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Ring-opening metathesis polymerization of biomass-derived levoglucosenol

Tapas Debsharma, Felix N. Behrendt, André Laschewsky, Helmut Schlaad*

Abstract: The readily available cellulose-derived bicyclic levoglucosenol was polymerized via ring-opening metathesis polymerization (ROMP) to yield polylevoglucosenol as a novel type of bio-based thermoplastic polyacetal, which contains–unlike polysaccharides–cyclic as well as linear segments in its main-chain. High molar mass polyacetals with apparent weight-average molar masses of up to 100 kg mol⁻¹ and dispersities of ~2 were produced despite the nonliving/controlled character of the polymerization due to irreversible deactivation or termination of the catalyst/active chain ends. The resulting highly functionalized polyacetals are glassy in bulk with a glass transition temperature of ~100 °C. In analogy to polysaccharides, polylevoglucosenol degrades slowly in acidic environment.

Fossil-based resources have been exploited commercially since the industrial revolution. However, fossil resources are not infinite on earth and exploitation will come gradually to a halt. Moreover, fossil-based resources are recognized to cause all kinds of pollution, whether it is global warming or plastic contamination of aquatic wildlife. Hence, the move towards renewable feedstocks and environmentally degradable systems, preferentially by valorization of biomass waste, presents a major challenge for chemistry, in particular for the production of thermoplastic and degradable polymers.^[1]

Cellulose is one of the most abundant products of biomass and therefore an attractive renewable feedstock for the production of value-added chemicals such as sugars, lactic acid, levulinic acid, furans, etc.^[2] Another special chemical that can be readily obtained from cellulose is 1,6-anhydro-3,4-dideoxy- Δ^3 - β -D-pyranosen-2-one (IUPAC name: (1*S*,5*R*)-6,8-dioxabicyclo[3.2.1]oct-2-en-4-one), also known as levoglucosenone.^[3] Levoglucosenone is a bridged heterocyclic vinyl ketone, which is used as a building block in organic synthesis but is reluctant toward polymerization. However, the simple reduction of the ketone functionality yields the alcohol levoglucosenol,^[4] which we found to be a suitable monomer for the ring-opening metathesis polymerization (ROMP)^[5] using a derivative of the 2nd generation Grubbs catalyst. To the best of our knowledge, this is the first example of a

 T. Debsharma, Dr. F. N. Behrendt, Prof. Dr. A. Laschewsky, Prof. Dr. H. Schlaad Institute of Chemistry, University of Potsdam Karl-Liebknecht-Straße 24-25, Potsdam 14476, Germany E-mail: schlaad@uni-potsdam.de Prof. Dr. A. Laschewsky Fraunhofer Institute of Applied Polymer Research IAP Geiselbergstraße 69, 14476 Potsdam, Germany Supporting information: Experimental details and synthetic procedures.

Supporting information: Experimental details and synthetic procedures. ESI-MS and NMR data of compounds 1 and 2 (¹H and ¹³C NMR), 3 (ESI-MS and ¹H, ¹³C, HSQC, HMBC, NOESY, COSY NMR), and 4 (¹H, ¹³C, and HSQC NMR). DSC/TGA curves and SEC traces of polymer 3 (Table 1). ¹H NMR spectra and SEC traces recorded during kinetic investigation and SEC traces for equilibration and degradation experiments. successful metathesis polymerization of a purely sugar-derived monomer. Sugar-related systems described so far include natural macrocyclic glycolipids, which are polymerized via the unsaturated fatty acid part,^[6] or saccharides attached to a norbornene or 7-oxanorbornene scaffold.^[7] Also, a structurally related carbohydrate lactone derived from gluconolactone was polymerized by ROP using a tin-based catalyst to yield low molar mass polyesters.^[8]

Pure levoglucosenone 1 (which is also commercially available, see SI) was readily obtained from the acid-catalyzed pyrolysis of cellulose (Scheme 1).¹ The attempts of free-radical or anionic polymerization of 1 with azobisisobutyronitrile (AIBN) or sec-butyl lithium (sBuLi) as initiators, respectively, were not successful, producing low molar mass, oligomeric materials only (data not shown). Also, despite its strained bicyclic ring structure, 1 did not undergo a ring-opening olefin metathesis polymerization, possibly due to the interference of the keto moiety in proximity to olefin.^[9] We, therefore, decided to eliminate the keto group in levoglucosenone by quantitative reduction, hoping that the resulting bicyclic allylic alcohol levoglucosenol 2 could be polymerized by ROMP to yield the polyacetal 3 (Scheme 1).[10] Levoglucosenol 2 was readily obtained by reduction of 1 with sodium borohydride in water,[4] followed by extraction with ethyl acetate, and purification of the concentrate by sublimation. The isolated product 2 was a mixture of two diastereomeric alcohols, the major isomer (\geq 95%) being the 1,6-anhydro-3,4-dideoxy- β -Dthreo-hexopyranose (see SI).



Scheme 1. Synthesis of levoglucosenone 1 by pyrolysis of cellulose and subsequent reduction to levoglucosenol **2.** Production of polyacetal **3** by ring-opening metathesis polymerization of **2.** Reagents and conditions: (a) 1% H₃PO₄, 300 °C, Kugelrohr oven, (b) NaBH₄, H₂O, r.t., (c) **C6**, 1,4-dioxane, r.t.

First attempts to polymerize **2** involved the use of 1st, 2nd, and 3rd generation Grubbs catalysts (Figure 1, **C1-C3**) as well as 1st and 2nd generation Hoveyda-Grubbs catalysts (**C4-C5**), all of which failed (as did the attempted free-radical polymerization initiated by AIBN). However, the polymerization turned out to be successful with the mono-*ortho*-substituted *N*-heterocarbene (NHC) derivative of the 2nd generation Grubbs catalyst **C6**, which is known as a highly efficient catalyst for the ring closing metathesis (RCM) of bulky tetrasubstituted olefins.^[11] Metathesis polymerizations were performed in 1,4-dioxane solution at room temperature (Table 1). Monomer conversion (x_p) reached 50-60% (by ¹H NMR spectroscopy) within 24 h, and, depending on the catalyst loading ([**2**]₀ = 4M, [**2**]₀/[**C6**] = 66-1000), the polymers exhibited apparent weight average molar masses (M_w^{app}) in the range of 29 to 100 kg·mol⁻¹ and dispersities (*Đ*) of 1.8-2.9 (by size

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exclusion chromatography (SEC) with polystyrene calibration). The polymer **3** was found to be soluble in 1,4-dioxane, *N*,*N*-dimethylformamide (DMF), *N*-methyl-2-pyrrolidone (NMP), dimethylsulfoxide (DMSO), or sulfolane but insoluble in dichloromethane (DCM), tetrahydrofuran (THF), toluene, dimethyl-carbonate, alcohols, or water. The glass transition temperature (T_g) of **3**, as determined by differential scanning calorimetry (DSC), is ~100 °C, and the polymer is thermally stable up to ~220 °C (by thermogravimetric analysis (TGA), see SI).



Figure 1. Screened Ru-based catalysts C1-C6 (Ph = phenyl) for ring-opening metathesis polymerization of levoglucosenol 2

Table 1. Polymerization of 2 ([2]_0 = 4M) with catalyst C6 in 1,4-dioxane solution at room temperature for 24 h.

Entry	[2] ₀ /[C6]	x _p ª (%)	<i>M</i> w ^{app b} (kg·mol⁻¹)	а	<i>T</i> _g ^d (°C)
1	66	60	29	1.8	100
2	100	59	37	2.0	100
3	200	59	47	2.2	92
4	1000	50	100	2.9	98

^aMonomer conversion, determined by ¹H NMR spectroscopy. ^bApparent weightaverage molar mass, determined by SEC. ^cDispersity index, determined by SEC. ^dGlass transition temperature, determined by DSC.

The molecular structure of polymer **3** was resolved via ESI-MS and NMR techniques (see SI). Mass spectrometric analysis revealed a molar mass of the repeating unit of 128 Da, which is in agreement with the expected structure of **3** shown in Scheme 1. All proton and carbon signals in ¹H and ¹³C NMR spectra (Figure 2 and 3, respectively) were assigned to the polyacetal **3** with the help of various 2D NMR experiments (see SI). It is important to note that the three stereocenters of monomer **2** (at carbons C1, C2, and C5; cf. Scheme 1 and Figure 2) were preserved during metathesis polymerization (**3** (entry 2): $[\alpha]_p = -35^\circ$; 1,4-dioxane).

Still, the ¹H NMR spectrum (Figure 2) showed in total 8 different types of protons and, interestingly, two multiplet peaks of the same intensity ratio (~0.5 H) at 5.13-5.16 ppm and 5.27-5.31 ppm. These disappeared upon the addition of D₂O (see SI), suggesting that these two signals arise from the hydroxyl protons. This peak assignment was confirmed with HMBC and HSQC measurements (see SI). The appearance of the hydroxyl protons in two regions as two sets of multiplets indicates the existence of different isomeric structures in the polymer chain. Also, the ¹³C NMR spectrum (Figure 3) revealed four distinct peaks of the characteristic acetal carbon (C1) at ~106 ppm, which corresponds to four isomeric configurations.

The occurrence of different isomers can be well expected because **2** is an asymmetric (chiral) monomer, which can add to the growing chain in different orientations (sequences), in addition to the *cis-trans* isomerism (*cis/trans* ratio not determined) at the main-chain double bond. Since the NMR spectrum of the hydrogenated polymer **3** (obtained by the reaction with H₂/Pd-C with 98% conversion of double bonds to alkane \rightarrow polymer **4**) still showed two signals for OH (¹H) and four signals for C1 (¹³C) (see SI), the multiplicity of signals does not originate from *cis/trans* but from sequence isomers, *i.e.*, head-to-tail, head-to-head, and tail-to-tail.



Figure 2. ¹H NMR (500 MHz) spectrum of polyacetal 3 (entry 2) in DMSO-d₈; δ 5.90–5.79 (m, 1H), 5.79–5.65 (m, 1H), 5.37–5.10 (m, 1H), 4.78–4.64 (m, 1H), 4.58–4.42 (m, 1H), 4.05–3.87 (m, 2H), 3.54–3.42 (m, 1H).



Figure 3. 13 C NMR (150 MHz) spectrum of polyacetal 3 (entry 2) in DMSO-d₆; δ 132.7, 131.1, 129.9, 128.5, 105.7, 76.4, 71.5, 69.2.

We moved on with a kinetic investigation of the polymerization and optimization of reaction conditions. As mentioned above, the monomer conversion just reached 50-60% (Table 1) (note: unreacted monomer **2** could be recovered almost quantitatively in pure form by sublimation, see SI), which is indicative of termination reactions and hence a non-living character of the polymerization. Indeed, the pseudo-first-order time-conversion plot (Figure 4a) for the polymerization of **2** with **C6** at room temperature is not linear but could be fitted with a model of unimolecular termination (see equation in Figure 4a). Furthermore, the evolution of the polymer molar mass (M_w^{app} , SEC) with monomer conversion (x_p , ¹H NMR spectroscopy, see SI) deviates strongly from linearity (Figure 4b), and molar masses are much higher than calculated from the monomer-to-catalyst ratio. High molar mass polymers were formed in the early stage of the reaction, *i.e.*, $x_p < 20\%$, and the chains grew shorter with increasing depletion of monomer, as it is typically observed for non-living processes.^[12] Compliantly, the resulting polymer **3** exhibits a Schulz-Flory type molar mass distribution with a dispersity of $\mathcal{D} \sim 2$ (Table 1 and Figure 4c).

Such kinetic behavior suggests that the rate of initiation is much slower as compared to the monomer addition (propagation) step, and active chains are continuously produced and grow very quickly until they undergo irreversible termination or deactivation. Indeed, the deactivation of catalyst or active chain ends could be observed with the naked eye by the occurrence of blackening of the reaction mixture. Further, with ongoing reaction time, the catalyst gives rise to chain length equilibration, *e.g.*, via backbiting, thus contributing to the reduction of polymer molar mass (see equilibration experiment in SI).



Figure 4. Polymerization of **2** with catalyst **C6** ([**2**]₀ = 4M, [**2**]₀/[**C6**] = 100) in 1,4dioxane at room temperature: (a) pseudo-first-order time-conversion plot, (b) evolution of weight-average molar mass (M_w^{app}) with conversion (x_p) ($M_w^{heor} = 2(D)$ [**2**]₀/[**C6**] x_p), (c) SEC-RI trace (eluent: NMP) of polymer **3** obtained at 24 h after precipitation into DCM, and (d) photograph of polymer **3** isolated as a thin film.

We further tried to optimize the reaction conditions in order to maximize the monomer conversion and polymer molar mass; results are summarized in Table 2. Best results were obtained at [**2**]₀ = 2-4 M at a temperature of 0-5 °C (temperature window is limited by the freezing of the solution): $x_p = 62-74\%$, $M_w^{app} = 87-104$ kg·mol⁻¹ (entries 8 and 12 in Table 2). As before, the apparent polymer molar masses were much higher than expected for a living polymerzation mechanism ($M_w^{\text{theor}} = 25.6$ kg·mol⁻¹ at 100% conversion). However, both monomer conversions and molar masses decreased drastically when the polymerizations were conducted at higher temperature (> 40 °C) or dilution (1 M). Table 2. Polymerization of 2 with catalyst C6 ($[2]_0/[C6] = 100$) in 1,4-dioxane solution at different monomer concentrations ($[2]_0$) and reaction temperatures ($[1 \text{ for } 24 \text{ p}^2]$

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Entry	[2] ₀	Т	Xp ^b	Appearance	M _w ^{app c}	Ð ď
		(°C)	(%)		(kg·mol⁻¹)	
5	4 M	90	12	Liquid	2.3	1.6
6	4 M	60	33	Liquid	18	1.7
7	4 M	40	49	Liquid	33	1.9
2	4 M	28	59	Liquid→Gel ^e	37	2.0
8	4 M	0	62	Liquid→Gel ^e	87	2.2
9	2 M	60	2	Liquid	_f	_f
10	2 M	40	16	Liquid	8.8	1.9
11	2 M	28	28	Liquid	13	2.3
12	2 M	5	74	Liquid→Gel ^e	104	2.0
13	1 M	10	13	Liquid	13	1.7

^aAll reactions were repeated at least once and results were consistent within experimental errors. ^bMonomer conversion, determined by ¹H NMR spectroscopy (see SI). ^cApparent weight-average molar mass, determined by SEC. ^dDispersity index, determined by SEC. ^eReaction solutions were initially liquid but slowly turned into a gel (gel liquefied upon dilution with 1,4-dioxane). ^rNot determined.

An interesting property of the polyacetal **3** is its amorphous character and high glass transition temperature ($T_g \sim 100$ °C, see Table 1), despite of the double bonds and stereocenters in the main-chain. Hence it might serve as a thermoplastic polymer^[10] and for the fabrication of transparent polymer films (see Figure 4d). Also, it contains functionalizable hydroxyl and olefin groups and degradable acetal units in the main-chain. A high molar mass polymer **3** was found to degrade completely in 1,4-dioxane solution at room temperature in the presence of *p*-toluenesulfonic acid/water within about 40 days (see SI).

In summary, we introduced levoglucosenol, which is an olefinic derivative of a bicyclic carbohydrate, as a novel sustainable monomer for producing thermoplastic polyacetals by ROMP. The use of a derivative of 2nd generation Grubbs catalyst (C6) yielded high molar mass polymers, the structure of which was characterized in detail by MS and NMR techniques, as well as by SEC and DSC. The polylevoglucosenol exhibited a surprisingly high glass transition temperature of ~100 °C, which might be explained by the combined stiffening effects of the dioxolane ring in the main chain and hydrogen-bonding interactions of the alcohol moieties. The polymerization does not show living characteristics with respect to control over polymer molar masses and their distributions, which is likely due to slow initiation, chain equilibration, and limited stability of the used catalyst. Ongoing research is devoted to the further optimization of catalyst design and polymerization conditions, for instance by variable temperature protocols,[13] aiming at implementing living/controlled ROMP of levoglucosenol and derivatives thereof, and exploring the post-polymerization modification potential of the new polymer class.

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Entry for the Table of Contents

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Ring-opening metathesis Tapas Debsharma, Felix N. polymerization (ROMP) of Behrendt, André Laschewsky, ROMP Cellulose levoglucosenol, which Helmut Schlaad* derives from a pyrolysis Page No. – Page No. product of cellulose, Polylevoglucosenol yields a fully sustainable, $M_{\rm w}$ up to ~100 kg/mol, $T_{\rm g}$ ~ 100 °C **Ring-opening metathesis** high molar mass polymerization of biomassthermoplastic polyacetal. derived levoglucosenol

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