Synthesis of new Biginelli polycondensates: renewable materials with tunable high glass transition temperatures

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Abstract

The Biginelli reaction was applied as a simple one-pot multicomponent polycondensation approach to efficiently synthesize a set of 15 new and fully renewable poly(3,4-dihydropyrimidin-2(1H)-one)s. One of six bis-acetoacetates or three bis-acetoacetamides, terephthalic aldehyde and (methyl-)urea were used as renewable starting materials in various combinations, hence significantly expanding the known set of monomers as well as polymer structures. The bis-acetoacetates and bis-acetoacetamides with different spacer lengths were synthesized in yields of up to 99% in a one-step process. Thermal analysis of the obtained set of polymers revealed high glass transition temperatures (T_g) ranging from 160 to 308 °C. The T_g was tunable in small steps of 10 °C by simple variation of bis-acetoacetate or bis-acetoacetamide monomers as well as the choice of (methyl-)urea. The poly(3,4-dihydropyrimidin-2(1H)-one)s showed good thermal stability with T_d5% values well above the respective high T_g values.

Supporting information may be found in the online version of this article.

Keywords: multicomponent reaction; Biginelli reaction; glass transition temperature; renewable resources; polycondensation

INTRODUCTION

Multicomponent reactions (MCRs) are defined as convergent one-pot reactions with high atom economy, in which three or more starting materials efficiently form complex product structures that contain structural elements of each starting material.1,2 One-pot procedures allow the reduction of workup steps, material use and energy consumption. Thus, one-pot MCRs allow shorter overall reaction times, fewer purification steps and generally lead to high overall yields providing a tool for more sustainable chemical processes.1,3,4 In addition, MCRs are a valuable tool for the field of combinatorial chemistry due to their modular character, enabling the quick synthesis of large compound libraries.5,6 Prominent examples are the Strecker amino acid synthesis (1850),7 the Hantzsch dihydropyrimidin synthesis (1881),8 the Biginelli dihydropyrimidinone synthesis (1891),9 the Mannich aminomethylation (1912),10 as well as the isocyanide based Passerini α-acyloxy amide synthesis (1921)11 and the Ugi bis-amide synthesis (1959).2,11

Besides being a valuable tool for target-oriented synthesis12 and diversity oriented synthesis,13 MCRs receive increasing interest from polymer and material scientists.14–16 The properties of a polymer mainly depend on the chemical structure, the sequence of the repeating units and the topology. All three can be controlled via MCRs. More precisely, MCRs allow the synthesis of interesting new monomers for known polymerization techniques, for instance the ring-opening metathesis polymerization of norbornene monomers synthesized via the Ugi four-component reaction,17 and enable the direct polymerization of multifunctional components. This was shown for a Passerini polyaddition of a dicarboxylic acid, a dialdehyde and various isocyanides.18 Moreover, it is possible to readily synthesize new polymers via post-polymerization modification techniques, as shown in the modification of a substituted polymethacrylate copolymer via the Biginelli reaction.19

The Biginelli-3-component reaction (Biginelli-3CR) was first described in 1891 by Pietro Biginelli, who observed the formation of a precipitate during the reaction of benzaldehyde, ethyl acetoacetate and urea in ethanol with catalytic amounts of hydrochloric acid.9 Later, Biginelli identified the precipitate as 3,4-dihydropyrimidin-2(1H)-one (DHPM).20 The Biginelli-3CR and the resulting DHPMs were investigated due to their pharmaceutical activity, e.g. for the treatment of cardiovascular diseases,
benign prostatic hyperplasia or as cancer treatment, prior to becoming an interesting tool for polymer chemists. Different mechanisms for the Biginelli-3CR have been discussed in the literature. The currently accepted mechanism for the formation of DHPMs in solution under Brønsted acid catalysis was published by Kappe in 1997. Accordingly, the reaction starts with a nucleophilic addition of urea compound to aldehyde forming the hemiaminal. Subsequently, acid promoted dehydration leads to a highly reactive N-acyliminium ion, which reacts with the 1,3-dicarbonyl resulting intermediate undergoes cyclocondensation yielding the DHPM (Scheme 1). The rate determining step is considered to be the first addition of and 2. The application of bifunctional molecules like terephthalic acid and bis-acetoacetates leads to the formation of Biginelli polycondensates.

Applying the post-polymerization modification approach, the Biginelli-3CR was used to modify starch. It was additionally used as a tool to build polymer libraries from a polymer precursor with acetoacetate moieties in its backbone, besides the above mentioned synthesis of a water soluble adhesive. The resulting intermediate undergoes cyclocondensation yielding the DHPM (Scheme 1). The rate determining step is considered to be the first addition of and 2. The application of bifunctional molecules like terephthalic acid and bis-acetoacetates leads to the formation of Biginelli polycondensates.

Applying the post-polymerization modification approach, the Biginelli-3CR was used to modify starch. It was additionally used as a tool to build polymer libraries from a polymer precursor with acetoacetate moieties in its backbone, besides the above mentioned synthesis of a water soluble adhesive. The first Biginelli polycondensates were synthesized by Tao and colleagues using the direct polymerization approach and were applied as adhesives. Later, the same group reported on the synthesis of copolycondensates by a combination of the Biginelli-3CR and the Hantzsch dihydropyridine synthesis and showed three possible post-polymerization modifications of poly(dihydropyrimidinethiones). In addition, they built a library of Biginelli polycondensates to predict the glass transition temperature of polycondensates within the mapped spectrum of compounds. In 2016, Meier et al. reported on the synthesis of renewable Biginelli polycondensates with high and tunable by a variation of the applied dialdehydes and bis-acetoacetates. Herein, we report on the synthesis and comparison of novel renewable poly(DHPM)s (Scheme 2). We introduce (i) methyl-urea and (ii) three bis-acetoacetamides as well as (iii) three bis-acetoacetamides to the set of starting materials described in the literature so far. This set includes (thio-)urea, terephthalic aldehyde, divanillin and bis-acetoacetates besides several AB- monomers containing aldehyde and acetate moieties in different combinations. The resulting polymers are fully characterized and show very high, tunable Tg of up to 308 °C. Importantly, all starting materials can be derived from renewable resources.

**MATERIALS AND METHODS**

**Materials**

1,4-Butanediol (99%), 1,10-decanediamine (97%), 1,10-decanediol (98%), 1,2-ethylenediamine (99%), 1,6-hexanediol (≥99.0%), methyl-urea (97%), potassium trifluoroacetate (98%), 1,3-propanediol (98%), terephthalic aldehyde (99%) and 2,2,6-trimethyl-4H-1,3-dioxin-4-one (95%), diketene acetone adduct were supplied by Sigma (Munich, Germany). Dimethyl sulfoxide (99.7%), 1,6-hexanediol (97%), p-toluenesulfonic acid (99%) and tert-buty lacetate (97%) were supplied by Acros Organics (Geel, Belgium). Ethylene glycol (≥99.5%) was bought from Honeywell Riedel-de Haën (Charlotte, North Carolina, USA). 1,1,1,3,3,3-Hexafluorisopropanol (HFIP) was purchased from Fluorochem (Hadhfield, United Kingdom). Urea and the solvents cyclohexane, ethyl acetate and methanol were used in technical grade without further purification.

**General methods and instrumentation**

**Thin layer chromatography (TLC)**

Fluorescent silica coated aluminium plates were used for TLC. The plates were developed using either a UV lamp to quench fluorescence at 254 nm or to excite fluorescence of the compounds at 365 nm, or Seebach stain (phosphomolybdic acid, cerium(IV) sulfate, sulfuric acid, water) to visualize UV-inactive compounds. The Rf values and used solvent mixtures are given in the respective synthesis procedure of each compound.

**Flash column chromatography**

Flash column chromatography was performed using a method similar to the method introduced by Still et al. The glass column with built in fritted glass filter was filled with a slurry of eluent (the eluent is given in the respective synthesis procedure of each compound) and stationary phase (silica, Aldrich, technical grade, 60 Å pore size, 230–400 mesh size, 40–63 μm particle size). The crude substance was applied in a liquid state dissolved in a small amount of eluent. The pressure was applied with a manual pump.

**Nuclear magnetic resonance (NMR) spectroscopy**

1H and 13C NMR spectra were recorded on a Bruker Avance NEO spectrometer at a frequency of 400.13 MHz and 100.62 MHz, respectively. For sample preparation, 10–15 mg of substance were dissolved in approximately 0.50 mL deuterated dimethyl sulfoxide (DMSO-d6) (99.80 at% D) in an NMR tube with a diameter of 5 mm. The chemical shift (δ) was given in parts per million (ppm) relative to δ of tetramethylsilane (δ(TMS) = 0.00 ppm).

The chemical shifts of DMSO-δ6 were used for referencing: 1H NMR 2.50 ppm; 13C NMR 39.52 ppm. Splitting patterns were denoted as follows: s (singlet), d (doublet), dd (doublet of doublets), t (triplet), q (quartet), p (pentet), m (multiplet) and br (broad). The respective coupling constants in hertz (Hz).

**Infrared (IR) spectroscopy**

IR spectra were recorded on a Bruker Alpha FTIR spectrometer equipped with platinum ATR technology. The resulting transmittance spectra were averaged from 24 measurements. The energies of the IR bands were given in cm⁻¹.
High resolution mass spectrometry (HRMS)

High resolution mass spectra were recorded on a Finnigan MAT 95 spectrometer using electron ionization.

Vacuum oven

Polymer samples were dried in a ThermoScientific™ Vacutherm VT6025 S vacuum drying oven at 100 °C under vacuum prior to analysis.

Size exclusion chromatography (SEC)

SEC was performed on a Tosoh EcoSEC HLC-8320 SEC system. For sample preparation, 2 mg of sample were dissolved in 2 mL hexafluoroisopropanol with 0.1wt% potassium trifluoroacetate. The same solvent mixture was used as mobile phase. The solvent flow was 0.40 mL min⁻¹ at 35 °C. The analysis was performed on a three-column system: PSS PFG Micro precolumn (3.0 × 0.46 cm, 10 000 Å), PSS PFG Micro (25.0 × 0.46 cm, 1000 Å) and PSS PFG Micro (25.0 × 0.46 cm, 100 Å). The system was calibrated with linear poly(methyl methacrylate) standards (PSS, M_p 102–981 kDa).

DSC experiments were performed on a DSC821e (Mettler Toledo) calorimeter. Samples were prepared by compressing 15–20 mg of sample in a 100 μL aluminium crucible. The measurements were performed under a nitrogen atmosphere with two heating cycles in the temperature range −50 to 300 °C (or −50 to 350 °C) with a cooling rate of 15 K min⁻¹ and a heating rate of 30 K min⁻¹. For the calculation of the thermal transitions, the second heating cycle was used. The T_g were determined using the inflection points of the respective second-order transitions.

Thermogravimetric analysis (TGA)

The TGA was performed on a Netzsch STA 490C with Al_2O_3 as the crucible material and reference sample. The samples of 10–20 mg were heated from room temperature to 500 °C with a temperature gradient of 5 K min⁻¹ under synthetic air flow. The temperature at which a weight loss of 5% is reached (T_d5%) was determined via intersection of the TGA curve with a line at y = 0.95 − a, where a is the weight loss at 105 °C (to exclude the weight loss due to water evaporation).

Bis-acetoacetate and bis-acetoamide synthesis

Bis-acetoacetates

All bis-acetoacetates were synthesized using the following general procedure. The respective diol (1.00 eq) was mixed with tert-butylacetocetate (t-BuAA) (5.00 eq) and stirred in a preheated oil bath at 150 °C for 7 h. Evolving tert-butyl alcohol (t-BuOH) was continuously removed via distillation. Afterwards, the crude product was purified by column chromatography using a gradual mixture of c-C_6H_12 and EtOAc. The formed t-BuOH as well as the excess of t-BuAA were recovered via distillation and column chromatography, respectively.

Detailed information on the synthesis, purification and analytical data of all bis-acetoacetates is available in the Supporting information.
Bis-acetoacetamides
All bis-acetoacetamides were synthesized using the same general procedure. The respective diamine (1.00 eq) was added dropwise to preheated (130 °C) 2,2,6-trimethyl-4H-1,3-dioxin-4-one (2.10 eq) under vigorous stirring. Afterwards, the mixture was stirred at 130 °C for 5 h. Subsequently, the mixture was cooled to 100 °C and ethanol was directly added to the hot mixture in order to recrystallize the crude product. The resulting white/off-white crystals were filtered, washed with cold ethanol and dried under high vacuum (<10⁻² mbar).

Detailed information on the synthesis and analytical data of all bis-acetoacetamides is available in the Supporting information.

Polymer synthesis
General procedure for poly(DHPMs)
All poly(DHPMs) were synthesized according to the same general procedure. Nevertheless, the reaction times and the solvent/solvent mixture that was used for precipitation and washing (depending on the polymer structure (details are given for the respective polymer)) differed.

(Methyl-)urea (3.50 eq) and the respective bis-acetoacetate (or bis-acetoacetamide) (1.00 eq) were mixed in DMSO (1 mol L⁻¹ solution regarding 1.00 eq). Afterwards, terephthalic aldehyde (1.00 eq) and p-toluenesulfonic acid (0.10 eq) were added. The mixture was immediately heated to 125 °C in a preheated oil bath and stirred for 22.5 h (30 min for P2aMe, P2dMe and P2eMe each and 1.5 h for P2e). The flask was left open to allow water to evaporate. Afterwards, the polymer solution was precipitated in 100 mL of the respective solvent/solvent mixture and stirred for 3 h. Subsequently, the precipitated polymer was filtered and washed with the same solvent/solvent mixture. The resulting material was dried in a vacuum drying oven overnight at 85 °C under reduced pressure resulting in the final product.

Detailed information on the synthesis, purification and analytical data of all polymers is available in the Supporting information.

Samples for kinetic investigation via SEC were prepared by precipitating 5 µL of the reaction mixture in water. After decanting and drying in a vacuum oven the samples were dissolved in 2 mL HFIP with 0.1 wt% KCO₂(CF₃).
water to remove (methyl)-urea. The molecular weights and dispersities $D$ of $P1e$ and $P1eMe$ increased over time and reached an $M_n$ of 4.9 kDa ($D = 3.24$) and 8.7 kDa ($D = 2.88$), respectively, when the reaction was stopped after 22.5 h. If 9f was used as bis-acetoacetate, the $M_n$ of $P1f$ and $P1fMe$ developed similarly, while the mass distributions were significantly broader after 22.5 h ($D = 10.1$ and 13.1, respectively). Since sufficiently high molecular weights were obtained under these conditions, the same conditions were chosen for the polycondensations $P1a – P1f$ and $P1aMe – P1fMe$ obtaining similar molecular weights. Some of these molecular weights, and especially the obtained dispersities, are atypical for polycondensation reactions. This will be discussed in the following sections. 

The poly(DHPM)s $P1a – P1f$ or $P1aMe – P1fMe$ were synthesized using stoichiometric amounts of bis-acetoacetates 9a–9f and terphthalic aldehyde, as well as a 1.75-fold excess of (methyl)-urea and 10 mol% of $p$-toluenesulfonic acid as a catalyst in DMSO as solvent. After the reaction, the polymer was precipitated and subsequently dried in a vacuum oven yielding the final polymer in yields up to 86%. The polymers were fully characterized using $^1$H NMR, SEC, DSC, IR and TGA. The $^1$H NMR spectra of poly(DHPM)s $P1a – P1f$ showed the characteristic signals (Fig. 1, top example shows the $^1$H NMR spectrum of $P1d$) of the NHC–C protons at 9.2 ppm, the NH–C at 7.7 ppm, the aromatic protons around 7.2 ppm, the NH–CH–CAr protons at 5.1 ppm and the O=CO–CH$_2$ protons at 3.9 ppm. The signal of the C=CH$_3$ protons was visible at 2.3 ppm. Signals for aliphatic protons were furthermore visible between 1.5 and 1.1 ppm for poly(DHPM)s with aliphatic spacers longer than C$_2$H$_4$. For $P1aMe – P1fMe$ (Fig. 1, bottom example shows the $^1$H NMR spectrum of $P1dMe$), the signal at 9.2 ppm was absent while a new signal for the H$_3$C–NC=C protons at 3.0 ppm was observed. The NHC–C proton was shifted by +0.2 to 7.9 ppm and the C=CH$_2$ protons were shifted by +0.2 to 2.5 ppm. The signals of the aldehyde end-groups are observed at 10.2 ppm and were used to calculate the $M_n$ of the poly(DHPM)s (Table 1). The obtained results indicate a higher degree of polymerization for longer spacer units and methyl-urea, possibly due to better solubility of the respective polymers in the reaction solvent DMSO. $P1b$, $P1d$ and $P1e$ have already been reported$^{34}$ prior to this work. The $^1$H NMR spectra and IR spectra correlate well, while molecular weights were higher by a factor of approximately 2 compared to this work. $T_g$ for $P1b$ and $P1d$ were not observed in these previous reports.$^{34}$

The molecular weight distributions of the poly(DHPM)s were investigated via SEC (Table 1; see also Figs S16 and S24 for chromatograms) using hexafluoroisopropanol with 0.1 wt% KCO$_2$(CF$_3$)$_2$ as eluent. Other eluents were not suitable due to the insolubility of the poly(DHPM)s in water, acetonitrile, methanol, ethanol, dimethyacetamide or tetrahydrofuran. $P1a – P1d$ showed increasing $M_n$,SEC values from 3.80 to 8.30 kDa ($M_n$,$^1$H NMR up to 12.2 kDa) with varying dispersities $D$ from 2.8 to 4.2. Two possible reasons for the increasing $M_n$,SEC for longer spacers were considered in accordance with the NMR results. First, a larger size of the spacer unit resulted in a higher degree of polymerization and thus a larger hydrodynamic volume and consequently a higher $M_n$,SEC. Second, in a material with longer aliphatic spacer units, the frequency of hydrogen bonds throughout the material is lower, which possibly results in less intramolecular hydrogen bonding and thus a larger hydrodynamic volume. The $M_n$,SEC of $P1e$ did not follow this trend, perhaps due to the lower solubility of $P1e$ in hexafluoroisopropanol with 0.1 wt% KCO$_2$(CF$_3$)$_2$. This possibly led to lower hydrodynamic volumes, overcompensating the above explanations for higher $M_n$,SEC values. Low solubility and problems using SEC analysis, especially for higher degrees of polymerization, have already been reported$^{34}$ for poly(DHPM)s and are generally known for polymers with strong hydrogen bonding, such as polyamides or polyureas.

The $M_n$,NMR values of $P1aMe – P1fMe$ obtained by $^1$H NMR end-group analysis show a similar trend with increasing $M_n$,NMR for longer spacer units up to 36.7 kDa, while being considerably higher
Several other renewable polymers with 6-cetate on the thermal properties of the poly(DHPM)s was investigated by the polymer backbone. In addition, if the same bis-acetoacetamides are used for analyzing the molecular weight analysis, it is obvious that the polymerization, while the hydrodynamic volume was dependent on the spacer or the use of methyl-urea seemed to accelerate the polymerization, hence leading to inhomogeneous polymerization mixtures throughout the reaction and therefore to a broadened molecular weight distribution.

The optimized synthesis of P1f and P1fMe led to polymers with a high $M_{\text{N,NMR}}$ of 30.7 and 23.0 kDa, respectively. The $M_{\text{SEC}}$ values were 6.2 and 8.4 kDa with broad dispersities ($\mathcal{D}$ = 8.07, 8.71). Since the reaction mixtures of P1f and P1fMe were very viscous, the stirring was possibly not sufficient, thus leading to inhomogeneous polymerization mixtures throughout the reaction and hence to a broadened molecular weight distribution.

The results discussed are an important indication that the intramolecular hydrogen bonding in poly(DHPM)s, which is more pronounced for P1a–P1e, highly influences the reaction progress and leads to a compact structure in solution. Thus, small hydrodynamic volumes were observed by SEC. To conclude, a longer spacer or the use of methyl-urea seemed to accelerate the polymerization, while the hydrodynamic volume was dependent on the molecular weight rather than the molecular structure. Summarizing the molecular weight analysis, it is obvious that the obtained values must be considered with care, as an accurate analysis is difficult due to the mentioned solubility and aggregation issues. Nonetheless, the results clearly show that sufficiently high molecular weight polycondensates were obtained as confirmed by SEC and NMR.

The influence of the choice of urea/methyl-urea and bis-acetoacetamides on the thermal properties of the poly(DHPM)s was investigated via DSC. Generally, the poly(DHPM)s showed $T_g$ values between 160 and 308 °C (Table 1), as expected from the highly rigid and strongly hydrogen bonding repeating units. Comparing the $T_g$ values, a clear trend was observed: the $T_g$ were lower for polymers with longer spacers. This seems reasonable considering the above assumptions that an increasing spacer length resulted in decreasing hydrogen bond frequency and thus increased flexibility of the polymer backbone. In addition, if the same bis-acetoacetamide was used, the respective $T_g$ was lower for polymers P1aMe–P1fMe compared to P1a–P1e. In line with the above considerations, P1f and P1fMe showed the highest $T_g$ of 308 and 266 °C, respectively, due to the rigid bicyclic structure of isosorbide. Considering all data (Table 1), it was possible to adjust the $T_g$ of the poly(DHPM)s (P1a–P1f and P1aMe–P1fMe) in small steps (<10 °C) within a 150 °C range from 160 to 308 °C by a simple variation of the combination of starting materials.

Table 1. SEC and DSC data for polymers P1a–P1f and P1aMe–P1fMe

| Sample | $R_i$   | $M_{\text{N,NMR}}$ (g mol$^{-1}$) | $M_{\text{SEC}}$ (g mol$^{-1}$) | $M_{\text{n,SEC}}$ (g mol$^{-1}$) | $\mathcal{D}$ | $T_g$ (°C) |
|--------|---------|----------------------------------|----------------------------------|----------------------------------|-------------|------------|
| P1a    | C$_2$H$_4$ | 5500                             | 3800                             | 14 800                            | 3.88        | 280        |
| P1b    | C$_3$H$_6$ | 5700                             | 4900                             | 18 000                            | 3.65        | 255        |
| P1c    | C$_4$H$_8$ | 6100                             | 5600                             | 16 600                            | 2.85        | 239        |
| P1d    | C$_5$H$_{12}$ | 10 100                        | 8300                             | 34 700                            | 4.20        | 220        |
| P1e    | C$_{10}$H$_{20}$ | 12 200                      | 6600                             | 18 200                            | 2.76        | 198        |
| P1f    | Isosorbide | 30 700                           | 6200                             | 50 000                            | 8.07        | 308        |
| P1aMe  | C$_2$H$_4$ | 11 300                           | 10 800                           | 43 000                            | 3.99        | 248        |
| P1bMe  | C$_3$H$_6$ | 24 000                           | 10 500                           | 33 800                            | 3.21        | 222        |
| P1cMe  | C$_4$H$_8$ | 21 400                           | 7600                             | 19 700                            | 2.58        | 211        |
| P1dMe  | C$_5$H$_{12}$ | 31 800                        | 9500                             | 42 800                            | 4.94        | 175        |
| P1eMe  | C$_{10}$H$_{20}$ | 36 800                      | 8700                             | 24 900                            | 2.88        | 159        |
| P1fMe  | Isosorbide | 23 000                           | 8400                             | 73 100                            | 8.71        | 266        |

The $T_g$s of other renewable polymers from various resources are usually below 150 °C. Several other renewable polymers with a higher $T_g$ are known. For example, polyamides with a $T_g$ of 273 °C were obtained using monomers synthesized via [2 + 2]-cycloaddition of 4-aminoacrylic acid. Applying isosorbide and its diastereomers isomannide and isoidide as monomers, different polyesters with a $T_g$ between 180 and 196 °C were obtained, and poly-carbonates with a $T_g$ up to 175 °C were obtained.

TGA revealed that the poly(DHPM)s from bis-acetoacetates have high thermal stability under synthetic air flow. The observed $T_{5\%}$ values were between 264 and 314 °C (Table S11). The $T_{5\%}$ of P1a–P1aMe and P1aMe–P1fMe surpassed the respective $T_g$, indicating a possible thermal processing of these polymers. However, the $T_{5\%}$ of P1f was lower (289 °C) than its $T_g$ at 308 °C.

Poly(DHPM)s using bis-acetoacetamides

The investigation of the polymerization kinetics of P2a and P2aMe (see the Supporting information) revealed that an insoluble gel was formed if the reaction time was longer than approximately 2.5 h for P2e and 0.5 h for P2fMe. The gelation is indicated by a broadening of the molecular weight distribution (shoulder at high molecular weights) prior to gelation (see Figs S32 and S37). As a consequence, the synthesis of P2e was stopped after 1.5 h. The reaction time of P2a and P2d was kept at 22.5 h, since no gelation was observed. The polymerizations P2aMe, P2dMe and P2eMe were stopped after 0.5 h to avoid gelation. Except for the reaction time, the same procedure as for P1a–P1f and P1aMe–P1fMe was applied yielding poly(DHPM)s in yields of up to 67%.

The polymers were fully characterized using $^1$H NMR, SEC, DSC, IR and TGA. P2a, P2d and P1e showed the characteristic signals (Fig. 2, top example shows the $^1$H NMR spectrum of P2d) of the NHC=CH protons at 8.5 ppm, the NHC–C at 7.6 ppm, the O=C (NH)–CH$_2$ at 7.5 ppm, the aromatic protons around 7.2 ppm, the NH–CH–C$_{Ar}$ proton at 5.2 ppm and the O=C(NH)–CH$_2$ protons at 3.1 ppm. The signal of the C=CH–C$_2$H$_2$ protons was observed at 2.0 ppm. Signals for aliphatic protons were furthermore visible between 1.5 and 0.9 ppm for poly(DHPM)s with aliphatic spacers longer than C$_3$H$_6$. For P2aMe, P2dMe and P1eMe (Fig. 2, bottom example shows the $^1$H NMR spectrum of P2dMe), the signal at 8.5 ppm was absent, while a new signal for the H$_2$(N=CH)–C protons at 3.0 ppm was observed, overlapping with the broad O=C (NH)–CH$_2$ signal. The latter was confirmed via phase edited.
heteronuclear single quantum coherence spectroscopy (Fig. S42). The NHC–C proton remained at 7.6 ppm, the O=CNH–CH2 was shifted by +0.3 to 7.8 ppm, the NH–CCH2 proton was shifted −0.1 to 5.1 ppm, and the C=CC3H protons were shifted by +0.2 to 2.2 ppm.

The obtained molecular weights (Mn,SEC) of the resulting polymers were 5.00 kDa (P2a), 12.4 kDa (P2d) and 11.8 kDa (P2e), 6.00 kDa (P2aMe), 5.30 kDa (P2dMe) and 15.2 kDa (P2eMe). D ranged from 2.06 to 5.07 (Table 2). With respect to their Mn,NMR, the poly(DHPM)s from bis-acetoacetamides seemed to show larger hydrodynamic radii compared to the poly(DHPM)s from bis-acetoacetates.

A Tg (Table 2) was observed for P2d (265 °C), P2e (235 °C) and P2eMe (194 °C). Compared to P1d (220 °C), P2e (198 °C) and P2eMe (159 °C), respectively, the Tgs were expectedly higher (35–45 °C higher compared to poly(DHPM)s from bis-acetoacetates) for the polymers that contained an amide moiety due to additional hydrogen bonding. No thermal transition was observed for P2a, P2aMe and P2dMe, although different heating/cooling rates for DSC investigations (range of 5–35 K min⁻¹, respectively) were considered. For P2a it is possible that the Tg is above the Td5% and is therefore not observable. Consequently, the Tgs for bis-acetoacetamide derived poly(DHPM)s can possibly be tuned in a similar manner compared to bis-acetoacetate derived poly(DHPM)s. A TGA showed that the poly(DHPM)s from bis-acetoacetamides have high thermal stability under synthetic air flow. The observed Td5% values were 278–314 °C (Table S11) and thus in a similar range to the poly(DHPM)s from bis-acetoacetates.

CONCLUSION

Herein, we synthesized a set of 15 new poly(DHPM)s via Biginelli polycondensation introducing methyl-urea and several bis-acetoacetate and bis-acetoacetamide monomers as new building blocks. In addition, three literature known poly(DHPM)s, which fit in this series of investigated polymers, were prepared. The Tgs of two of them was analysed for the first time. The monomers can be derived from renewable resources in yields from 43% to 99%.

![Figure 2. 1H NMR spectra of P12d (top) and P2dMe (bottom) showing, as examples, the characteristic signals of poly(DHPM)s from bis-acetoacetamides.](image)

| Sample | R1     | Mn,NMR (g mol⁻¹) | Mn,SEC (g mol⁻¹) | Mn,SEC (g mol⁻¹) | D     | Tg (°C) |
|--------|--------|-----------------|-----------------|-----------------|-------|---------|
| P2a    | C₂H₄   | 9600            | 5000            | 23 400          | 4.71  | —       |
| P2d    | C₆H₁₂  | 5300            | 12 400          | 63 000          | 5.07  | 265     |
| P2e    | C₁₀H₂₀ | 5500            | 11 800          | 40 300          | 3.40  | 235     |
| P2aMe  | C₂H₄   | 2400            | 6000            | 12 400          | 2.06  | —       |
| P2dMe  | C₂H₆   | 3900            | 5300            | 13 000          | 2.47  | —       |
| P2eMe  | C₁₀H₂₀ | 3800            | 15 200          | 71 100          | 4.71  | 194     |

*Not observed.
approximately 10 °C from 160 to 308 °C by exploitation of the established structure–property relations, rendering poly(DHPM)s more sustainable alternatives for high Tg thermoplastics. In addition, the high thermal stability of the poly(DHPM)s potentially allows for thermal processing techniques.

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SUPPORTING INFORMATION
Supporting information may be found in the online version of this article.

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