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Introducing Multicomponent Reactions to Polymer Science: Passerini Reactions of Renewable Monomers

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S *Supporting Information*

ABSTRACT: Combination of the Passerini three component-reaction (3CR) and olefin metathesis led to the formation of poly[1-(alkyl carbamoyl)alkyl alkanoates], a new class of polyesters with amide moieties in their side chain, from renewable resources. Two different approaches were studied and compared to each other. First, monomers were synthesized by the Passerini-3CR and then polymerized via acyclic diene metathesis. Alternatively, bifunctional monomers were synthesized by self-metathesis and then polymerized by Passerini-3CR. Both approaches led to the formation of high-molecular-weight polymers. Moreover, Passerini-3CRs were shown to be a versatile grafting-onto method. The results clearly demonstrate that the Passerini-3CR offers an interesting new access to monomers and polymers and thus broadens the synthetic portfolio of polymer science.

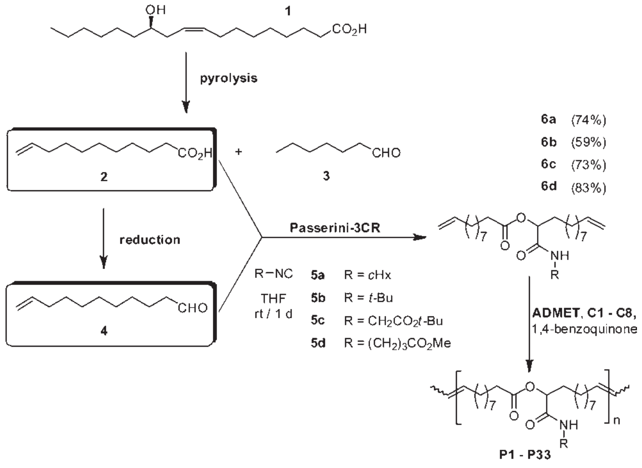

Figure 1. Products of pyrolysis of ricinoleic acid (**1**), their use for Passerini-3CRs to prepare monomers **6a**−**d**, and subsequent ADMET polymerization of these monomers.

Passerini described the first isonitrile-based multicomponent reaction (IMCR) in 1921, in which carboxylic acids and aldehydes undergo an addition reaction with isonitriles to obtain 1-(alkyl carbamoyl)alkyl alkanoates.[1,2] Today, the Passerini three-component reaction (3CR) and the more famous Ugi four-component reaction (4CR) play important roles in combinatorial chemistry, for drug discovery as well as natural product synthesis.[3,4] The use of IMCRs in the syntheses of polymers has been, until now, only described in one example, from 2003 by Wright et al., who performed ring-opening metathesis polymerization (ROMP) with products derived from Ugi-4CR with norbornenyl starting materials.[5] The combination of IMCRs and acyclic diene metathesis (ADMET) polymerization has not yet been described in the literature, and, more importantly, the use of IMCRs for direct polymer synthesis via polycondensation, as described in this Communication, is a completely new approach in polymer science. Thus, in order to investigate a new method for the preparation of a new class of polymers, we studied Passerini-3CRs with **2** and **4** in combination with olefin metathesis. As can be seen from Figure 1, ricinoleic acid (**1**, (9*Z*,12*R*)-12-hydroxyoctadec-9-enoic acid), the major fatty acid of castor oil triglycerides (content up to 95%),[6] is industrially pyrolyzed to yield 10-undecenoic acid (**2**) and heptanal (**3**).[6] **2** was already shown to be of high value for the synthesis of a large variety of polymers from renewable resources.[7] Moreover, **2** is used industrially for the synthesis of polyamide **11**, the only fully renewable polyamide on the market today.[6] To expand the possibilities for application of **2**, we started to investigate the behavior of **2** and its reduced product 10-undecenal (**4**) in IMCRs to yield novel ADMET monomers (Figure 1).

The Passerini-3CRs of **2** and **4** were thus performed with four different isonitriles (**5a**−**d**, Figure 1). After **2** and **4** were stirred with **5a** in a small amount of THF at room temperature for about 1 day, the crude product could be easily purified by recrystallization from hexane. **6a** was obtained as colorless crystals in a yield of 74%. The use of **5b** yielded **6b** as a colorless oil after purification by column chromatography. The commercially available *tert*-butyl isocyanoacetate **5c**, derived from glycine, was also successfully subjected to the Passerini-3CR to yield **6c** in a yield of 73%. Moreover, the Passerini-3CR of **5d** with **2** and **4** led to the formation of **6d** in a yield of 83%. Products **6c**,**d** are especially interesting since they offer further derivatization possibilities due to their ester functional group.

Subsequently, the behavior of the obtained α,ω-unsaturated compounds **6a**−**d** as monomers for ADMET polymerization was investigated. In a screening experiment, eight ruthenium-based olefin metathesis catalysts (see Supporting Information for structures) were tested for the polymerization of **6a** (Figure 1) in order to investigate their functional group tolerance toward this

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Table 1. GPC Results (after Precipitation) of ADMET Polymerizations of Monomers 6a−d with 1% Loading of C3[a]

entry	monomer	M_n, g/mol	PDI (M_w/M_n)
P10	**6a**	21 650	1.35
P28	**6b**	16 500	1.45
P30	**6c**	11 450	1.40
P32	**6d**	17 800	1.44

[a] Conditions: neat/1,4-benzoquinone (3 equiv per Ru catalyst)/80 °C/4 h reaction time/N_2-purged.

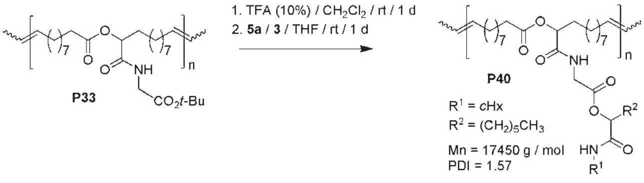

Figure 2. Saponification and subsequent grafting-onto reaction via Passerini-3CR.

novel class of monomers. It is known that double bonds with a high "distance" to functional groups are tolerated during ADMET polymerization.[8] Thus, all catalysts polymerized **6a** quite well at 80, 100, and 120 °C and catalyst amounts of 2.0, 1.0, and 0.5 mol %. **C3**, the Hoveyda−Grubbs second-generation catalyst, gave the highest molecular weights, and **C4**−**C8** also showed high molecular weights (10−19 kDa; see Table 1 of the Supporting Information). Only the Grubbs first-generation catalyst **C1** showed a significantly lower activity in the ADMET polymerization of **6a**. The poly[1-(alkyl carbamoyl)undecyl undecenoates] **P1**−**P27** thus obtained behaved as sticky, rubbery substances, with good solubility in THF, chloroform, and dichloromethane.

Having learned about the polymerization behavior of **6a**, we next polymerized **6b**−**d** with the catalysts **C3** and **C8** (1.0 mol %) at 80 °C, and the results were similar with those for **6a** (Table 1 and Supporting Information). The obtained polymers **P28**−**P33** showed molecular weights between 11 and 18 kDa and polydispersity indexes (PDIs) between 1.4 and 1.5, as determined by gel permeation chromatography (GPC). Identical to the polymers derived from **6a**, **6b**−**6d** were sticky, rubbery substances. Determination of the exact degree of polymerization (DP) by ^{1}H NMR was not possible, since terminal double bonds were not observed, even in high enlargement. Thus, **7** was used as a chain-stopper to produce telechelics with defined end groups. This study clearly showed that the investigated polymers possess significantly higher molecular weights than determined by GPC (see Supporting Information section 1.4.5 and Table 3).

To demonstrate the possibilities of postmodifications, the *tert*-butyl ester of **P33** was hydrolyzed with trifluoroacetic acid (TFA) to obtain the polycarboxylic acid derivative **P39** (Figure 2).

The free carboxylic acid groups of **P39** should undergo additional IMCRs to generate diverse substructures in the side chain of these polymers and thus versatile and adjustable polymer properties. As an example, the Passerini-3CR of **P39** with **5a** and **3** (see Figures 1 and 2) led to the formation of **P40**. In contrast to **P39**, which was insoluble in chloroform, **P40** shows a high solubility in this solvent. Analysis of **P40** via ^{1}H NMR revealed a complete conversion of all carboxyl groups, thus showing that IMCRs can also be used for efficient grafting-onto reactions.

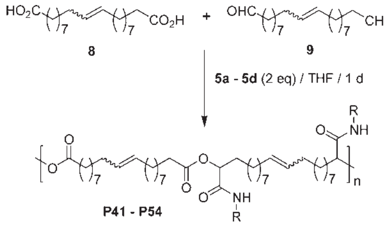

Figure 3. Passerini-3CR with dialdehyde **8**, dicarboxylic acid **9**, and isonitriles **5a,b,d**.

Table 2. Results of Polycondensation of 8 and 9 via Passerini-3CR[a]

entry	isonitrile	THF solvent, mL	M_n, g/mol	PDI (M_w/M_n)
P44	**5a**	2.0	8 000	1.40
P45	**5a**	1.0	29 900	1.53
P46	**5a**	0.5	50 500	1.46
P49	**5a**	0.3	55 550	1.62
P50	**5a**	0.2	56 450	1.42
P51	**5b**	0.5	42 250	1.60

[a] Conditions: 40 °C/1 day reaction time/N_2-purged.

Based on these promising results, the Passerini-3CR was also investigated as a direct polymerization method by studying the self-metathesis products of **2** and **4**, namely **8** (after saponification) and **9** (Figure 3), in polymerizations with **5a** to directly obtain poly[1-(alkyl carbamoyl)undecyl undecenoates] (Figure 3). It should be noted here that the polymer architecture of these polymers is different from that of the polymers obtained from **6a**−**d** via ADMET, since ADMET allows head-to-tail, head-to-head, and tail-to-tail additions, whereas the reaction of **8** and **9** with isonitriles leads to a more regular repeat unit structure. The polymerization experiments showed that reducing the amount of solvent led to the formation of higher molecular weight polymers (up to ∼56 kDa for **P49** and **P50**, Table 2) at reaction temperatures of only 40 °C. Therefore, the poly-Passerini-3CR seems to be a very powerful new approach for polymer synthesis, starting from two bifunctional building blocks, in this case of renewable origin. Increasing the temperature to 50 °C led to polymers with lower molecular weights (**P48**). If dichloromethane was used, dissolution of the starting materials **8** and **9** was incomplete, but high molecular weight could be obtained (**P42**).

In conclusion, IMCRs, in this case Passerini-3CRs, offer manifold new possibilities for polymer chemistry, as demonstrated with the synthesis of monomers and grafting-onto reactions as well as direct polymerizations. Thus, a new class of polyester offering high molecular weights was prepared that should open interesting possibilities for applications due to the amide side chain. It is also important to note that the prepared polymers are mainly of renewable origin and might thus contribute to a sustainable development. In the future, it will be interesting to see if this approach can be generalized to other dicarboxylic acids and dialdehydes in order to achieve a large variety of new polymer properties via this new polymerization approach. Moreover, the variation of the isonitrile component will be an interesting approach to tune the properties of these polymers.

ASSOCIATED CONTENT

Supporting Information. Experimental details, synthesis procedures, and additional results (GPC, NMR, and DSC). This material is available free of charge via the Internet at http://pubs.acs.org.

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