 3-phenylpropionic acid (TCI chemicals), Whatman 1 filter paper (Cat No. 1001 125, 125 mm diameter), Cytiva nylon membrane filters 0.2µm Diameter 47mm, ethanol (ETAX Aa and B – ALTIA Oyj),, Deionized H_2O, DMSO (Sigma-Aldrich), $[P_{4444}][OAc]$/DMSO-d_6 (Innotope),uranyl formate (EMS), formvar carbon-coated copper grids (FCF400-CU, Electron Microscopy Sciences).

The ball milling was carried out in a Retsch MM400 mill with a frequency of 30 Hz in a stainless-steel jar (14 mL) with a single stainless-steel ball (4.0 g) from InSolido Technologies. All solid compounds were weighed on the Satorius Entris 224i-1S analytical scale. The liquids used for the reaction were pipetted via Eppendorf Research Plus pipettes (1-10 µl; 10-100 µl; 100-1000 µl). The aging experiments were performed either in the Memmert™ Natural Convection Standard Incubator, 53 L (55 °C) or Binder FED-53 – 100 °C).

The crude product was dissolved in $[P_{4444}][OAc]$ DMSO-d_6 and analysed using diffusion edited ^{1}H NMR spectroscopy. The devices used for performing NMR measurements were Bruker NMR Spectrometer AV III. The chemical shifts are given in ppm and the solvent signal can be found at 2.50 ppm (d_6-DMSO) and 2.50–0.75 ppm $[P_{4444}][OAc]$. The elemental analyser used for the characterization was FlashSmart EA CHNS/O from Thermo Scientific. The ATR-IR analysis was done with Perkin Elmer Spectrum Two Polymer QA/QC Analysis. The powder X-ray diffraction analysis was carried out with a Panalytical X'Pert MDP X-ray diffractometer, in the 2Θ range from 4° to 40°, using Cu-Kα (λ = 1.54 Å) radiation. TEM imaging was then carried out by using a FEI Tecnai 12 instrument at 120 kV acceleration. Molecular mass distribution of cellulose was determined on a Dionex UltiMate 3000 HPLC System using pullulan standards. Thermal analysis was performed on a Netzsch STA 449 F3 Jupiter system.

1.1 Synthesis of CNCs by HCl-gas hydrolysis

Whatman 1 filter papers with 95% dry matter were subjected to HCl gas (1 bar) acid hydrolysis for 24 hours, adhering to the methodology and utilizing the custom-built reactor described by Pääkkönen et al[1]. After the acid hydrolysis reaction, the product was transferred to a Büchner filtration setup, which was equipped with a cloth filter of 10 µm pore size. The hydrolysed cellulose was then washed twice, each time using 2 litres of distilled water and left to dry in the fume hood.

The degree of polymerization (DP) of the hydrolysed cellulose was assessed by measuring the limiting viscosity of cellulose dissolved in a cupri-ethylenediamine (CED) solution, following the ISO 5351:2004 standard. The obtained limiting viscosity (η) was then converted into the viscosity-average degree of polymerization (DPv) using the Mark-Houwink equation, $\eta=Q'\times DP_v\alpha$. Since DP < 950 in this case, then the constants Q' and α were set to 2.28 and 0.76, respectively.[2] DP_V of the hydrolysed cellulose is 230.4, which shows that the levelling off degree of polymerization was reached. This, together with the very high crystallinity (Figure 3) of the remaining cellulose, indicate that CNCs were obtained. As no specific steps of CNC individualization (sonication or fluidization) were carried out, the CNCs remain arranged in the fiber matrix, which restricts the size and shape analysis of the CNCs. Previously Kontturi, et al. showed by dispersing the CNCs obtained by HCl gas hydrolysis in formic acid,[3] that the obtained CNCs have similar dimensions (width 7-8 nm and length 200-300 nm) to CNCs obtained from conventional liquid/solid system.[4]

1.2 Synthesis of Sulf-CNCs

The CNCs were prepared by hydrolysis in 64-wt % sulfuric as described previously.[5,6] For a typical procedure, 15 g of teared into small pieces Whatman 1 filter paper were put in a 1-L three-neck flask. After addition of 272.3 mL 64-wt % sulfuric acid, hydrolysis was carried out in a water bath pre-heated to 45 °C using vertical stirring for 45 minutes. The hydrolysis was quenched by pouring the slurry into 3 L deionized water CNCs were then isolated and purified by centrifugation and dialysis against Milli-Q water (membrane: SpectraPor® 7, MWCO 6 kDa) to a conductivity of < 5mS, respectively. After the first dialysis cycle, the CNC dispersion was filtered through a Whatman 541 ashless filter paper (Whatman GmbH, Dassel, Germany) for removing larger aggregates and non- hydrolyzed residues. Then, the pH of the suspension was adjusted to ~7.25 with 0.01 M NaOH solution ensuring a complete counter ion exchange from $–OSO_3H$ to $–OSO_3Na$,[7] followed by repeated dialysis against Milli-Q water for 7 days and freeze-drying. In the end, the freeze-dried CNCs were purified by ethanol-Soxhlet extraction for 48 hours.[8]

1.3 Solution-state NMR

Solution-state NMR experiments were performed according to a procedure initially reported for cellulose nanocrystals (CNCs).[9,10] The used $[P_{4444}][OAc]$/DMSO-d_6 (w/w = 1:4) solvent was prepared according to the literature. All spectra were recorded on a Bruker NMR AV III 400 spectrometer at an acquisition temperature of 65 °C. For standard sample preparation, 50 mg of the freeze-dried cellulosic material was weighed into a 4 mL screw cap glass vial, before $[P_{4444}][OAc]$/DMSO-d_6 (w/w = 1:4) was added up to a final weight of 1.0 g, resulting in a

concentration of 5 wt%. The sealed mixture was stirred with a small magnetic stirring bar and heated to 65°C by means of an oil bath for 16 to 20 h. Thereafter, the homogenous samples were transferred into standard 4 mm NMR tubes.

1.4 Infrared spectroscopy

FTIR spectra were obtained on a Frontier FTIR spectrophotometer from PerkinElmer operating in the attenuated total reflection (ATR) mode. The diamine cellulose samples were dried under reduced pressure before analysis. The parameters for all measurements included 4 cm^{-1} resolution, the 4000–650 cm^{-1} spectral range, and accumulation of 32 scans per sample.

1.5 Thermal properties

The thermal behaviour of HCl-CNC (starting material), **1** 60 min (tosylated CNC), and **2** (dodecylamine-modified CNC) was analysed using a Netzsch STA 449 F3 Jupiter system. Each sample was heated with a heating rate of 20 K/min under helium atmosphere from 40 to 900ºC. The data was evaluated via NETZSCH Proteus Thermal Analysis 8.0 software and the graphs have been produced via OriginPro 2024.

1.6 Elemental Analysis

EA was performed by combustion EA on a Thermo Flash Smart CHNSO elemental analyser. For sample preparation, 1–3 mg of the material was accurately weighed into tin foil cups. Cellulosic samples were thoroughly freeze-dried before measurement. The device was calibrated by a linear calibration using sulphanilamide as the standard. All measurements were carried out at least in triplicate and averaged. C, H, N, and S were directly analysed, and degree of substitution (DS) calculations were based on the sulphur and nitrogen values.

$$DS_{Tosyl} = \frac{(M_{AGU} \cdot S\%)}{(M_S \cdot 100\%) - (M_{Tosyl} \cdot S\%)} \quad \text{Eq. 1}$$

$$DS_{Nu} = \frac{(M_{AGU} \cdot N\%)}{(M_N \cdot 100\%) - (M_{Nu} \cdot N\%)} \quad \text{Eq. 2}$$

The DS value is determined by the ratio of modified anhydroglucose units to the unmodified ones (M_{AGU} = 162.1 g mol^{-1}). The calculation of DS involves the sulphur and nitrogen content in percent, and the molar mass used for the calculations are M_S= 32.1 g mol^{-1} and M_N = 14 g mol^{-1} each respectively. The modification of the AGU is either done via tosylation (M_{tosyl} = 155.1 g mol^{-1}) or amination (M_{dodec} = 184.35 g mol^{-1} and $M_{aniline}$ = 92.13 g mol^{-1}).

1.7 Powder X-ray diffraction (PXRD)

The powder X-ray diffraction analysis was carried out with a Panalytical X'Pert MDP X-ray diffractometer, in the 2Θ range from 10° to 40°, using Cu-$K\alpha$ (λ = 1.54 Å) radiation. Crystallinity index (CrI) was calculated according to the empirical Segal peak height method (Eq. 3),[11] by comparing the intensity of the 2 0 0 diffraction peak at 2Θ = 22° (I_(2 0 0)), representing the sum of crystalline and amorphous contributions, with the intensity at the minimum between the 1 1 0 and 2 0 0 peaks at 2Θ = 18° (I_AM) which represents the amorphous-only component. Note, that the CrI based on Segal's peak height method reveals relative changes in crystallinity within the same material type upon different reaction conditions, and should not be taken as an absolute value of crystalline and amorphous fractions in the materials.[12,13]

$$Crystallinity\ index\ (CrI) = 100 \times (I_{200} - I_{AM})/I_{200} \quad \text{Eq. 3}$$

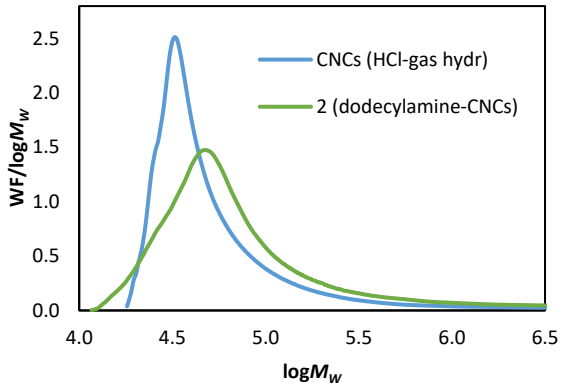
1.8 Transmission electron microscopy (TEM)

Samples were prepared according to the protocol from Meija et al. paper[14] with minor modifications. All main samples (Figure S4) were diluted to a concentration of 0.02 w% in water, vortexed, and sonicated for 20min. The sample was observed using Formvar carbon-coated copper grids (400 mesh, Electron Microscopy Sciences) and were plasma cleaned (20 seconds oxygen plasma flash using a Gatan Solarus) before applying the sample. The grids were dipped in 10 µL of sample solution and left for 4 minutes, after which excess was blotted with filter paper. They were cleaned with MilliQ water by pipetting 10 µL to the grid and bloating it. The same was repeated with uranyl format to negatively stain the samples, but 30 seconds was waited before bloating uranyl acetate. Samples were left to dry overnight at room temperature. TEM imaging was then carried out by using a FEI Tecnai 12 instrument at 120 kV acceleration.

1.9 Gel permeation chromatography (GPC)

The molecular mass distributions of starting material (CNCs from HCl-gas hydrolysis) and the end-product of nucleophilic substitution (**2**) were determined by gel permeation chromatography (GPC). The CNC starting material was prepared for GPC analysis by the water-acetone-*N*,*N*-dimethylacetamide (DMAc) solvent exchange procedure. Namely, 50 mg of the material was mixed on a polyethylene frit with 4 mL of MilliQ water, kept overnight and then dewatered by vacuum filtration and rinsing with 2 mL of acetone. Thereafter 4 mL of acetone was added, and the sample was kept for at least 6 hours, after which the acetone was removed and replaced with 4 mL of DMAc (from Sigma Aldrich, HPLC grade, purity > 99.9%). The sample was kept in DMAc overnight, after which the DMAc was removed, and the sample dissolved in 5 mL of 90 g L^{-1} LiCl/DMAc (LiCl from VWR, purity > 98.5%) at room temperature with slow speed overnight magnetic stirring. The freeze-dried reaction end-product **2** (50 mg) was directly dissolved in 5 mL of 90 g L^{-1} LiCl/DMAc. The resulting 10 mg mL^{-1} samples were diluted in pure DMAc to 1 mg mL^{-1} (9 g $^{-1}$ LiCl/DMAc) and filtered (0.2 µm) before GPC analysis. Dionex UltiMate 3000 HPLC System equipped with an isocratic pump, PLgel MIXED-A 7.5 x 300 mm column, Shodex RI-101 refractive index detector and a Viscotek/Malvern SEC/MALS 20 multi-angle light scattering detector, was used to elute the samples and pullulan standards with 9 g L^{-1} LiCl/DMAc at a flow rate of 0.75 mL min^{-1}, with the injection volume of 100 µL. Detector constants (MALS and DRI) were determined using narrow polystyrene sample (Mw = 96 000 g/mol, $Đ$ = 1.04) dissolved in 0.9% LiCl in DMAc. Broad polystyrene sample (Mw = 248 000 g/mol, $Đ$ = 1.73) was used for checking the detector calibration. The $\partial n/\partial c$ value of 0.136 mL g^{-1} was used for celluloses in 9 g L^{-1} LiCl/DMAc (Potthast et al., 2015). Viscotek OmniSEC software was used to determine the cellulose molar mass distribution, based on the pullulan standards (343 Da – 2500 kDa, Polymer Standard Service GmbH, Mainz, Germany; 1600 kDa from Sigma Aldrich) according to the equation $M_{cellulose} = 12.19 \times \left(M_{pullulan}\right)^{0.78}$, according to Berggren, et al.[5] Each sample was measured twice, giving average DP_n (CNCs, HCl-gas hydr.) = 270 and DP_n (**2** dodecylamine-CNCs) = 280.

The DP_n of the CNCs and modified CNCs are within the measurement error (10-20%) of each other. Graph S1 shows the molecular mass distribution of cellulose in these materials.



*Graph S1. Molecular mass distribution graph of the reaction end-product (**2**) in comparison to the reaction starting material (CNCs).*

2 Experimental details and results

2.1 Interpretation of the degree of substitution based on elemental analysis data

The degree of substitution (DS_{Tos} or DS_{Nu}) of the obtained materials was calculated, after washing and freeze-drying, as bulk DS (Eq. S1 and S2,[15]) from the elemental analysis results. Different models for the crystallites of CNCs have been proposed (ellipsoid, cuboid or rectangular cross-section),[15] to estimate the amount of exposed surface chains in CNCs, yielding also $DS_{surface}$ values,[16] however due to limitations in precise size and shape analysis of the aggregated uncharged CNCs we opted to report the bulk DS value, which is an empirical result independent of shape and size-based assumptions. Based on one of the commonly used models of CNCs with a cross-section of 14 × 7.3 nm, the ratio of cellulose chains accessible on a CNC surface is 0.24.[16] Therefore, bulk DS of 0.24 could be taken to represent full substitution of the surface exposed 6-OH with the tosyl group.

2.2 Interpretation of the solution-state NMR data

The sample preparation was done as described in section 1.3 and the acquisition followed the protocol from Fliri et al.[9,10] The diffusion edited ^{1}H NMR of the dissolved modified cellulose products eliminates resonances from low-molecular-weight compounds present in the NMR sample, such as H_2O, $[P_{4444}][OAc]$, DMSO-d_6, and therefore the observable peaks arise from chemical moieties attached to the polymeric molecules, providing evidence for the covalent modification of the cellulose backbone.

The peaks corresponding to the cellulose backbone appear in the region of 3.0–4.5 ppm (Figure S1). Characteristic peaks of the tosyl group at 7.3–8.0 ppm (aromatic) and at 2.4 ppm (CH_3) within the diffusion band of cellulose. The diffusion edited ^{1}H-NMR shows the covalently linked tosyl on the cellulose backbone (aromatic peaks at 7.75 and 7.38 ppm; CH_3 at 2.4ppm) and an acetate peak (2.02 ppm) arising from the ionic liquid displacing the tosyl groups.

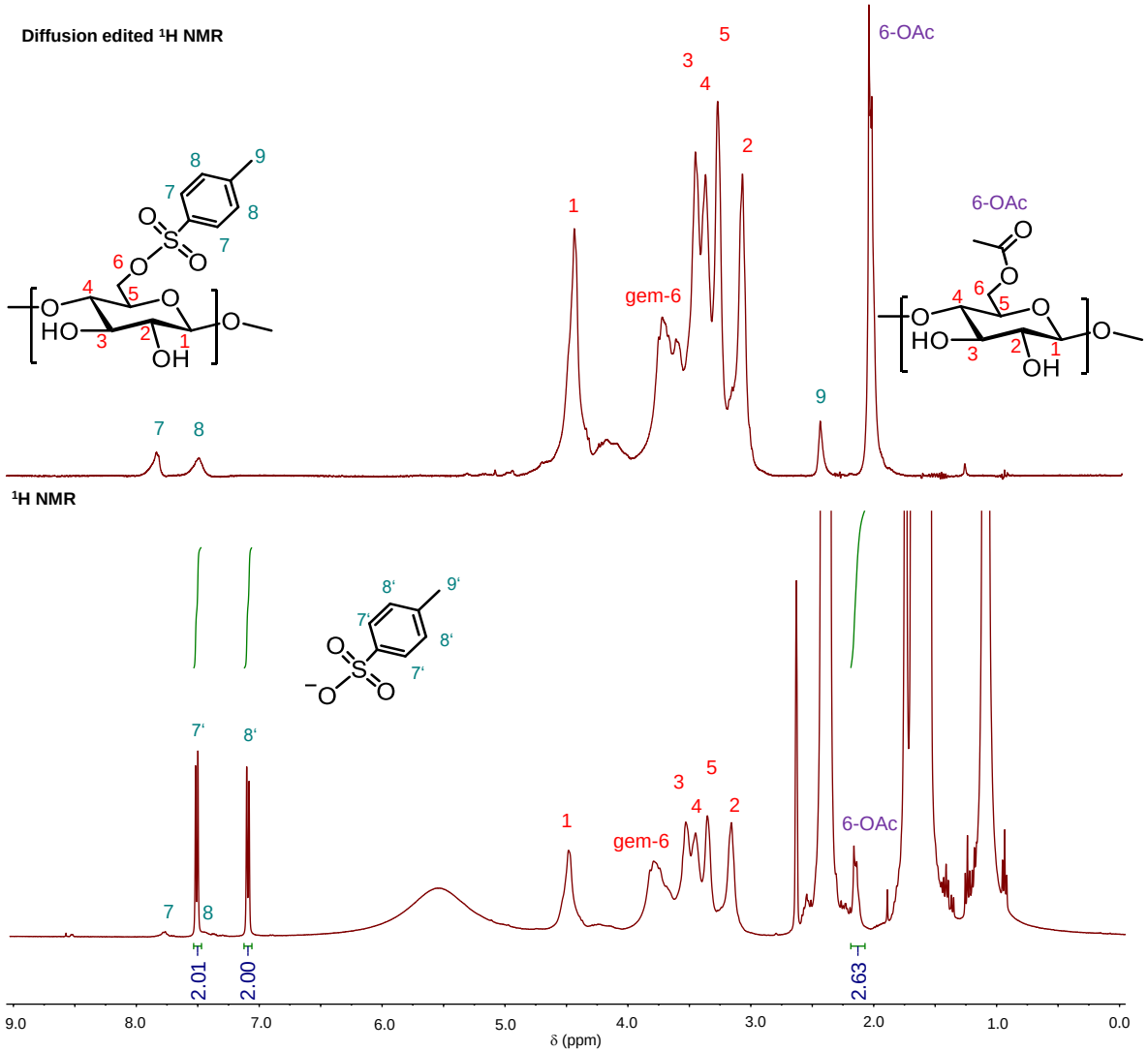


Figure S1: Showing different NMR experiments from 1 60 min after dissolving it in [P_{4444}][OAc]/DMSO-d_6 at 65 °C for 16-20h: top) diffusion edited ^{1}H NMR aromatic peaks of the bound tosyl (7.75 and 7.38 ppm) and the 6-OAc at 2.02 ppm; bottom) ^{1}H-NMR integrated aromatic peaks substituted free tosyl (7.5 and 7.1 ppm) with the its correlating 6C acetate peak at 2.02 ppm). Regardless of a partial overlap of the 6-OAc signal with the NMR-signals of the ionic liquid, integration of the 6-OAc peak from quantitative ^{1}H NMR was possible and corresponded to the aromatic peaks of the released tosyl 7' and 8'. The remaining tosyl signals in the aromatic region 7.3–8.0 ppm (7 and 8) are likely to originate from unreacted C6-tosyl and/or less reactive C2-tosyl groups.

Following NMR experiments were performed at higher dissolution temperature (80 °C) (Figure S2) in the ionic liquid to obtain a full substitution reaction of C6-tosyl to C6-OAc, allowing us to also estimate the regioselectivity of the tosylation reaction based on integrating the released tosyl (7.50 and 7.1 ppm; Figure S3) against the unreacted cellulose-bound tosyl peaks (7.8 and 7.4 ppm; Figure S3) by quantitative ^{1}H-NMR, In addition, a diffusion edited ^{1}H NMR (Figure S4) was done as well to have a closer look at the acetate peak to ensure to have only C6-OAc. A very small shoulder (insert Figure S2) appears in the DOSY on the C6-OAc, which would correlate with a shift of a C6-OAc of a disubstituted AGU. [17]

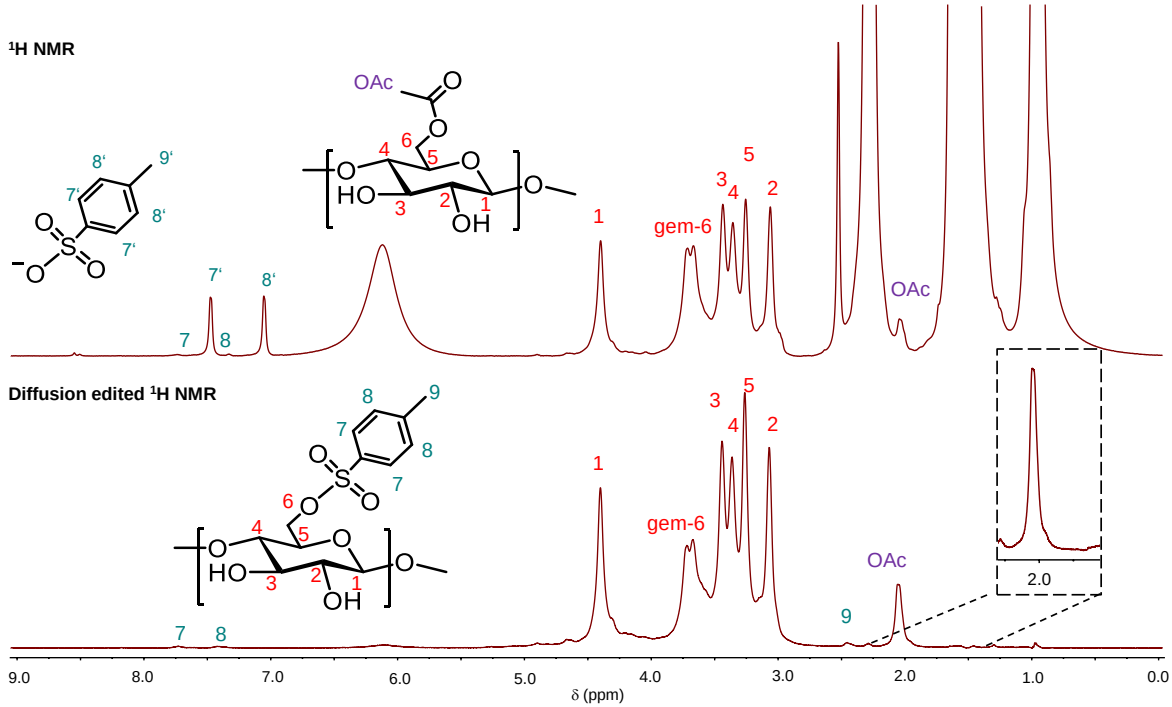


Figure S2: Showing different NMR experiments from 1 60min after dissolving it in [P_{4444}][OAc]/DMSO-d_6 at 80 °C for 24h to push the substitution reaction of C6-tosyl to C6-OAc to completion: top) ^{1}H-NMR; bottom) diffusion edited ^{1}H NMR. 6-OAc peak from ^{1}H NMR corresponded to the aromatic peaks of the released tosyl 7' and 8'. The remaining tosyl signals in the aromatic region 7.3–8.0 ppm (7 and 8) are likely to originate from less reactive C2-tosyl groups., which do not seem to undergo substitution reactions even at higher dissolution temperatures, as no 2-OAc or 3-OAc peaks can be observed in the sample (diffusion edited ^{1}H NMR).[18]

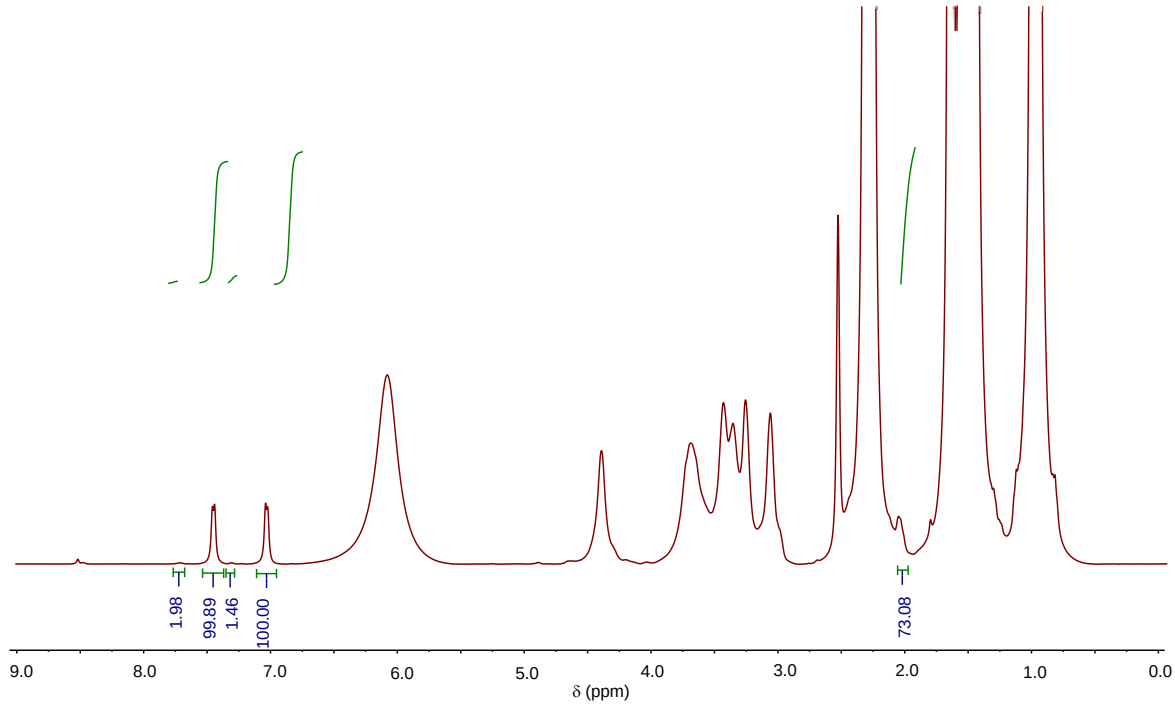


Figure S3: Showing a quantitative ^{1}H-NMR experiments from 1 60min after dissolving it in [P_{4444}][OAc]/DMSO-d_6 at 80 °C for 24h with integrated aromatic peaks of the bound tosyl (7.75 and 7.38 ppm) and substituted free tosyl (7.5 and 7.1 ppm) with the its correlating bound 6C-OAc.The experiment gives us an estimate on the regioselectivity of the tosylation reaction based on integrating the peak area for released tosyl (7.50 and 7.1 ppm) against the unreacted cellulose-bound tosyl peaks (7.8 and 7.4 ppm) by quantitative ^{1}H-NMR, assuming that the unreacted cellulose-bound tosyl signals arise solely from C2-tosyl groups. Very high ratio between the substituted and bound tosyl, integrals 100 to 2 respectively, shows selectivity of C6 position over C2.

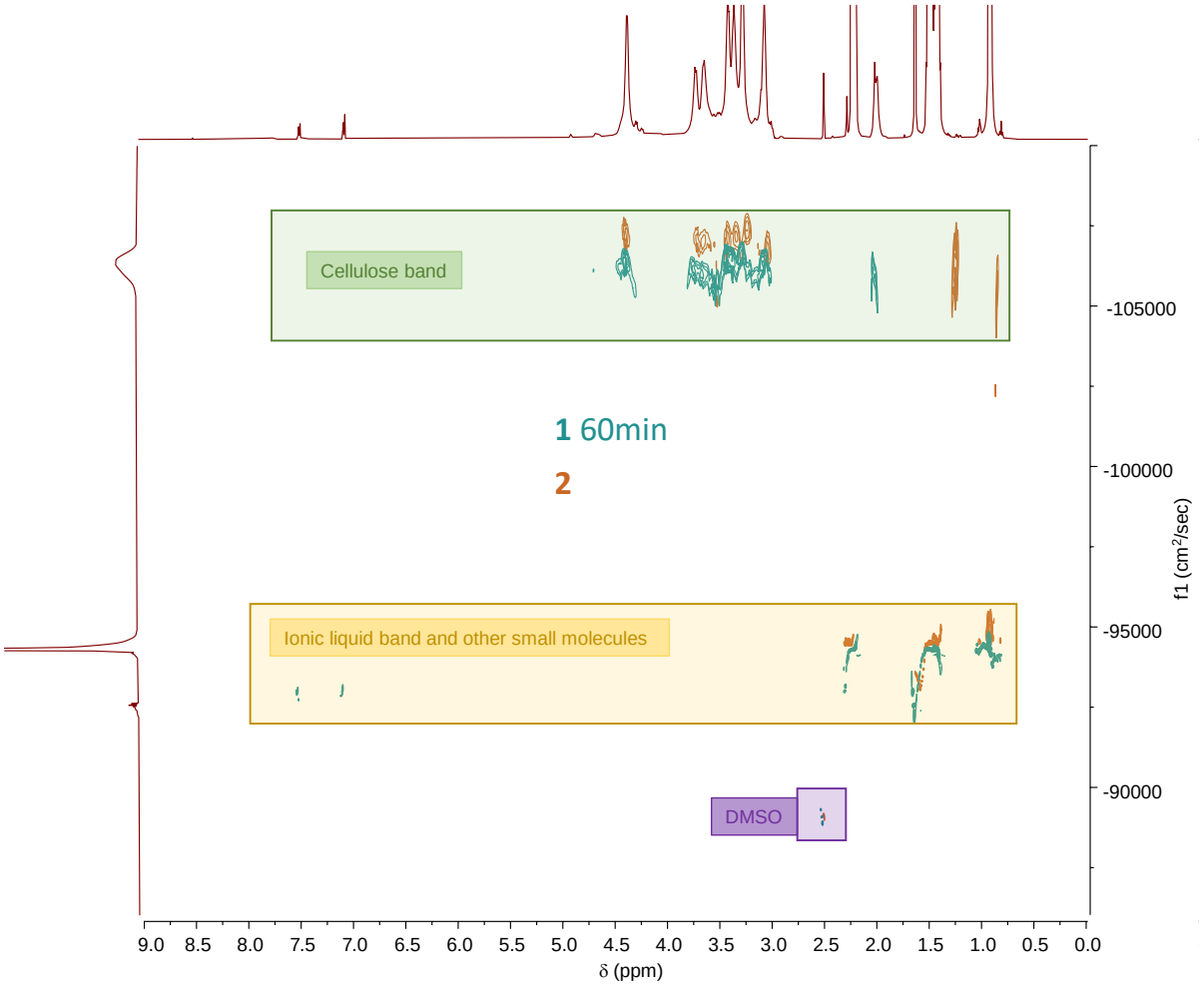


*Figure S4: Showing a 2D-DOSY NMR experiment with **1** 60min (tosyl-CNCs) and **2** (dodecylamine-modified CNCs). Signals belong to three groups, with different diffusion coefficients: the green band contains signals for the cellulose polymer and small molecules covalently attached to it (as these diffuse together with cellulose); the yellow band contains to the ionic liquid ([P_{4444}][OAc]) signals and small molecules not attached to cellulose; finally the purple band corresponds to DMSO. The tosylated CNCs (**1** 60 min, signals shown with green colour) show the covalently linked acetate group (2.00 ppm) in the cellulose band and the corresponding released tosylate (through substitution with acetate) in the yellow band. The dodecylamine-modified CNCs (**2**) show the covalently linked aliphatic chain from dodecylamine at 1.25 and 0.75 ppm.*

2.3 All entries diffusion edited ^{1}H NMR vs ^{1}H NMR

2.3.1 Procedure for evaluating the influence of milling duration on the tosylation of CNCs.

CNCs obtained by HCl gas hydrolysis (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for either 60, 90 or 120 minutes at 25 Hz, with the resulting off-white paste transferred to a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solids were transferred in 50 mL falcon tubes and freeze dried. The resulting white powders were characterized with ATR-IR, EA, NMR and XRD.

Table S1: Screening of milling time conditions for the tosylation process.

Entry	**CNC** (mg)	TsCl (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]
1 60min	201.3	376.6	pyridine	200	0.357	60	-	0.113
1 90min	200.6	384	pyridine	200	0.357	90	-	0.173
1 120min	203.5	369.1	pyridine	200	0.357	120	-	0.294

[a]DS calculated from sulphur content, which was obtained by elemental analysis.

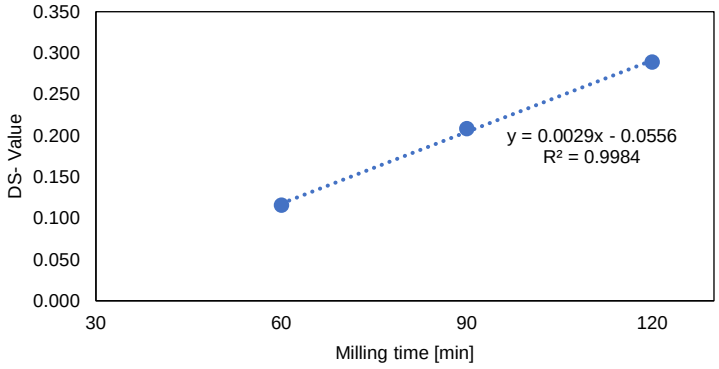


Figure S5: Plot which shows the increase of DS-Value changing with milling time.

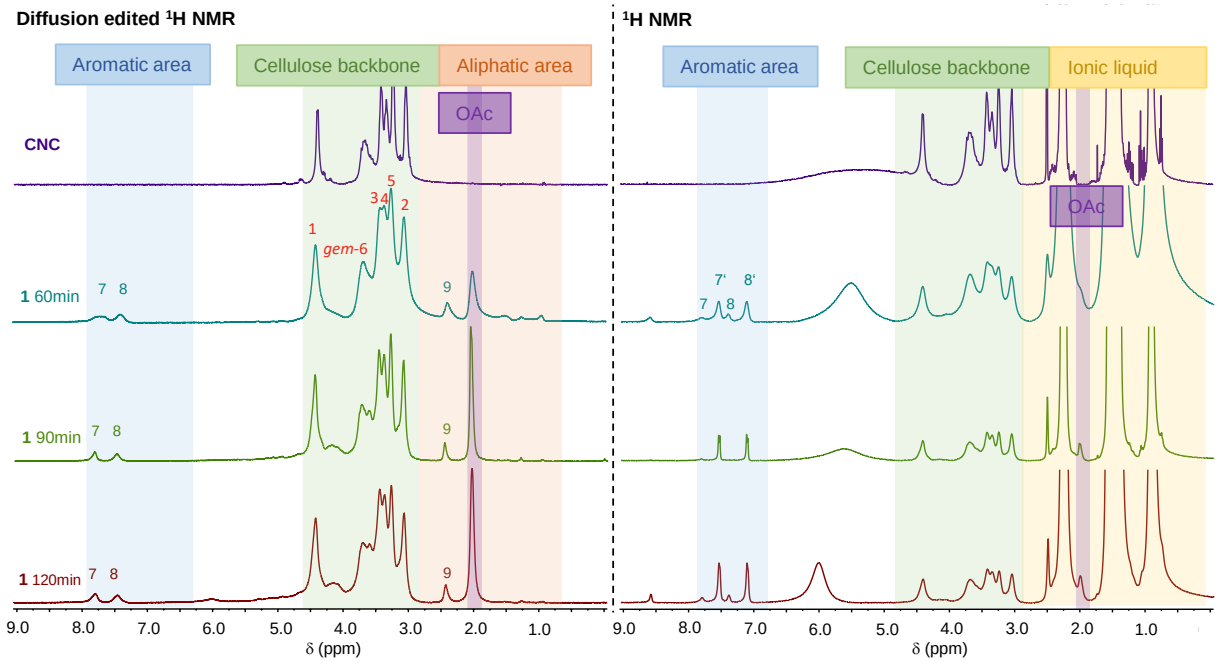


Figure S6: Comparison between left, diffusion edited 1H NMR of all entries and right. 1H NMR of all entries. Full experimental details are shown in Table S1, entries 1 60min, 1 90min and 1 120min. Yellow band shows the area of the [P_{4444}][OAc]/DMSO-d_6 ionic liquid in ^{1}H NMR. The green band marks the cellulose backbone. The blue band marks the aromatic area and shows there with 7 and 8 the bound tosyl and 7' and 8' the released tosyl due to substitution with acetate (purple band) from the ionic liquid.

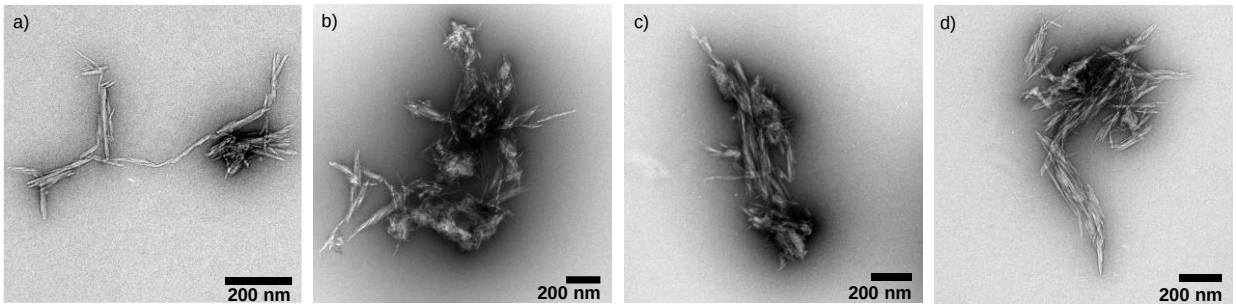


*Figure S7: Original uncropped TEM images of a) CNC starting material, b) **1** 60min, c) **1** 90min. d) **1** 120min.*

2.3.2 Procedure for SN reaction of tosylated CNCs:

Previously synthetized tosylated CNCs (150 mg), dodecylamine (131.25 mg, 0.708 mmol) or aniline (66 µL, 0.708 mmol) or 3-phenylpropionic acid (106.34 mg, 0.708 mmol), 100 µL of DMSO (η = 0.357 µL mg^{-1}) or no additional liquid if the nucleophile was in a liquid state and K_2CO_3 (100 mg) in case of 3-phenylpropionic acid were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator at 55 °C for three days. Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and

washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, NMR and XRD*.

Table S2:Screening of different nucleophiles at the nucleophilic substitution under optimized conditions.

Entry	Tos-CNC (mg)	Nucleophile (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
2	150.0	135.5	DMSO	100	0.357	60	+	0.023	0.131
3	150.1	66	none	0	0*	60	+	0.050	0.100
4	157.8	106.5	K_2CO_3/DMSO	104.8mg/100	0.357	60	+	ND*	ND*

[a]DS calculated from sulphur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis.
*Elemental analysis could not be used to calculate the DS, as there are no S or N atoms in 3-phenylpropionic acid

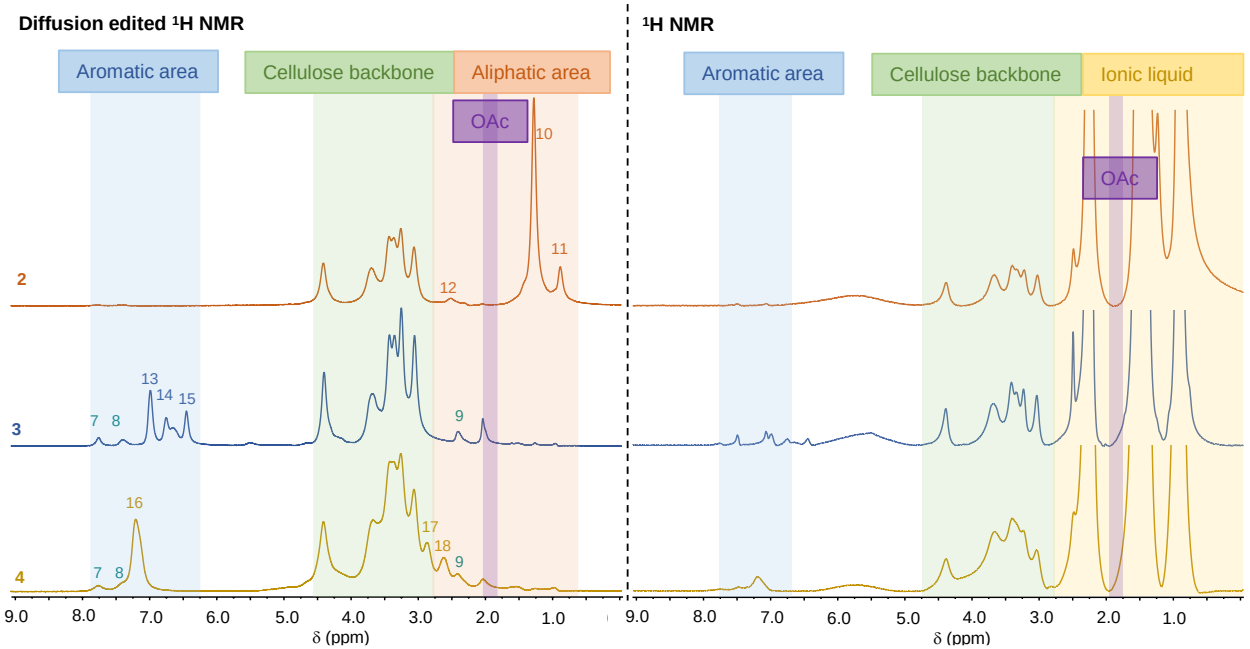


Figure S8: Comparison between left, diffusion edited 1H NMR of all entries and right. 1H NMR of all entries. Full experimental details are shown in Table S2 entries 2, 3 and 4. Yellow band shows the area of the [P_{4444}][OAc]/DMSO-d_6 ionic liquid in ^{1}H NMR. The green band marks the cellulose backbone. The blue band marks the aromatic area and shows there with 7 and 8 the bound tosyl and 7' and 8' the released tosyl due to substitution with acetate (purple band) from the ionic liquid.

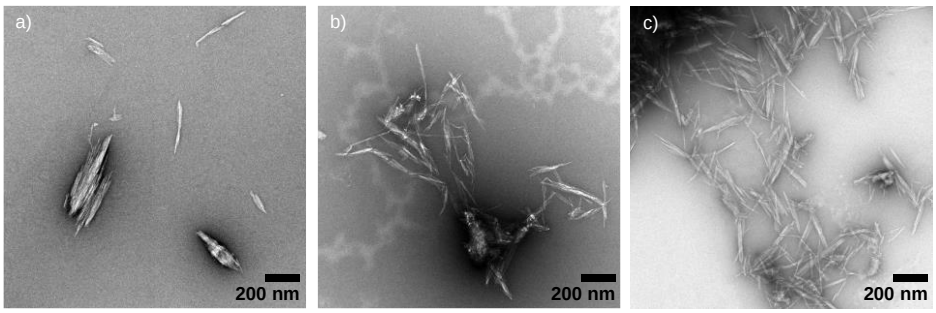


Figure S9: Original uncropped TEM images of nucleophilic substitution a) dodecylamine, b) aniline; c) 3-phenylporpionic acid

2.3.3 Procedure for one-step reaction of CNC modification:

CNCs obtained by HCl gas hydrolysis (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol), dodecylamine (131.25 mg, 0.708 mmol) or 3-phenylpropionic acid (106.34 mg, 0.708 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The

washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA,and NMR.

Table S3: Screening of different nucleophiles at one-step reaction.

Entry	CNC (mg)	TosCl (mg)	Nucleophile [mg]	Base/ liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
1.2	209	364	142	py$^{\Delta}$	200		60	-	0.058	0.022
1.3	200.9	366.6	66	py$^{\Delta}$	100		60	-	0	0
1.4	201.5	373.5	106.4	py$^{\Delta}$	200		60	-	ND*	ND*

[a]DS calculated from sulphur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis. *Elemental analysis could not be used to calculate the DS, as there are no S or N atoms in 3-phenylpropionic acid. $^{\Delta}$py = pyridine

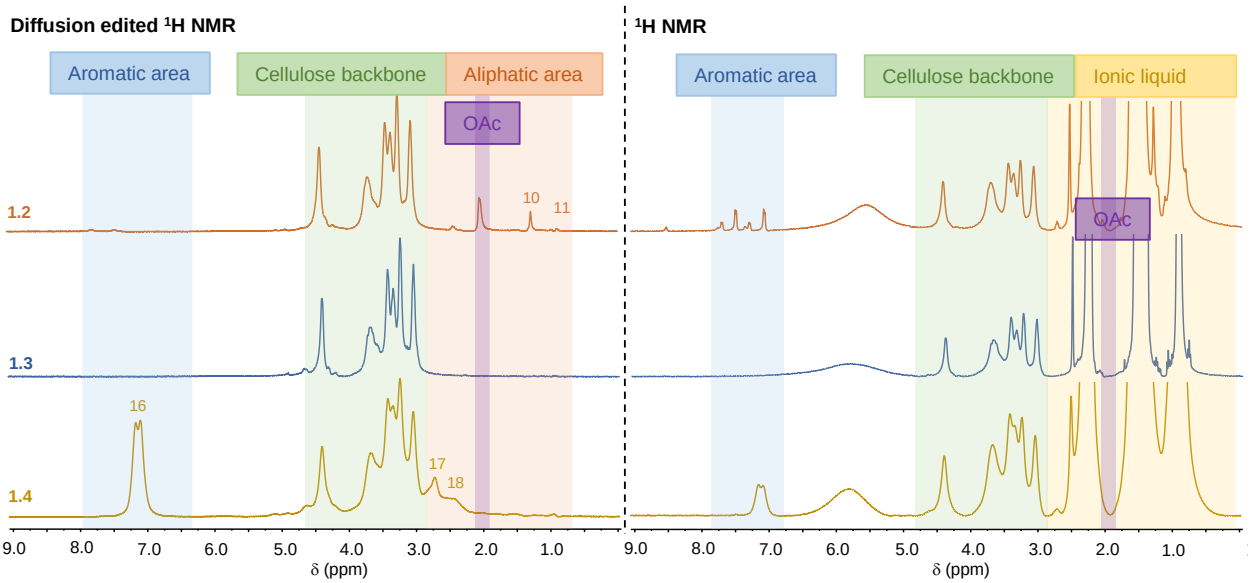


Figure S10: Comparison between left, diffusion edited ^{1}H NMR of all entries and right. ^{1}H NMR of all entries. Full experimental details are shown in Table S3 entries 1.2 and 1.4. Yellow band shows the area of the [P_{4444}][OAc]/DMSO-d_6 ionic liquid in ^{1}H NMR. The green band marks the cellulose backbone. The blue band marks the aromatic area and shows there with 7 and 8 the bound tosyl and 7' and 8' the released tosyl due to substitution with acetate (purple band) from the ionic liquid.On the left side diffusion edited ^{1}H NMR, on the right side ^{1}H NMR. Full experimental details are shown in Table S9, entries 3 and 3_DMSO.

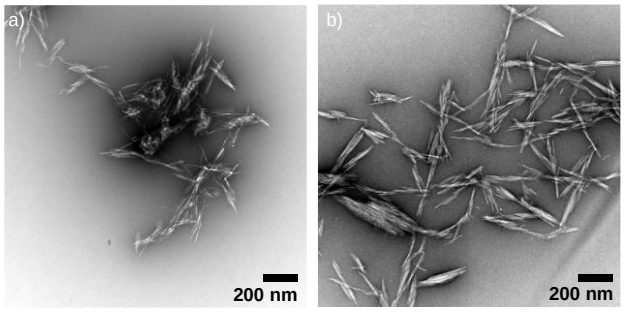


Figure S11: Original uncropped TEM images of one-step reaction with a) dodecylamine; b) 3-phenylpropionic acid

2.4 Tosylation with(out) K_2CO_3 as additional base

CNCs obtained by HCl gas hydrolysis (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) (**1** 60min) or 100 µL of pyridine and 302 mg of K_2CO_3 (**1_K_2CO_3**) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S4: Comparison between "standard" tosylation and tosylation with half of the liquid and solid base K_2CO_3 instead.

Entry	**CNC** (mg)	TsCl (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]
1 60min	201.3	376.6	pyridine	200	0.357	60	-	0.113
1_K_2CO_3	201	371	Pyridine+ K_2CO_3	100 + 302mg	0.125	60	-	0.091

[a]DS calculated from sulphur content, which was obtained by elemental analysis.

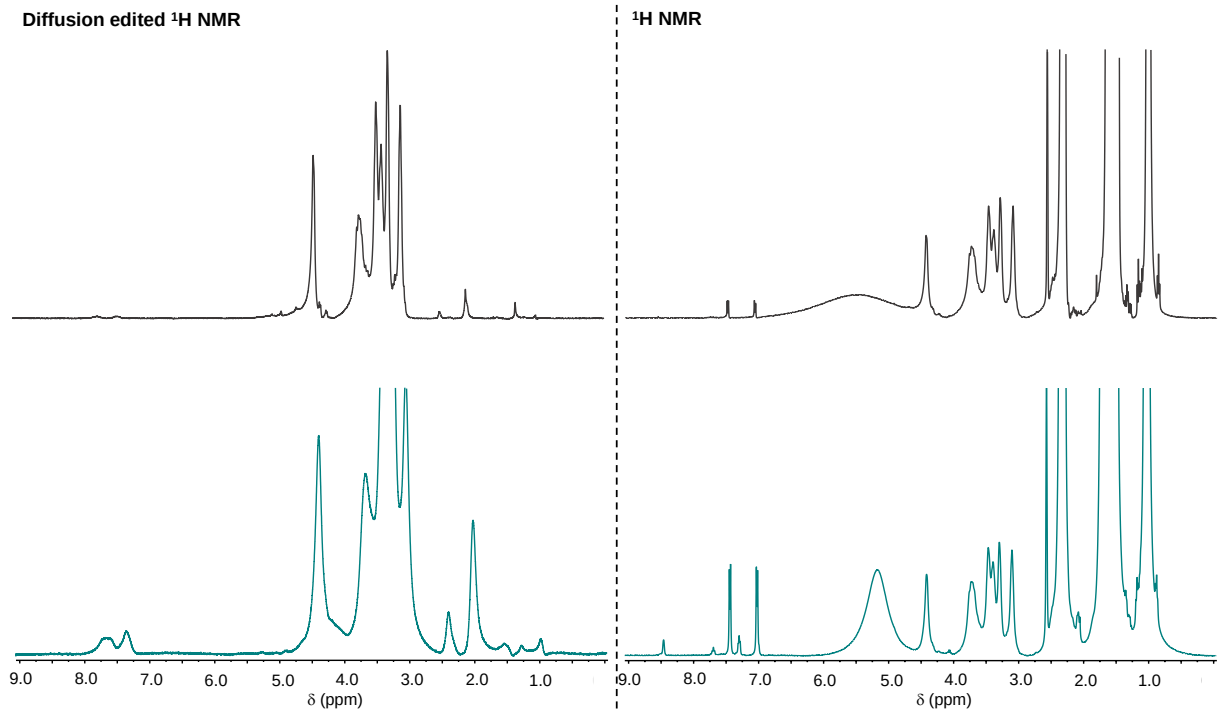


Figure S12: Comparison between left, diffusion edited 1H NMR and right 1H NMR of tosylation 60 min (petrol), tosylation 60 min + K_2CO_3 (blue Full experimental details are shown in Table S6, entries 1 60min and 1_K_2CO_3.

2.5 Tosylation long term storage stability experiment

CNCs obtained by HCl gas hydrolysis (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) (**1** 60min) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR. The powder of the **1**_2.5years was stored in a falcon tube at room temperature and analysed 2.5 years later investigate the stability of **1** 60min.

Table S5:Comparison between "standard" tosylation and tosylation after 2.5 years in storage under dry conditions.

Entry	**CNC** (mg)	TsCl (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]
1 60min	201.3	376.6	pyridine	200	0.357	60	-	0.113
1_2.5years	200	360	pyridine	200	0.357	60	-	0.184

[a]DS calculated from sulfur content, which was obtained by elemental analysis.

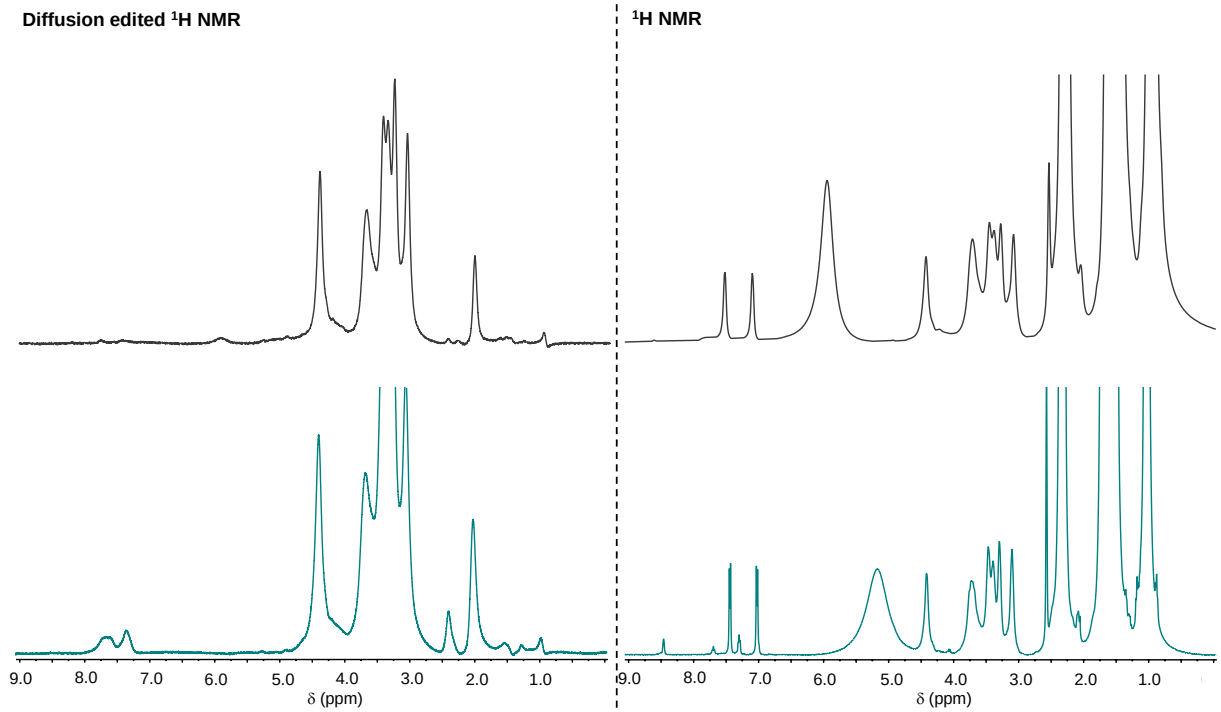


Figure S13:Comparison between left, diffusion edited 1H NMR and right 1H NMR of tosylation 60 min (petrol), tosylation 60 min after 2.5 years of dry storage. Full experimental details are shown in Table S5.

2.6 Degradation of cellulose via aging process

Control experiments for aging conditions of the tosylation process:

Figure S14: Degradation of cellulose in the attempt to carry out tosylation with the aging process (55°C).

The combination of cellulose with pyridine and *p*-toluenesulfonyl chloride at elevated temperature of 55 °C in the incubator showed clear signs of degradation and therefore no further analysis was done.

2.7 Tosylation: HCl vs Sulf CNC vs Whatman 1 filter paper

CNCs obtained by HCl gas hydrolysis (**CNC**) or sulphated CNCs (Sulf-**CNC**) or cellulose fibres from Whatman 1 filter paper (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S6:Parameters for comparison of different cellulosic starting material for tosylation process.

Entry	**CNC** (mg)	TsCl (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]
1 60min	201.3	376.6	pyridine	200	0.357	60	-	0.113
Sulf- **1** 60min	200.6	360	pyridine	200	0.357	60	-	0.174
Whatman **1** 60min	206.1	368.3	pyridine	200	0.357	60	-	0.104

[a]DS calculated from sulfur content, which was obtained by elemental analysis.

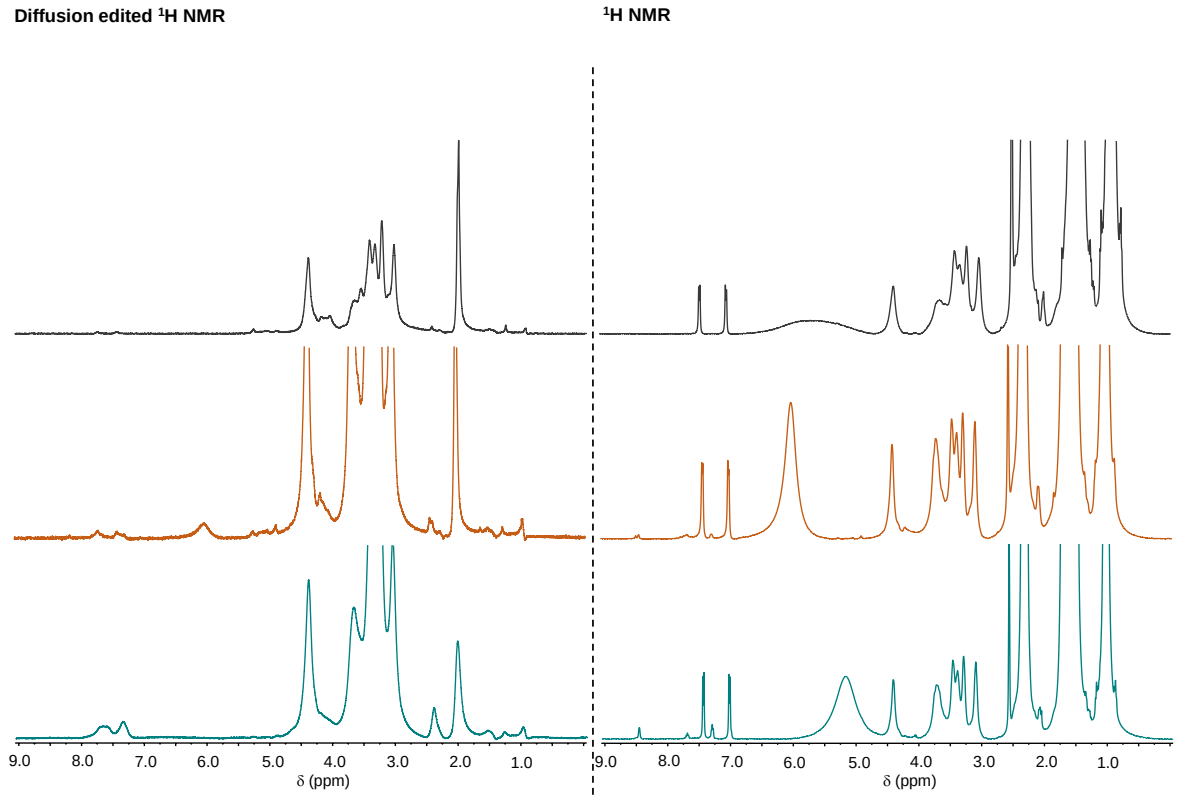


Figure S15: Comparison between left, diffusion edited 1H NMR and right. 1H NMR of Whatman 1 filter paper (grey), Sulphated CNCs (orange) and HCl CNCs (petrol). On the left side diffusion edited 1H NMR, on the right side 1H NMR. Full experimental details are shown in Table S6, entries.

2.8 Scalability of tosylation:

CNCs obtained by HCl gas hydrolysis flakes (200, 300 or 400 mg), *p*-toluenesulfonyl chloride (360, 540 or 720 mg, 1.888 mmol) and 200, 300 or 400 µL of pyridine (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, NMR and XRD*.

Table S7: Screening of different amounts of starting material for scalability.

Entry	**CNC** (mg)	TsCl (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]
1 60min	200.6	360	pyridine	200	0.357	60	-	0.113
1 300mg	300	540	pyridine	300	0.357	60	-	0.086
1 400mg	400	720	pyridine	400	0.357	60	-	0.037

[a]DS calculated from sulfur content, which was obtained by elemental analysis.

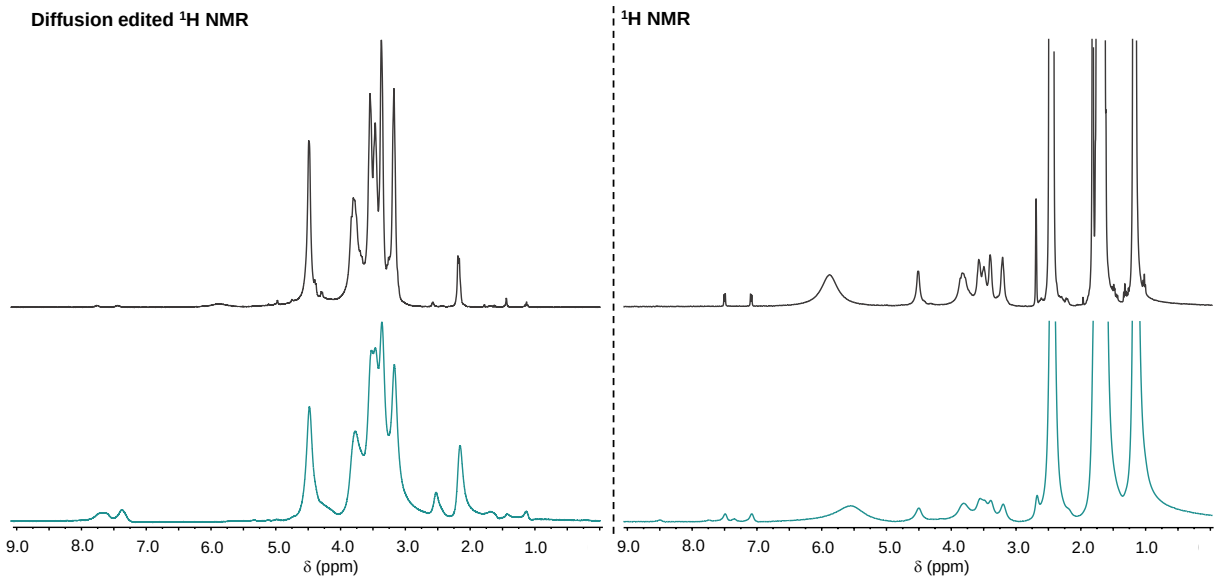


Figure S16: Comparison between left, diffusion edited ^{1}H NMR and right ^{1}H NMR of Tos_60 400mg (grey); tos_60_200mg (petrol). On the left side diffusion edited ^{1}H NMR, on the right side ^{1}H NMR. Full experimental details are shown in Table S7, entries 1 60 min, and 1 400 mg.

2.9 SN optimization on dodecylamine through milling vs milling + aging

Previously synthetized tosylated CNCs (150 mg,), dodecylamine (131.25 mg, 0.708 mmol), 100 µL of DMSO (η = 0.357 µL mg^{-1}) in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz and directly purified (**2_M**) and freeze dried or milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator at 55 °C for three days (**2**). Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, NMR and XRD*.

Table S8: Reaction condition for nucleophilic substitution to optimize the milling and aging conditions.

Entry	Tos-CNC (mg)	Nucleophile (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
2	150.0	135.5	DMSO	100	0.357	5	+	0.023	0.131
2_M	200	175	DMSO	135	0.357	60	-	0.073	0.021

[a]DS calculated from sulphur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis.

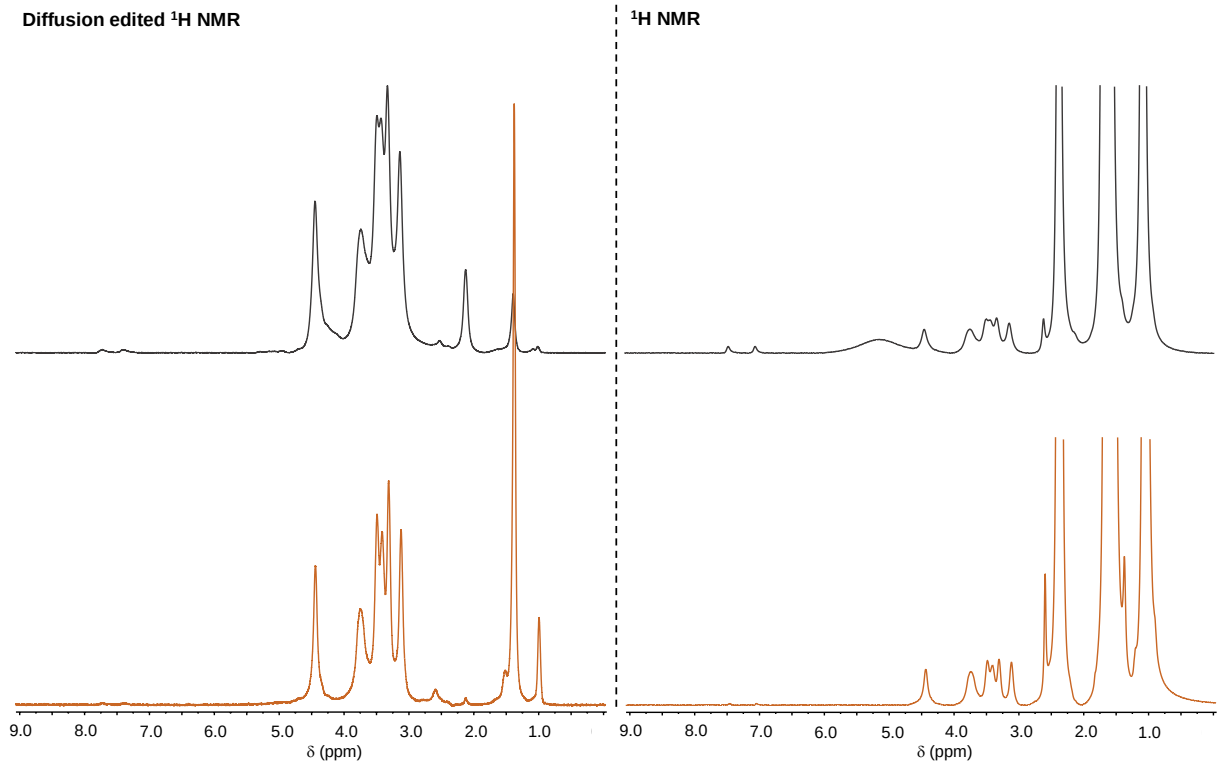


Figure S17: Comparison between left, diffusion edited ¹H NMR and right ¹H NMR of SN dodecylamine milling (grey); SN dodecylamine milling + aging (orange). Full experimental details are shown in Table S8, entries 2 and 2_M.

2.10 SN optimization on dodecylamine through aging: 55 vs 70°C ➔ 3 vs 2 days

Previously synthetized tosylated CNCs (150 mg), dodecylamine (131.25 mg, 0.708 mmol), 100 µL of DMSO (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator for either three days at 55 °C (**2**) or two days at 70 °C **(2_111**). Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, NMR and XRD*.

Table S9: Comparison between of aging conditions at the nucleophilic substitution of dodecylamine.

Entry	Tos-CNC (mg)	Nucleophile (mg)	Base/ liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging		DS[a]	DS[b]
							55 °C/ 72 h	70 °C/ 48 h		
2	150.0	135.5	DMSO	100	0.357	5		+	0.023	0.131
2_111	150.1	133.3	DMSO	100	0.357	5		+	0.008	0.110

[a]DS calculated from sulphur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis.

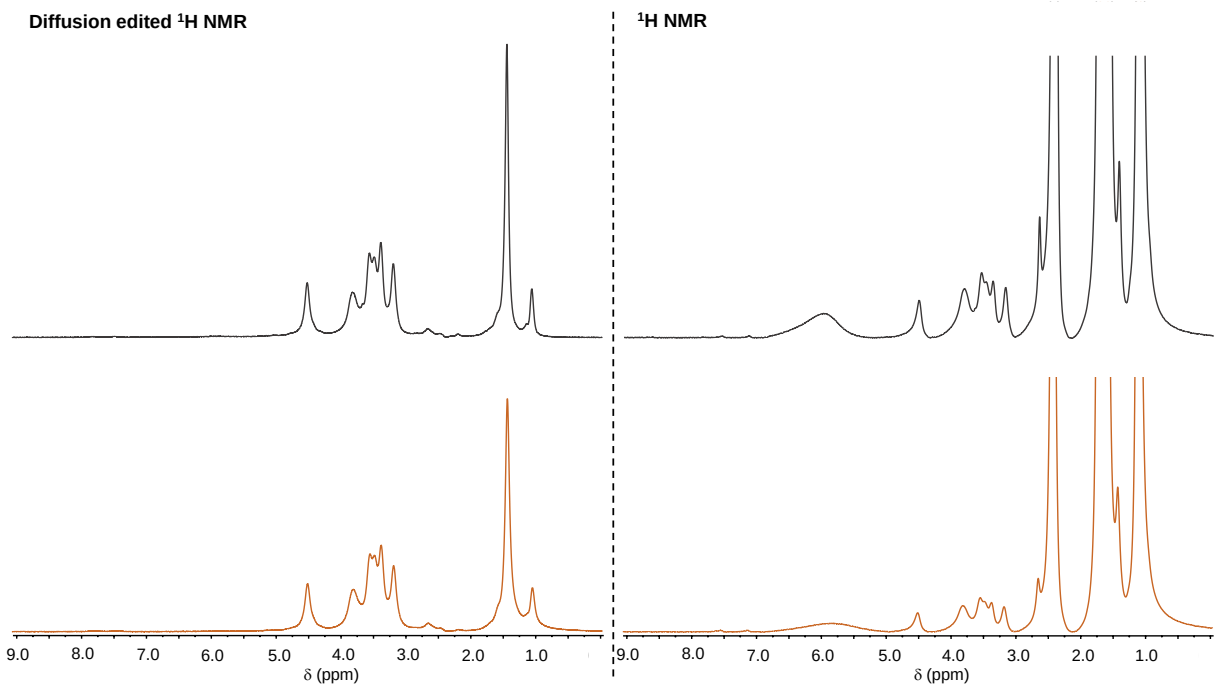


Figure S18: Comparison between left, diffusion edited ^{1}H NMR and right ^{1}H NMR of SN dodecylamine 70 °C for 2 days (grey), SN dodecylamine 55 °C for 3 days (orange).. Full experimental details are shown in Table S9, entries 2 and 2_111.

2.11 SN optimization on liquid nucleophiles through Aniline with and without DMSO

Previously synthetized tosylated CNCs (150 mg,), aniline (66 µL, 0.708 mmol) 34 µL of DMSO (η = 0.357 µL mg^{-1}) (**3_DMSO**) or no additional liquid since aniline is liquid (**3**) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator at 55 °C for three days. Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S10. Comparison between aniline with and without additional DMSO.

Entry	Tos-CNC (mg)	Nucleophile (µL)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
3	150.0	66	none	0	N.A.[*]	5	+	0.050	0.100
3_DMSO	155.3	66	DMSO	34	0.357*	5	+	0.088	0.096

[a]DS calculated from sulphur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis.
[*]For 2, η Etha not applicable (N.A.) since aniline is already liquid no additional liquid needed.

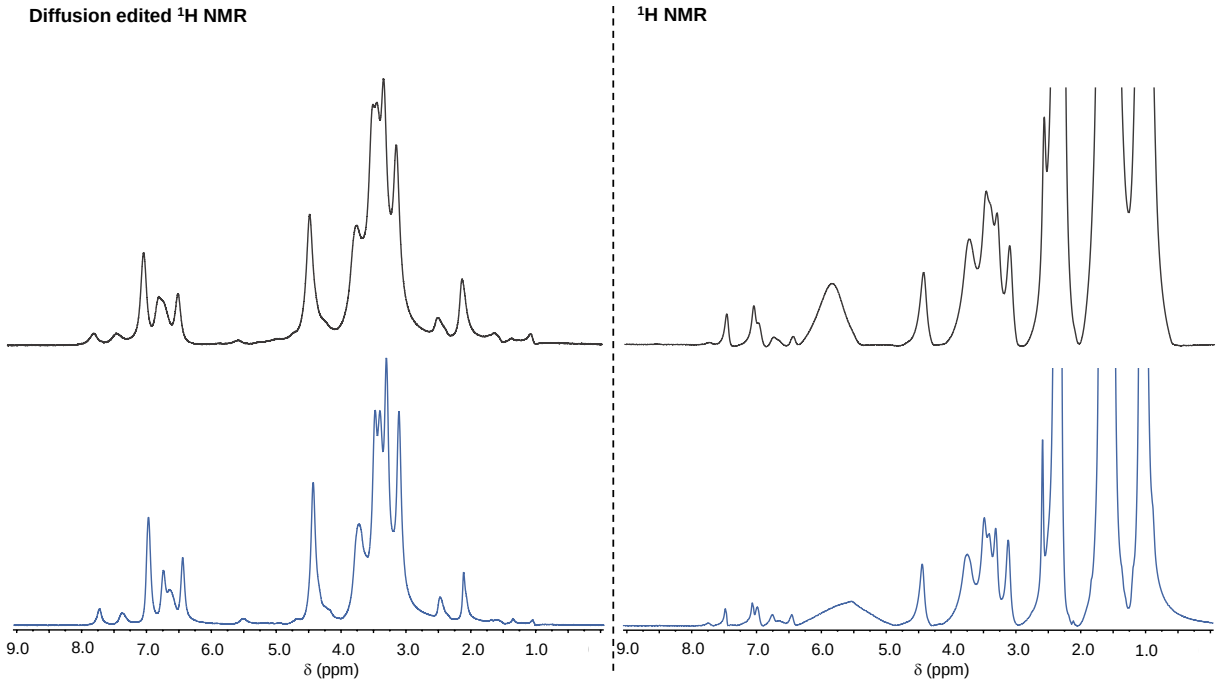


Figure S19: Comparison between left, diffusion edited ^{1}H NMR and right ^{1}H NMR of Aniline + DMSO (grey): Aniline (blue). Full experimental details are shown in Table S10, entries 3 and 3_DMSO.

2.12 SN optimization on esters through 3-phenyl propionic acid with and without K_2CO_3

Previously synthetized tosylated CNCs (150 mg,), 3-phenylpropionic acid (106.34 mg, 0.708 mmol), 100 µL of DMSO (η = 0.357 µL mg^{-1}) and K_2CO_3 (100 mg) (**4**) or without K_2CO_3 (**4_x**) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator at 55 °C for three days. Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S11: Comparison between esterification as nucleophilic substitution with and without the base K_2CO_3.

Entry	Tos-CNC (mg)	Nucleophile (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
4	157.8	106.5	K_2CO_3/ DMSO	104.8 mg/ 100	0.278	5	+	ND*	ND*
4_x	153	109.2	DMSO	100	0.357*	5	+	ND*	ND*

[a]DS calculated from sulfur content, which was obtained by elemental analysis. [b]DS calculated from nitrogen content which was obtained by elemental analysis.
*Elemental analysis could not be used to calculate the DS, as there are no S or N atoms in 3-phenylpropionic acid.

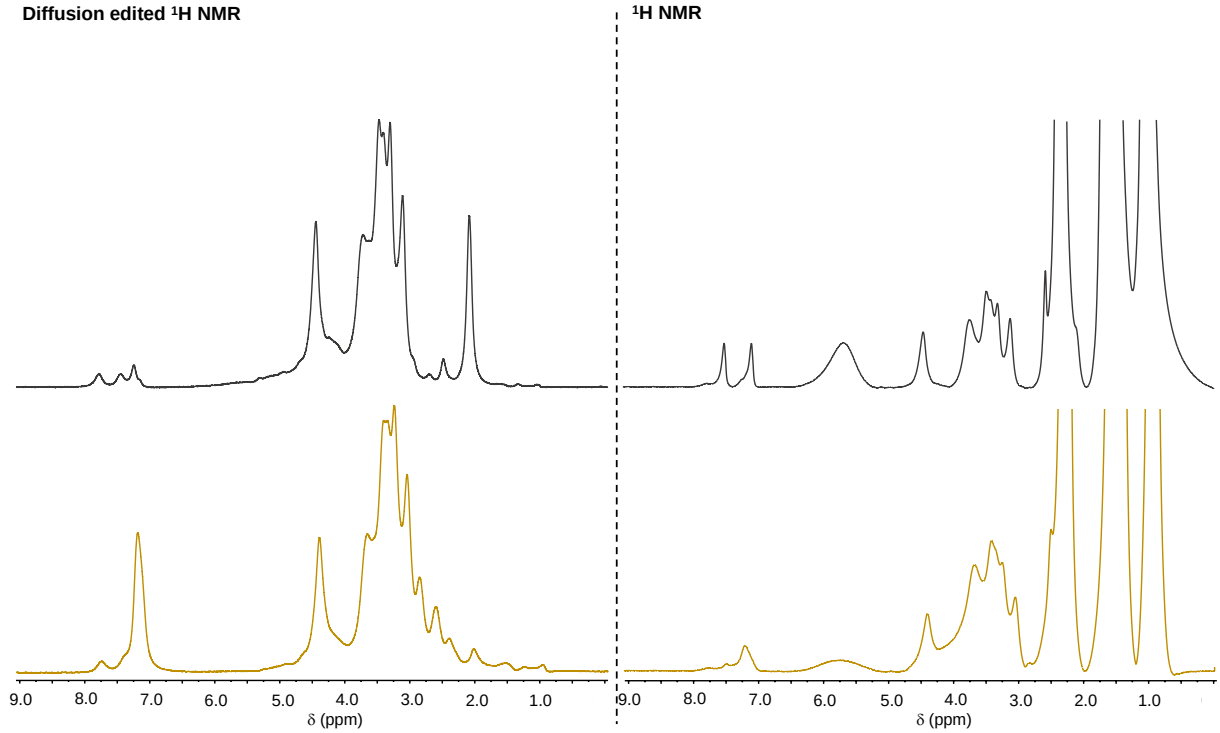


Figure S20: Comparison between left, diffusion edited ^{1}H NMR and right ^{1}H NMR of SN 3-phenylpropionic acid (grey); SN 3-phenylpropionic acid + K_2CO_3 (yellow). Full experimental details are shown in Table S11, entries 4 and 4_x.

2.13 Limitations: Ether bond (negative example)

Previously synthetized tosylated CNCs (150 mg), ethanol (32 µL, 0.708 mmol) and K_2CO_3 (100 mg) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 5 minutes at 25 Hz, then the resulting paste transferred in a 4 mL glass vial with a screw cap and put in the incubator at 55 °C for three days. Afterwards, the paste was transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S12: Comparison between etherification with EtOH with and without the base K_2CO_3.

Entry	Tos-CNC (mg)	Nucleophile (mg)	Base/liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
5	156	32	K_2CO_3/ DMSO	100 mg / 100		5	+	ND*	ND*
5_x	150.4	32	DMSO	100	0.357*	5	+	ND*	ND*

*Elemental analysis could not be used to calculate the DS, as there are no S or N atoms in EtOH. Furthermore, the NMR (Figure S20) showed no signals that could be interpreted as the ethanol substitution product.

CNCs obtained by HCl gas hydrolysis (200 mg, 1.233 mmol), *p*-toluenesulfonyl chloride (360 mg, 1.888 mmol), dodecylamine (131.25 mg, 0.708 mmol) or 3-phenylpropionic acid (106.34 mg, 0.708 mmol) and 200 µL of pyridine (η = 0.357 µL mg^{-1}) were placed in the 14 mL stainless steel jar with a single 10 mm stainless steel ball (4.0 g). The mixture was milled for 60 minutes at 25 Hz, then the resulting paste transferred in a Buechner filter with a nylon membrane filter with 0.2 µm pore size and washed three times with ethanol and five times with deionized water. The washed solid was transferred in a 50 mL falcon tube and freeze dried. The resulting white powder was characterized with ATR-IR, EA, and NMR.

Table S13: one-step reaction of etherification with EtOH.

Entry	CNC (mg)	TosCl (mg)	Nucleophile (mg)	Base/ liquid	Base/liquid v (µL)	η (µL mg^{-1})	Milling time. (min)	Aging (55 °C for 72 h)	DS[a]	DS[b]
5.1	206	370	61.3	py	138.7		60	-	ND*	ND*

*Elemental analysis could not be used to calculate the DS, as there are no S or N atoms in EtOH. Furthermore, the NMR (Figure S20) showed no signals that could be interpreted as the ethanol substitution product.

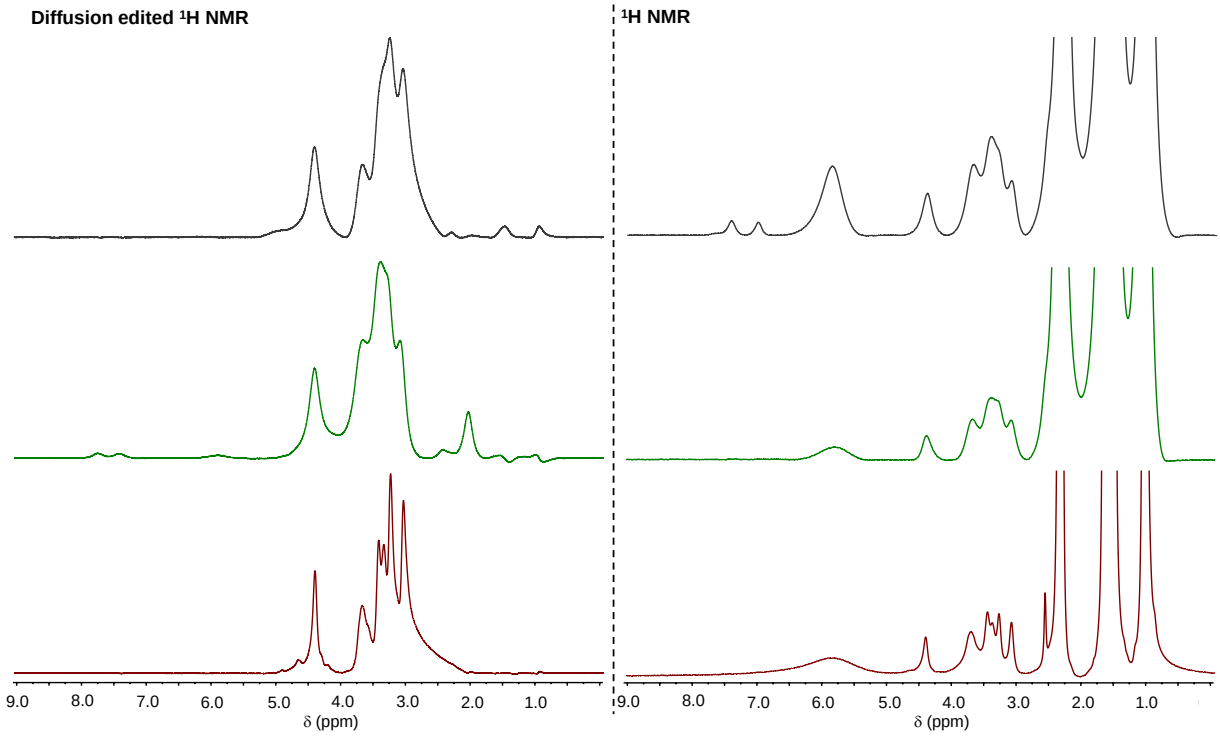


Figure S21: Comparison between left, diffusion edited ^{1}H NMR and right ^{1}H NMR of SN EtOH (grey); SN EtOH+K_2CO_3 (green); 1-pot EtOH (red). Full experimental details are shown in Table S12, entries 5 and 5_x and Table S13 entry 5_1-pot.

2.14 Thermal properties:

TGA was conducted to study the thermal stability of the materials (Figure S22). The starting material HCl-CNC shows a distinct thermal behaviour illustrating a main degradation reaction at 352°C similar to values reached with cotton linters by Kröger et al.[19] The chemical modification of the starting material (HCl-CNC) causes the appearance of degradation peaks at lower temperatures. The tosyl-modified CNCs (**1** 60 min) show one main degradation reaction at a temperature of 202°C, which causes a loss of mass of 37%. This degradation reaction is followed by 2 transformations at around 290 and 486°C until it stabilizes at around 650°C and reaches a final yield of 28%. Dodecyl-modified CNCs (**2**) show a main reaction appearing at around 290°C, causing a mass loss of around 62%, followed by a stabilization degradation and finally reaching a yield of 20% at 700°C. Consequently, due to the introduction of functionalities, **1** 60 min and **2** exhibit lower thermal stabilities compared to the unmodified CNCs.

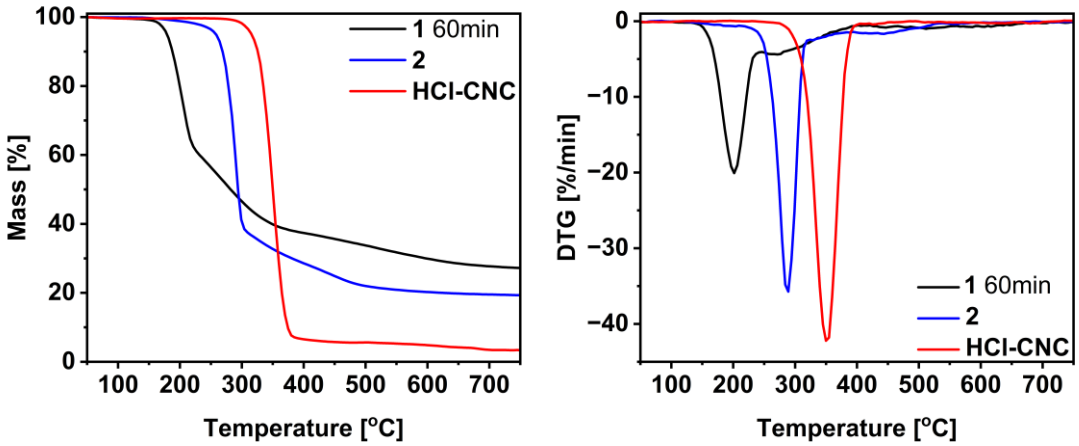


*Figure S22: Illustration of the thermal behaviour of the starting material HCl-CNC, the tosylated CNCs (**1** 60 min) and the dodecylamine-modified CNCs (**2**) by thermo-gravimetric (TG, left) and derivative thermo-gravimetric (DTG, right) analysis.*

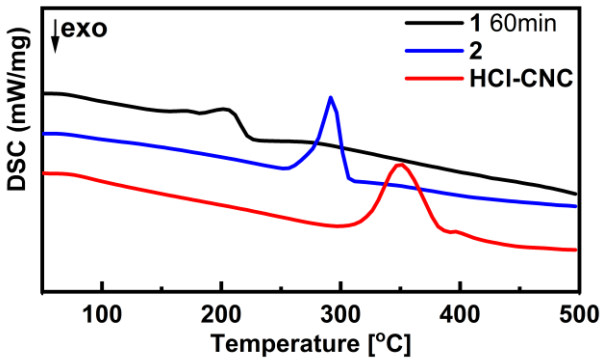


*Figure S23: Illustration of the thermal behaviour of the samples HCl-CNC (starting material), the tosylated CNCs (**1** 60 min) and the dodecylamine-modified CNCs (**2**) by DSC analysis.*

The DSC curves are presented in Figure S23. The degradation enthalpy of HCl-CNC was 337 J/g, which is higher than that of **1** 60 min and **2**. Consequently, the chemical treatments result in a more instable structure causing a reduction of inner hydrogen bondings and the degree of crystallinity.

Table S14 shows the characteristic temperatures, mass changes and the degradation enthalpies of the modified samples in comparison to the starting material HCl-CNC.

*Table S14: Characteristic temperatures, mass losses and degradation enthalpies of the samples HCl-CNC (starting material), the tosylated CNCs (**1** 60 min) and the dodecylamine-modified CNCs (**2**).*

sample	transformations	temperature at maximum mass loss per min [°C]	onset temperature [°C]	mass loss [%]	Yield at 700°C [%]	degradation enthalpy [J/g]
1 60 min	1 (main)	202	180	37	-	106
	2	290	-	23	-	-
	3	486	-	11	-	-
	-	700	-	-	28	-
2	1 (main)	290	269	62	-	223
	2	400	-	15	-	-
	-	700	-		20	-
HCl-CNC	1 (main)	352	328	93	-	337
	-	700	-	-	4	-

3 Author contribution

The authors (in brackets) have contributed to the following tasks, in order of contribution: data acquisition (DL, NA), data analysis (DL, NA, SK, MAK), drafting (all equal), funding acquisition (DL, SK, MAK).

4 Bibliography

1 T. Pääkkönen, P. Spiliopoulos, A. Knuts, K. Nieminen, L.-S. Johansson, E. Enqvist and E. Kontturi, *React. Chem. Eng.*, 2018, **3**, 312–318.
2 M. Marx-Figini, *Angew. Makromol. Chem.*, 1978, **72**, 161–171.
3 E. Kontturi, A. Meriluoto, P. A. Penttilä, N. Baccile, J. Malho, A. Potthast, T. Rosenau, J. Ruokolainen, R. Serimaa, J. Laine and H. Sixta, *Angew. Chem. Int. Ed.*, 2016, **55**, 14455–14458.
4 S. Elazzouzi-Hafraoui, Y. Nishiyama, J.-L. Putaux, L. Heux, F. Dubreuil and C. Rochas, *Biomacromolecules*, 2008, **9**, 57–65.
5 R. Salminen, N. Baccile, M. Reza and E. Kontturi, *Biomacromolecules*, 2017, **18**, 1975–1982.
6 K. Heise, T. Koso, L. Pitkänen, A. Potthast, A. W. T. King, M. A. Kostiainen and E. Kontturi, *ACS Macro Lett.*, 2019, **8**, 1642–1647.
7 S. Beck, J. Bouchard and R. Berry, *Biomacromolecules*, 2012, **13**, 1486–1494.
8 M. Labet and W. Thielemans, *Cellulose*, 2011, **18**, 607–617.
9 A. W. T. King, V. Mäkelä, S. A. Kedzior, T. Laaksonen, G. J. Partl, S. Heikkinen, H. Koskela, H. A. Heikkinen, A. J. Holding, E. D. Cranston and I. Kilpeläinen, *Biomacromolecules*, 2018, **19**, 2708–2720.
10 L. Fliri, K. Heise, T. Koso, A. R. Todorov, D. R. Del Cerro, S. Hietala, J. Fiskari, I. Kilpeläinen, M. Hummel and A. W. T. King, *Nat. Protoc*, 2023, **18**, 2084–2123.
11 L. Segal, J. J. Creely, A. E. Martin and C. M. Conrad, *Textile Research Journal*, 1959, **29**, 786–794.
12 K. S. Salem, N. K. Kasera, Md. A. Rahman, H. Jameel, Y. Habibi, S. J. Eichhorn, A. D. French, L. Pal and L. A. Lucia, *Chem. Soc. Rev.*, 2023, **52**, 6417–6446.
13 P. Ahvenainen, I. Kontro and K. Svedström, *Cellulose*, 2016, **23**, 1073–1086.

14 J. Meija, M. Bushell, M. Couillard, S. Beck, J. Bonevich, K. Cui, J. Foster, J. Will, D. Fox, W. Cho, M. Heidelmann, B. C. Park, Y. C. Park, L. Ren, L. Xu, A. B. Stefaniak, A. K. Knepp, R. Theissmann, H. Purwin, Z. Wang, N. De Val and L. J. Johnston, *Anal. Chem.*, 2020, **92**, 13434–13442.
15 N. Lin and A. Dufresne, *Nanoscale*, 2014, **6**, 5384–5393.
16 L. Jasmani, S. Eyley, R. Wallbridge and W. Thielemans, *Nanoscale*, 2013, **5**, 10207.
17 H. Kono, H. Hashimoto and Y. Shimizu, *Carbohydr. Polym.*, 2015, **118**, 91–100.
18 T. Koso, M. Beaumont, B. L. Tardy, D. Rico Del Cerro, S. Eyley, W. Thielemans, O. J. Rojas, I. Kilpeläinen and A. W. T. King, *Green Chem.*, 2022, **24**, 5604–5613.
19 M. Kröger, O. Badara, T. Pääkkönen, I. Schlapp-Hackl, S. Hietala and E. Kontturi, *Biomacromolecules*, 2023, **24**, 1318–1328.