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Poly(phosphonate)-mediated Horner-Wadsworth-Emmons Reactions

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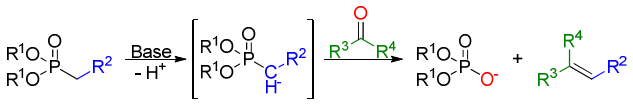
ABSTRACT: A novel, general protocol for a polymer-mediated Horner-Wadsworth-Emmons (HWE) reaction is reported. The polyvalent polymeric reagent was prepared via acyclic diene metathesis (ADMET) polymerization. Homo- and copolymers of reactive poly(phosphonate)s with molecular weights up to 40,000 g·mol^{-1} and molecular weight dispersities $Đ < 2$ were successfully synthesized. Subsequent application of these polymers in the HWE reaction to prepare a library of aromatic α,β-unsaturated ketones (chalcons) has proven to be an efficient

synthetic pathway to minimize purification efforts, as the polymeric side-product can be removed by simple precipitation. In this paper we also demonstrate for the first time the preparation of a linear polyphosphate from a polyalkylphosphonate.

Introduction

The olefination of aldehydes and ketones is one of the most important reactions in organic chemistry. Many different routes have been proposed to introduce carbon-carbon double bonds selectively and with control over the stereochemistry,[1] but mainly the phosphonium-based Wittig[2-4] and the phosphonate-based Horner-synthesis[5, 6] (the latter often referred to as the "Horner-Wadsworth-Emmons" or also -even if not fully correct- the "Wittig-Horner" reaction) have found far-reaching applications in academia and industry.[7-9]

The HWE reaction (Scheme 1) has several advantages over the Wittig reaction, which are a result of the strong nucleophilic nature of the phosphonate carbanion created during the reaction, whereas the phosphonium ylides are known to be less nucleophilic.[6, 10, 11] This increase in nucleophilicity allows milder reaction conditions, tolerating a variety of functional groups during synthesis and the use of less electrophilic aldehydes and ketones. Furthermore, phosphonates are readily available by the well-established and high-yielding Arbuzov reaction.



Scheme 1. General Scheme for the HWE reaction (R^1 = alkyl, phenyl; R^2 = electron withdrawing group; R^3 = alkyl, phenyl, R^4 = H, alkyl).

A major drawback of both the Horner- and the Wittig syntheses remains the purification and workup after the reaction. During the HWE synthesis, typically water-soluble phosphates are produced that can be extracted from the reaction mixture, but column chromatography remains the typical purification technique. Only few polymeric phosphonium and phosphonate reagents have been developed to facilitate purification by filtration of an insoluble, i.e. cross-linked polymer.[12, 13] However, the advantage of insolubility and heterogeneity of the phosphonate during the workup procedure, resulted in low yields and long reaction times compared to the homogenous reaction.[13-15] Moreover, the capacity of the resin is limited by the monomer or the polymer support (vinyl- or norbornyl-derivative, Figure 1). Furthermore, all reported systems carry the reactive phosphonate in the side-chain limiting the possibilities to adjust the polymer properties to special needs, e.g. solubility.

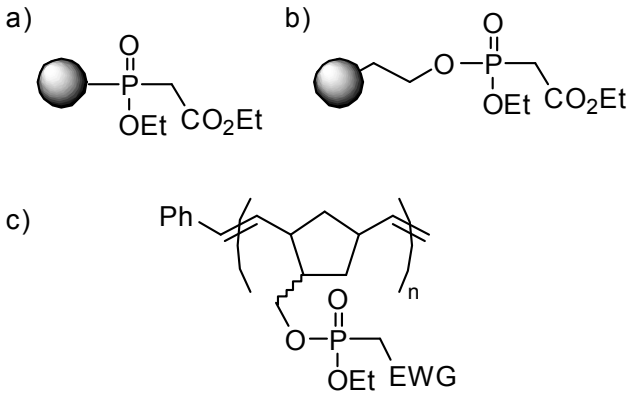


Figure 1. Literature-known heterogeneous, side-chain poly(phosphinate) (a) and -phosphonates (b & c).[13-15] (EWG: electron withdrawing group).

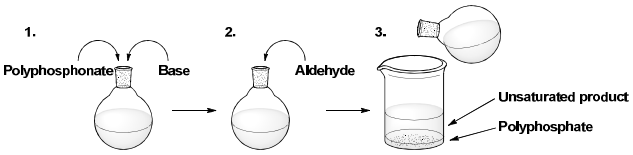
Poly(phosphonate)s, carrying the phosphorus center in the main-chain, are traditionally produced via classical polycondensation of dichlorides or diesters of aryl- or alkylphosphonic acids and diols.[16-20] Several reaction conditions have been reported to prepare polymers for applications in

lubricants, optics, medicine and, most importantly, as flame-retardant additives.[21-26] In order to widen the horizon for future applications in the biomedical field, our group has reported the controlled synthesis of highly water-soluble poly(phosphonate)s via AROP,[27] ring-opening metathesis polymerization (ROMP) and ADMET polymerization. ADMET of acyclic unsaturated phosphonates yields hydrophobic materials that show similar bone-targeting properties as their phosphate counterparts.[27, 28] Nevertheless, the alkyl side-chain in these systems remain untouched and unreactive, which is beneficial for biomedical applications and a controlled degradation behavior.

The introduction of functional side-chains into poly(phosphonate)s is considered to be very limited as the polycondensation techniques developed so far involve the employment of harsh conditions and strong electrophilic reagents, like phosphonic dichlorides. Therefore only a few examples of functional poly(phosphonate)s have been reported so far, carrying a vinyl or a sulfonic acid group.[29] In order to overcome this drawback we have employed ADMET step-growth polymerization, which is conducted in bulk at moderate temperatures between 60°-80°C. Furthermore, metathesis polymerization is known to tolerate a range of different functionalities, including carbonyl and phosphonate compounds.[30-34]

Herein, we have developed a modular, general platform to perform HWE reactions based on linear poly(phosphonate)s prepared via ADMET polymerization.[27] We have realised two approaches to functionalize poly(phosphonate)s for the HWE reaction: postpolymerization modification of a poly(alkylene methylphosphonate)s and polymerization of a prefunctionalized monomers.

In previous work, we have demonstrated the adjustability of different PPEs with respect to hydrophilicity or crystallinity to the individual need.[27, 28, 35-38] Tailoring these properties allowed us to enhance the HWE reaction and its workup procedure in several model reactions. Linear poly(methyl dialkenylphosphonate)s and copolymers containing an adjustable amount (up to 100%) of the HWE-reactive carbonyls have been prepared via ADMET. These polymer were used in various HWE reactions with aromatic aldehydes of different reactivity to produce the corresponding chalcones. The products exhibit a defined stereochemistry together with a reasonable purity after precipitation of the PPE reagent from the homogenous reaction mixture.



Scheme 2. Scheme for the homogeneous polymer-mediated HWE reaction: 1.) Deprotonation of the poly(phosphonate). 2.) Addition of the aldehyde (or ketone). 3.) Precipitation of the poly(phosphate) side-product leaves the pure olefin from the HWE-reaction in the supernatant.

This protocol (Scheme 2) is interesting in academia and industry as it reduces purification efforts for the olefination via the HWE-reaction and produces chalcones in high yield. In addition, this is the first report on the synthesis of linear poly(hydroxyalkylene phosphate)s from poly(alkylalkylene phosphonate)s. In our current and past work on this versatile class of materials we have demonstrated the usability of poly(phosphonate)s in materials science and the biomedical field.[27, 28, 35, 36, 38] With this report we introduce this material into the organic-chemical science and give chemists and researchers an adjustable and versatile tool to improve their synthesis in the lab and industry.

Experimental Section

Materials.

Solvents were purchased from Acros Organics, Sigma Aldrich, or Fluka and used as received, unless otherwise stated.

Dimethylmethylphosphonate (DMMP), thionyl chloride, *N,N*-dimethylformamide (DMF), dichloromethane (DCM), chloroform (TCM), pyridine over molecular sieve and 2-tert-butyl-1,1,3,3-tetramethylguanidine were used as received from Sigma-Aldrich (Germany). 2- and 3-Fluorobenzaldehyde were purchased from TCI Europe. 4-Nitrobenzaldehyde and 4-Fluorobenzaldehyde were used as received from Fluka. 4-Methoxybenzaldehyde (Anisaldehyde) and 4-Pyridinecarboxaldehyde (Isonicotinaldehyde) were used as received from Acros Organics (Germany). Tetrahydrofuran (THF) was purchased from Sigma-Aldrich and distilled from sodium prior to use. Undec-10-en-1-ol was purchased from Apollo Scientific (UK), distilled from CaH_2 prior to use and stored over molecular sieve (4 Å). Grubbs catalyst first generation was purchased from Sigma-Aldrich and stored under argon. Deuterated solvents were purchased from Deutero GmbH (Kastellaun, Germany) and used as received.

Instrumentation and Characterization Techniques.

Size exclusion chromatography (SEC) in chloroform or tetrahydrofuran was performed on an instrument consisting of a Waters 717 plus auto sampler, a TSP Spectra Series P 100 pump and a set of three PSS SDV columns (10^4/500/50 Å). Signal detection occurred by a UV (TSP Spectra System UV 2000, 254 nm), and a refractive index (Agilent 1260) detector. Calibration was carried out using poly(styrene) standards provided by Polymer Standards Service.

^{1}H, $^{13}C\{H\}$, ^{19}F and $^{31}P\{H\}$ NMR spectra were acquired on a 300 MHz Bruker system. The temperature was kept at 298.3 K and calibrated with a standard ^{1}H methanol NMR sample using Topspin 3.0 (Bruker). $^{13}C\{H\}$ NMR spectra were referenced internally to solvent signals. $^{31}P\{H\}$ NMR spectra were referenced externally to phosphoric acid. The $^{13}C\{H\}$ NMR (101 MHz) and $^{31}P\{H\}$ NMR (121 MHz) measurements were obtained with a ^{1}H powergate decoupling method using 30° degree flip angle. 2D ($^{1}H^{31}P$ HMBC) were measured on a Bruker Avance III 400 NMR spectrometer The spectra were referenced to the residual proton signals of the deuterated solvent ($CDCl_3$ (^{1}H) = 7.26 ppm; THF-d_8 (^{1}H) = 3.58 ppm). All 1D and 2D spectra were processed with MestReNova 9.0.0-12821.

The DOSY (Diffusion Ordered Spectroscopy) experiments were executed on a Bruker Avance III 400 NMR spectrometer with a 5 mm BBFO $^{1}H/X$ z-gradient probe and a gradient strength of 5.01 G cm^{-1} A^{-1}. The gradient strength was calibrated with the diffusion coefficient of a sample of $^{2}H_2O/^{1}H_2O$ at a defined temperature and compared with the literature.[39, 40] In this work, the gradient strength was 64 steps from 2% to 95%. The diffusion time d_{20} was optimized to 200 ms at a gradient pulse length of 2.5 s. All measurements were done with a relaxation delay of 1.0 s.

Synthetic procedures.

Synthesis of methylphosphonic dichloride (1). The dichloride was synthesized according to literature.[41] Briefly, a mixture of 62.0 g dimethyl methylphosphonate (0.5 mol) and DMF (0.5 mL) is added dropwise to refluxing thionyl chloride (90 mL). Strong gas evolution of methyl chloride and sulfur dioxide indicate the progress of the reaction. After 12 hours the gas evolution declined. To complete the reaction the bath temperature was increased to 120°C. Fractionated

distillation of the raw product yielded the desired dichloride as colorless crystals (49.82 g, yield: 75%, b.p. 71-73°C / 65 mbar). ^{1}H NMR ($SOCl_2$, ppm): δ 2.54 (d, $^{2}J_{PCH}$ = 15 Hz). ^{31}P{H} NMR ($SOCl_2$, ppm): δ 44.9.

Synthesis of di(undec-10-en-1-yl) methylphosphonate (2). Methylphosphonic dichloride (13.29 g, 100 mmol) was dissolved in dry THF (200 mL) and cooled to 0°C. A solution of 3-undec-10-en-1-ol (34.06 g, 200 mmol) and pyridine (15.82 g, 200 mmol) in THF (50 mL) was added dropwise. After complete addition the solution was stirred for 2 hours and stored over night at -28°C to facilitate the precipitation of the pyridinium hydrochloride. The precipitate was removed by filtration and the solvent was removed *in vacuo*. Column chromatography (ethyl acetate : petrol ether 1:2 R_f = 0.35) yielded the desired product (23.96 g, yield: 60%).^{1}H NMR ($CDCl_3$, ppm): δ 5.81 (ddt, J = 16.9, 10.2, 6.7 Hz, 2H, H_2C=C<u>H</u>-), 5.12 – 4.81 (m, 4H, <u>H_2</u>C=CH-), 4.13 – 3.86 (m, 4H, P-O-C<u>H_2</u>), 2.17 – 1.92 (m, 4H, H_2C=CH-C<u>H_2</u>), 1.74 – 1.57 (m, 4H, O-CH_2-C<u>H_2</u>-), 1.46 (d, $^{2}J_{PCH}$ = 17.4 Hz, 3H, P-C<u>H_3</u>), 1.28 (br. s, 24H). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 139.32 (H_2C=<u>C</u>H-), 114.28 (H_2<u>C</u>=CH-), 65.70 (d, J = 6 Hz, P-O-<u>C</u>H_2), 33.94 (=CH-<u>C</u>H_2), 30.68 (d, J = 6 Hz, O-CH_2-<u>C</u>H_2), 29.58, 29.31, 29.24, 29.06, 25.68 (O-CH_2-CH_2-<u>C</u>H_2), 10.14 (d, $^{1}J_{CP}$ = 144 Hz, P-<u>C</u>H_3). ^{31}P{H} NMR ($CDCl_3$, ppm): δ 30.7. ESI MS: 823 ($2MNa^+$).

Synthesis of di(undec-10-en-1-yl) (2-oxo-2-phenylethyl)phosphonate (5). A solution of HMDS (2.7 g, 16.5 mmol, 2.2 eq.) in dry THF was added to cold (-21°C) *n*-Butyllithium in hexane (1,6M) (9.9 mL, 10.5 mmol, 1.4 eq). The reaction mixture was cooled to -78°C and a solution of **2** (3.1 g, 7.5 mmol, 1.0 eq.) and benzoylchloride (1.1 g, 7.8 mmol, 1.1 eq.) in 30 mL dry THF was added dropwise. The cold solution was poured into a mixture of 2n HCl, ice and dichloromethane (DCM). The organic phase was separated and the aqueous phase extracted twice

with DCM. The combined organic layers were dried with magnesium sulfate and the solvent was removed *in vacuo*. The raw product was purified by column chromatography (ethyl acetate : petrol ether 1:2 R_f = 0.32) to obtain **5** (2.2 g, 59%) as a yellow oil. ^{1}H NMR ($CDCl_3$, ppm): δ 8.01 (dt, J = 8, 2 Hz, 2H, aryl), 7.58 (tt, J = 8, 2 Hz, 1H, aryl), 7.47 (tt, J = 8, 2 Hz, 2H, aryl), 5.85 – 5.75 (m, 2H, H_2C=C<u>H</u>-), 5.01 – 4.90 (m, 4H, <u>H_2</u>C=CH-), 4.09 – 4.00 (m, 4H, P-O-C<u>H_2</u>), 3.62 (d, $^2J_{PCH}$ = 24 Hz, 2H, P-C<u>H_2</u>), 2.06 – 2.00 (q, J = 8 Hz, 4H, H_2C=CH-C<u>H_2</u>), 1.61 – 1.56 (qi, J = 8, 4 Hz, 4H, O-CH_2-C<u>H_2</u>-), 1.38 – 1.24 (br. s, 24H). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 192.00 (<u>C</u>=O), 139.30 (H_2C=<u>C</u>H-), 136.66 , 133,73, 129.19, 128.70, 114.27 (H_2<u>C</u>=CH-), 65.74 (d, J = 6.0 Hz, P-O-<u>C</u>H_2), 38.49 (d, $^1J_{CP}$ = 129 Hz, P-<u>C</u>H_2), 33.93 ((=CH-<u>C</u>H_2), 30.54 (O-CH_2-<u>C</u>H_2), 30.48, 29.56, 29.51, 29.23, 29.04, 25.53. (d, $^1J_{CP}$ = 144 Hz, P-<u>C</u>H_3). ^{31}P{H} NMR ($CDCl_3$, ppm): δ 19.9. ν (cm^{-1}) 2924, 2853, 1681, 1640, 1599, 1448, 1256, 1198, 991, 907, 735, 688. ESI MS: 505 (MH^+).

Representative procedure for the acyclic diene metathesis polymerization of 2.[27] Monomer **2** (4.792 g, 12 mmol) was placed in an oven-dried Schlenk tube and Grubbs' first generation catalyst (118 mg, 144 µmol, 1.2 mol%) dissolved in 1 mL chlorobenzene was added under an argon atmosphere with stirring. The catalyst dissolves rapidly in the monomer yielding a purple liquid. Vacuum ($1\cdot10^{-3}$ mbar) was applied to remove the evolving ethylene. The reaction was stirred for 24 h at 60 °C and then colled to room temperture. To increase the molecular weight, Grubbs' first generation catalyst (118 mg, 144 µmol, 1.2 mol%) dissolved in 1 mL chlorobenzene was again added and the reaction continued for another 48 h at 80 °C under vacuum. The reaction was allowed to cool to room temperature and the resulting viscous oil was dissolved in 4 mL dichloromethane. 100 µL ethyl vinyl ether was added to terminate the active chain end. After treatment with activated charcoal and filtration over Celite, the polymer (**Poly(2)d**) was

precipitated from dichloromethane into methanol and finally dried *in vacuo* (2.73 g, yield: 61%). ^{1}H NMR ($CDCl_3$, ppm): δ 5.47 – 5.25 (m, C<u>H</u>=C<u>H</u>), 4.12 – 3.87 (m, C<u>H$_2$</u>-O-P), 2.19 – 1.78 (m, C<u>H$_2$</u>-CH), 1.74 – 1.54 (m, C<u>H$_2$</u>-CH$_2$-O), 1.45 (d, J = 17.4 Hz, P-CH$_3$), 1.26 (s, backbone). ^{13}C NMR ($CDCl_3$, ppm): δ 130.43 (<u>C</u>H=<u>C</u>H), 129.97 (<u>C</u>H=<u>C</u>H), 65.7 (d, J = 6.1 Hz, <u>C</u>H$_2$-O-P), 32.74, 30.69, 30.63, 29.89, 29.78, 29.75, 29.67, 29.63, 29.56, 29.52, 29.42, 29.32, 29.30, 29.23, 27.34, 25.67, 11.14 (d, $^{1}J_{PC}$ = 145.4 Hz, P-<u>C</u>H$_3$). ^{31}P NMR ($CDCl_3$, ppm): δ 30.6.

Representative procedure for the acyclic diene metathesis copolymerization of 2 and 5. Monomers **2** (298 mg, 745 µmol, 60 mol%) and **5** (247 mg, 490 µmol, 40 mol%) were placed in an oven-dried Schlenk tube and a solution of Grubbs' first generation catalyst (12 mg, 14.8 µmol, 1.2 mol%) in 500 µL chlorobenzene was added under an argon atmosphere with stirring. Vacuum ($1\cdot10^{-3}$ mbar) was applied to remove the evolving ethylene. The reaction was stirred for 24 h at 60°C before another 1.2 mol% Grubbs' first generation catalyst in chlorobenzene was added. Stirring and vacuum was continued for another 48 h at 60°C. The reaction was allowed to cool to room temperature and the resulting solid was dissolved in 1 mL dichloromethane. 100 µL ethyl vinyl ether was added to terminate the active chain end. After treatment with activated charcoal and filtration over Celite, the polymer (**Poly(2-*co*-5)b**) was precipitated from dichloromethane into methanol and finally dried *in vacuo* (261 mg, yield: 51%). ^{1}H NMR ($CDCl_3$, ppm): δ 8.01 (m, 0,67H, aryl), 7.58 (m, 0,33H, aryl), 7.46 (m, 0,67H, aryl), 5.40 – 5.29 (m, 4H, C<u>H</u>=C<u>H</u>), 4.09 – 3.91 (m, 4H, C<u>H$_2$</u>-O-P), 3.62 (d, $^{2}J_{PCH}$ = 24 Hz, 0,67H, P-C<u>H$_2$</u>), 2.01 – 1.94 (m, 4H, C<u>H$_2$</u>-CH), 1.69 – 1.57 (m, 4H, C<u>H$_2$</u>-CH$_2$-O), 1.45 (d, $^{2}J_{PCH}$ = 15 Hz, 1,71H, P-C<u>H$_3$</u>), 1.31 – 1.23 (br. m, 24H, backbone). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 192.00 (C=O), 136.67 (aryl), 133.74 (aryl), 130.47 (<u>C</u>H=<u>C</u>H, *trans*), 129.98 (<u>C</u>H=<u>C</u>H, *cis*), 129.20 (aryl), 128.71 (aryl), 65.73 (d, J = 6.1 Hz,

$\underline{C}H_2$-O-P), 38.49 (d, $^1J_{CP}$ = 128 Hz, $\underline{C}H_2$-P), 32.72 (=CH-$\underline{C}H_2$), 30.60 ($\underline{C}H_2$-CH_2-O), 29.92, 29.78, 29.62, 29.34, 27.37, 27.37, 25.68, 25.55, 11.13 (d, $^1J_{PC}$ = 143 Hz, P-$\underline{C}H_3$). $^{31}P\{H\}$ NMR ($CDCl_3$, ppm): δ 30.67 (P-CH_3), 19.94 (P-CH_2). ν (cm^{-1}) 2922, 2852, 1682, 1448, 1248, 990, 819, 723, 689.

Hydrogenation of Poly(2)d. A 575 mg sample of the polymer **Poly(2)d**, 15 mL of THF, and 60 mg of 20 wt% $Pd(OH)_2$/C catalyst were charged into a 250 mL ROTH autoclave. Hydrogenation was performed with vigorous stirring under a hydrogen pressure of 100 bar at room temperature for 48 h. The solution was then filtered over Celite to remove the catalyst. The product was isolated after precipitation into methanol and dried *in vacuo* to give a solid polymer (**Poly(3)**, 478 mg). ^1H NMR ($CDCl_3$, ppm): δ 4.15 – 3.87 (m, $C\underline{H_2}$-O-P), 1.73 – 1.55 (m, $C\underline{H_2}$-CH_2-O), 1.46 (d, J = 17.4 Hz, P-CH_3), 1.24 (br. m, backbone). $^{13}C\{H\}$ NMR ($CDCl_3$, ppm): δ 65.73 (d, J = 6.1 Hz, $\underline{C}H_2$-O-P), 30.70, 30.65, 29.86, 29.81, 29.74, 29.69, 29.35, 25.69, 11.17 (d, $^1J_{PC}$ = 144.4 Hz, P-$\underline{C}H_3$). $^{31}P\{H\}$ NMR ($CDCl_3$, ppm): δ 30.6. ν (cm^{-1}) 2915, 2848, 1467, 1312, 1239, 979, 912, 818, 720.

Postmodification of Poly(3). A solution of HMDS (63 mg, 392 µmol, 2.2 eq.) in 3 mL dry THF was added to cold (-21°C) *n*-butyl lithium in hexane (1.6 M) (220 µL, 250 µmol, 2.0 eq). The reaction mixture was cooled to -78°C and a solution of **Poly(3)** (50 mg, 2 µmol, 1.0 eq.) and benzoylchloride (26 mg, 185 µmol, 1.5 eq.) in 2 mL dry THF was added dropwise. The cold solution was stirred over night at -28°C and then added to 2 mL deionized water. The organic phase was separated and the aqueous phase extracted twice with DCM. The combined organic layers were precipitated in methanol and dried under reduced pressure. The obtained product (48 mg) was analyzed by ^1H NMR spectroscopy to estimate the content of 2-oxo-phenylethyl units to

be about 40%. ^{1}H NMR ($CDCl_3$, ppm): δ 8.01 (d, ^{3}J= 6 Hz, 0,79H, aryl), 7.58 (t, ^{3}J = 6 Hz, 0,51H, aryl), 7.47 (t, ^{3}J = 6 Hz, 0,89H, aryl), 4.08 – 3.94 (m, 4H, C$\underline{H_2}$-O-P), 3.63 (d, $^{2}J_{PCH}$ = 21 Hz, 0,87H, P-C$\underline{H_2}$), 1.68 – 1.61 (m, 4H, C$\underline{H_2}$-CH_2-O), 1.46 (d, $^{2}J_{PCH}$ = 18 Hz, 2.03H, P-C$\underline{H_3}$), 1.37 – 1.25 (br. m, 36H, backbone). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 191.98 (C=O), 136.68 (aryl), 133.75 (aryl), 129.21 (aryl), 128.72 (aryl), 66.74 (d, J = 6.1 Hz, $\underline{C}H_2$-O-P), 38.51 (d, $^{1}J_{CP}$ = 128 Hz, $\underline{C}H_2$-P), 30.62 ($\underline{C}H_2$-CH_2-O), 29.88, 29.83, 29.74, 29.68, 29.34, 27.37, 27.37, 25.70, 25.56, 11.14 (d, $^{1}J_{CP}$ = 143 Hz, P-$\underline{C}H_3$). ^{31}P{H} NMR ($CDCl_3$, ppm): δ 30.67 ($\underline{P}$-CH_3), 19.93 ($\underline{P}$-CH_2). ν (cm^{-1}) 2916, 2849, 1680, 1467, 1243, 1063, 999, 916, 721.

Representative procedure for the HWE reaction using Barton's base.

Poly(**2**-*co*-**5**)**b** (37.4 mg, 90 µmol, 37 µmol phenacyl units, 1.0 eq.) was dissolved in 0.6 mL THF-d_8 and transferred into a standard NMR tube. Barton's base (12.7 mg, 74 µmol, 2.0 eq.) was added via syringe. The NMR tube was closed with a septum and inverted to mix the reactants. 4-Anisaldehyde (5.0 mg, 37 µmol, 1.0 eq., **6f**) was added subsequently via syringe to start the HWE reaction. The reaction was monitored by repeated ^{1}H and ^{31}P{H} NMR measurements. After complete conversion (indicated by ^{31}P{H} NMR) the polymer was precipitated in *n*-pentane. The supernatant was collected and the solvent was removed under reduced pressure to yield the desired product **7f** (7.2 mg, 30 µmol, 82%). ^{1}H NMR (polymer residue, $CDCl_3$, ppm): δ 5.49 – 5.25 (m, 2H), 4.04 – 3.86 (m, 2H), 3.79 – 3.66 (m, 2H), 2.08 – 1.90 (m, 4H), 1.66 – 1.47 (m, 4H), 1.43 – 1.16 (br. m, backbone, 43H). ^{31}P{H} NMR (polymer residue, $CDCl_3$, ppm): δ 30.6 (P-CH_3), -0.81 (P-O^-).

7a ^{1}H NMR ($CDCl_3$, ppm): δ 8.35 – 8.24 (m, 2H, C<u>H</u>-C-NO_2), 8.07 – 8.00 (m, 2H, C<u>H</u>-C-C=O), 7.89 – 7.75 (m, 3H, C<u>H</u>-CH-C=O; C<u>H</u>-CH=C-NO_2), 7.71 – 7.57 (m, 2H, CH-C=O; *p*-C<u>H</u>$_{aryl}$), 7.58 – 7.50 (m, 2H, *m*-C<u>H</u>$_{aryl}$). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 189.80 (<u>C</u>=O), 141.67 (<u>C</u>-NO_2), 141.19 (<u>C</u>H=CH-C=O), 137.68 (<u>C</u>-CH=CH), 133.53 (*p*-<u>C</u>H$_{aryl}$), 130.06 (<u>C</u>-C=O), 129.09 (aryl), 128.98 (aryl), 128.75 (aryl), 125.86 (<u>C</u>H-C=O), 124.39 (<u>C</u>H=C-NO_2). ESI MS: m/z 507.25 ($2MH^+$).

7b ^{1}H NMR ($CDCl_3$, ppm): δ 8.05 – 7.99 (m, 2H, C<u>H</u>-C-C=O), 7.78 (d, *J* = 15.7 Hz, 1H, C<u>H</u>=CH-C=O), 7.68 – 7.56 (m, 3H, aryl), 7.54 – 7.49 (m, 2H, aryl), 7.47 (d, *J* = 16.0 Hz, 1H, C<u>H</u>-C=O), 7.16 – 7.08 (m, 2H, C<u>H</u>-C-F). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 190.47 (<u>C</u>=O), 164.21 (d, *J* = 251.7 Hz, <u>C</u>-F), 143.67 (<u>C</u>H-CH-C=O), 138.27 (<u>C</u>-C=O), 133.00 (*p*-<u>C</u>H$_{aryl}$), 131.29 (d, *J* = 3.5 Hz, <u>C</u>-CH=CH-C-F), 130.49 (d, *J* = 8.8 Hz, <u>C</u>H=CH-C-F), 128.80 (aryl), 128.63 (aryl), 121.92 (d, J = 2.7 Hz, <u>C</u>H-C=O), 116.29 (d, *J* = 22.0 Hz, <u>C</u>H=C-F). ^{19}F NMR ($CDCl_3$, ppm): δ -110.22 (m).

7c ^{1}H NMR ($CDCl_3$, ppm): δ 8.06 – 7.99 (m, 2H, C<u>H</u>=C-C=O), 7.76 (d, *J* = 15.7 Hz, 1H, C<u>H</u>-CH-C=O), 7.65 – 7.57 (m, 1H, *p*-C<u>H</u>$_{aryl}$), 7.53 (m, 2H, *m*-C<u>H</u>$_{aryl}$), 7.52 (d, *J* = 15.7 Hz, 1H, CH-C<u>H</u>-C=O), 7.44 – 7.31 (m, 3H, aryl), 7.17 – 7.07 (m, 1H, aryl). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 190.34 (<u>C</u>=O), 163.19 (d, $^{1}J_{CF}$ = 246.8 Hz, <u>C</u>-F), 143.45 (d, *J* = 2.7 Hz, =<u>C</u>H_2-Aryl), 138.06 (<u>C</u>-C=O), 137.28 (d, *J* = 7.7 Hz, <u>C</u>-CH=CH), 133.16 (*p*-<u>C</u>H$_{aryl}$), 130.66 (d, *J* = 8.3 Hz, <u>C</u>H-CH=CF), 128.84 (aryl), 128.67 (aryl), 124.69 (d, *J* = 2.8 Hz, <u>C</u>H-C=CH-CF), 123.34 (<u>C</u>H-C=O), 117.52 (d, *J* = 21.4 Hz, CH=<u>C</u>H-CF), 114.61 (d, *J* = 21.9 Hz, C=<u>C</u>H-CF). ^{19}F NMR ($CDCl_3$, ppm): δ -113.63 (m).

7d ^{1}H NMR ($CDCl_3$, ppm): δ 8.07 – 7.99 (m, 2H, C<u>H</u>-C-C=O), 7.91 (d, J = 15.9 Hz, 1H, C<u>H</u>-CH-C=O), 7.70 – 7.56 (m, 2H, C<u>H</u>=CH-C-F), 7.65 (d, J = 15.9 Hz, 1H, C<u>H</u>-C=O) 7.56 – 7.47 (m, 2H, *m*-C<u>H</u>$_{aryl}$), 7.43 – 7.34 (m, 1H, *p*-C<u>H</u>$_{aryl}$), 7.24 – 7.09 (m, 2H, C<u>H</u>-C-F, C<u>H</u>=CH-CH=C-F). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 190.68 (<u>C</u>=O), 161.89 (d, $^{1}J_{CF}$ = 254.4 Hz, <u>C</u>-F), 138.14 (<u>C</u>-C=O), 137.70 (d, J = 2.1 Hz, <u>C</u>H-C=CH-CF), 133.07 (*p*-<u>C</u>H$_{aryl}$), 131.99 (d, J = 8.8 Hz, <u>C</u>H-CH=CF), 129.95 (d, J = 2.9 Hz), 128.81 (aryl), 128.72 (aryl), 124.78 (d, J = 7.3 Hz, <u>C</u>H-C=CH-CF), 124.66 (d, J = 3.5 Hz, <u>C</u>H-C=O), 123.16 (d, J = 11.5 Hz, <u>C</u>-C-F), 116.46 (d, J = 22.0 Hz, <u>C</u>H-CF). ^{19}F NMR ($CDCl_3$, ppm): δ -114.50 (m).

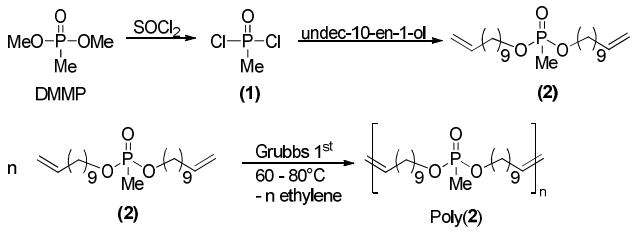
7e ^{1}H NMR ($CDCl_3$, ppm): δ 8.74 – 8.66 (m, 2H), 8.06 – 8.00 (m, 2H), 7.69 (d, J = 2.0 Hz, 2H), 7.66 – 7.59 (m, 1H), 7.57 – 7.50 (m, 2H), 7.49 – 7.46 (m, 2H). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 189.97 (<u>C</u>=O), 150.81 (<u>C</u>H-N), 142.21 (<u>C</u>-CH=CH), 141.70 (C-<u>C</u>H=CH), 137.64 (<u>C</u>-C=O), 133.50 (*p*-<u>C</u>H$_{aryl}$), 128.96 (aryl), 128.76 (aryl), 126.20 (<u>C</u>H-C=O), 122.17 (N-CH=<u>C</u>H). ESI MS: m/z 210.07 (MH^+).

7f ^{1}H NMR ($CDCl_3$, ppm): δ 8.06 – 7.97 (m, 2H, C<u>H</u>-C-C=O), 7.79 (d, J = 15.7 Hz, 1H, C<u>H</u>=CH-C=O), 7.66 – 7.46 (m, 5H, aromatic), 7.42 (d, J = 15.6 Hz, 1H, C<u>H</u>-C=O), 7.00 – 6.89 (m, 2H, C<u>H</u>-C-OMe), 3.83 (s, 3H, O-C<u>H</u>$_3$). ^{13}C{H} NMR ($CDCl_3$, ppm): δ 190.77 (<u>C</u>=O), 161.82 (<u>C</u>-OMe), 144.87 (<u>C</u>H=CH-C=O), 138.65 (<u>C</u>-C=O), 132.71 (*p*-<u>C</u>H$_{aryl}$), 130.38 (<u>C</u>H-C-CH=CH), 128.71 (aryl), 128.57 (aryl), 127.76 (<u>C</u>-CH=CH), 119.94 (<u>C</u>H-C=O), 114.57 (<u>C</u>H-C-OMe), 55.58 (-O-<u>C</u>H$_3$).

Results and Discussion.

Poly(phosphonate)s with a phenacyl side-chain were prepared to undergo HWE model reactions with a library of aldehydes. These polymers were synthesized either by postmodification of a poly(alkylene methylphosphonate) or by ADMET polymerization of a prefunctionalized monomer. The polyester is preserved during the postmodification, as well as during the actual HWE reaction. Therefore, the raw unsaturated product is not contaminated by possible degradation products of the polymer which can easily be removed completely by simple precipitation, minimizing purification efforts.

Postpolymerization modification. The acyclic diene phosphonate monomers are accessible in a single reaction step from methyl phosphonic dichloride and the corresponding ω-unsaturated alcohol (Scheme 3) as reported previously.[27] In the model system demonstrated in this work, undec-10-en-1-ol is used to create hydrophobic polymers.



Scheme 3. *Top:* Synthesis of monomer **2** by condensation of methylphosphonic dichloride (**1**) with undec-10-en-1-ol. **1** is readily accessible from the commercially available DMMP and thionyl chloride. *Bottom:* ADMET Polymerization of **2** using Grubbs first generation catalyst.

The polymerization of **2** was studied varying the amount of Grubbs first generation catalyst added (Scheme 3). All polymers synthesized herein exhibit monomodal molecular weight distributions. Their apparent molecular weights and molecular weight dispersities were determined via SEC vs. polystyrene standards (Table 1 and Figure S1, ESI).

Table 1. Molecular weights and thermal properties of linear poly(icos-10-en-1,20-dioxy methylphosphonate)s, poly(**2**), and poly(icos-1,20-dioxy methylphosphonate), poly(**3**), prepared by ADMET polymerization for subsequent postmodification.

Code	catalyst / mol %	Yield / %	M_n[a] / g·mol^{-1}	M_w[a] / g·mol^{-1}	M_w/M_n[a]
Poly(**2**)**a**	1.2	43	17 100	23 300	1.36
Poly(**2**)**b**	1.6	56	22 200	32 000	1.45
Poly(**2**)**c**	2.0	58	23 100	34 300	1.49
Poly(**2**)**d**	2.4	61	21 600	31 200	1.44
Poly(**3**)	-	-	20 400	25 500	1.25

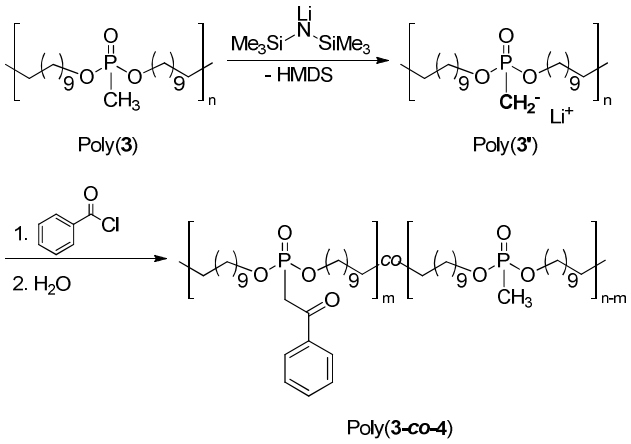
[a] Number average of the molecular weight and molecular weight dispersity (M_w/M_n) determined *via* SEC in THF *vs*. PS standards.

The molecular weight increases with increasing amount of catalyst, but reaches a maximum at about 2.0 mol% Grubbs catalyst with a number average molecular weight of ca. 23 000 g mol^{-1} under these reaction conditions. Interestingly, the molecular weight dispersity for all samples is below 2.0 which is unexpected for a polycondensation with a typical dispersity of 2 at full monomer conversion.

The ^{1}H NMR and the ^{13}C{H} NMR spectra reveal the unsaturated backbone of these polymers, as expected for ADMET polycondensation (Figure S2-S3, ESI). A multiplet from 5.40 – 5.29

ppm in the ^{1}H NMR spectrum and two signals at 130.47 and 129.98 ppm in the ^{13}C{H} NMR spectrum represent the internal *trans* and *cis* double bonds respectively. Due to the high molecular weight and the resulting high number of repeating units, the external double bonds at the chain ends are not observed in NMR. The internal double bonds of poly(**2**)**d** were hydrogenated in the presence of palladium hydroxide on activated charcoal. Successful hydrogenation was confirmed by NMR spectroscopy (Figure S5-S6, ESI) as the resonances for the double bonds disappear. SEC analysis revealed a negligible decrease in molecular weight and a narrowing of the distribution due to additional purification steps (repeated precipitation) (Figure S8, ESI).

Postmodification of poly(**3**) was carried out by reaction with LHMDS in dry THF. The intermediate polyanion was treated with benzoyl chloride to attach the desired phenacyl functionality to the polyphosphonate. High degrees of functionalization were achieved when 2.0 equivalents of LHMDS were added to the polymeric precursor resulting in a 40 mol% modification of all methylphosphonate groups. Higher degrees of modification are expected if more equivalents of LHMDS are employed. However, negligible postmodification was detected if less LHMDS was used to deprotonate the methylphosphonate units. The degree of functionalization can be calculated from the ^{1}H NMR spectrum. Successful transformation of the methylphosphonate to the phenacylphosphonate was also confirmed by ^{31}P{H} NMR spectroscopy as a new signal at 19.93 ppm besides the original signal at 30.67 ppm is detected (Figure S9, ESI).



Scheme 4. Postmodification of poly(**3**): Deprotonation of poly(**3**) produces polyanion Poly(**3'**) which is subsequently treated with benzoyl chloride to generate poly(**3**-*co*-**4**) after aqueous workup.

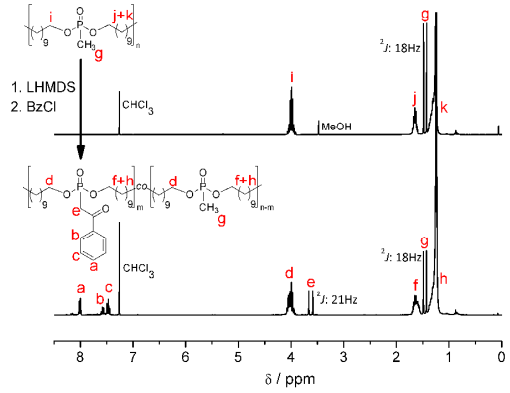


Figure 2. ^{1}H NMR (300 MHz, 298K, $CDCl_3$) comparison between poly(**3**) (*top*) and poly(**3**-*co*-**4**) (*bottom*).

SEC analysis revealed that the polyester is not degraded under these strong basic conditions, and that the phenacyl functionality was introduced evenly over the entire range of molecular weights as indicated by the absorption of the UV detector at 254 nm (Figure 3).

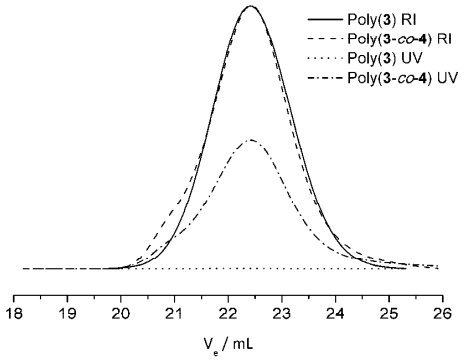
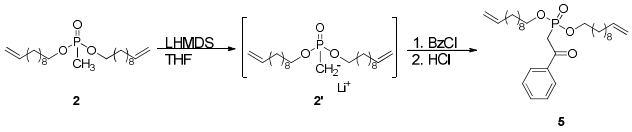


Figure 3. SEC traces of poly(**3**) and poly(**3**-*co*-**4**). Solid and dashed lines correspond to the RI signal and prove no degradation during the postmodification. Dotted and dash-dotted lines represent the UV signal measured at 254 nm. No absorbance is detected for the poly(**3**) (dotted line), whereas poly(**3**-*co*-**4**) exhibits a strong absorption (dash-dotted line).

Postmodification of poly(**3**) can be conducted in a single reaction step to obtain the HWE-reactive poly(phosphonate). However, the degree of functionality was difficult to adjust and the reaction conditions need to be determined empirically for new compounds. Nevertheless, the demonstrated postmodification allows the synthesis of polymeric reagents that are not accessible via metathesis and is the first report about a postmodification of a poly(phosphonate) synthesized in this manner.[42, 43] If the functional group of interest is not tolerated by the Ruthenium catalyst, the proposed route via a "blank" poly(**3**) might be feasible. Moreover, the synthesis of a suitable ADMET monomer and its purification can be avoided, making this route attractive.

Copolymerization. In order to adjust the degree of functionality, copolymerization of the corresponding phenacyl phosphonate monomer with **2** can be conducted stoichiometrically to produce a library of copolymers with a defined loading capacity.

The synthesis of monomer **5** is conducted analogous to the postmodification of poly(**3**): **2** was deprotonated with LHMDS in THF to produce the corresponding anionic intermediate (**2'**) which was stabilized by the lithium counterion. Addition of benzoyl chloride, aqueous workup and purification by column chromatography produced **5** (Scheme 5).



Scheme 5. Synthetic procedure of monomer **5** from **2**. Deprotonation yields the intermediate **2'** which is subsequently transformed into its phenacyl derivative after addition of benzoyl chloride and acidic workup.

The structure of the novel phenacyl phosphonat monomer **5** was confirmed by ^{1}H, $^{13}C\{H\}$ and $^{31}P\{H\}$ NMR spectroscopy (Figure S10-S12, ESI). Furthermore ESI mass spectrometry is in good agreement with the calculated mass of the desired product.

2 and **5** were copolymerized in bulk via the ADMET procedure developed for the homopolymerization of **2**. Different feed ratios of both monomers were added to demonstrate the adjustability and robustness of the developed system (Table 2).

Table 2. Molecular weights and thermal properties of linear poly(**2**-*co*-**5**) prepared by ADMET copolymerization for the HWE reaction. All polymerizations were catalyzed with 2.4 mol% Grubbs first generation catalyst and conducted at 60°C over a period of 48 hours.

Code	Feed ratio	[2]/[5][a]	Yield / %	M_n[b] / g·mol^{-1}	M_w[b] / g·mol^{-1}	M_w/M_n[b]
Poly(**2**-*co*-**5**)**a**	80:20	78:22	54	19 800	38 800	1.95
Poly(**2**-*co*-**5**)**b**	60:40	59:41	51	14 900	28 100	1.88
Poly(**2**-*co*-**5**)**c**	40:60	43:57	55	13 800	26 500	1.91
Poly(**2**-*co*-**5**)**d**	20:80	21:79	60	15 400	32 900	2.14
Poly(**5**)	0:100	0:100	52	20 100	41 000	2.04

[a] Calculated from ^{1}H NMR. [b] Number average of the molecular weight and molecular weight dispersity (M_w/M_n) determined *via* SEC in THF *vs*. PS standards.

The content of **5** was determined from the ^{1}H NMR spectra by comparing the integrals of the aromatic signals from 8.01 to 7.46 ppm with the integral of the multiplet from 4.09 to 3.91 ppm which corresponds to all methylene protons next to the phosphonate (Figure S13, ESI). The result of this calculation correlates also with the integral of the doublet of the methylene group at 3.62

ppm stemming from the phenacyl side chains. This doublet has a coupling constant of 24 Hz due to the strong proton-phosphorus coupling in contrast to the coupling of the methyl protons to the phosphorus in **2**, exhibiting a coupling constant of only 15 Hz. The increasing content of **5** was also verified qualitatively by the change in ratio of signal intensities observed in $^{31}P\{H\}$ NMR spectra (Figure S15, ESI): two distinct signals are observed at 30.67 and 19.94 ppm, the latter corresponding to the phenacyl phosphonate units which increases in intensity for increasing feed ratios, whereas the signal at 30.67 ppm decreases.

The copolymers poly(**2**-*co*-**5**)**a-d** and the homopolymer poly(**5**) were analyzed via SEC measurements in THF *vs.* PS standards (Figure S16, ESI). All polymers exhibited monomodal molecular weight distributions with $Đ$ values of ca. 2.0.

Horner-Wadsworth-Emmons Reaction. The copolymers with the phenacyl side group are a suitable polymeric phosphonate for the HWE reaction with aldehydes. The acidic methylene protons (doublet at 3.62 ppm, Figure S13, ESI) can be deprotonated by common bases and the subsequent HWE reaction of the deprotonated polyphosphonate was studied in homogeneous solution with several (electron-rich and electron-deficient) aromatic aldehydes. After the reaction, the depleted poly(phosphate-*co*-phosphonate) can be removed by precipitation into *n*-pentane while the respective chalcone remains in the supernatant and can be recovered by evaporation of the solvent.

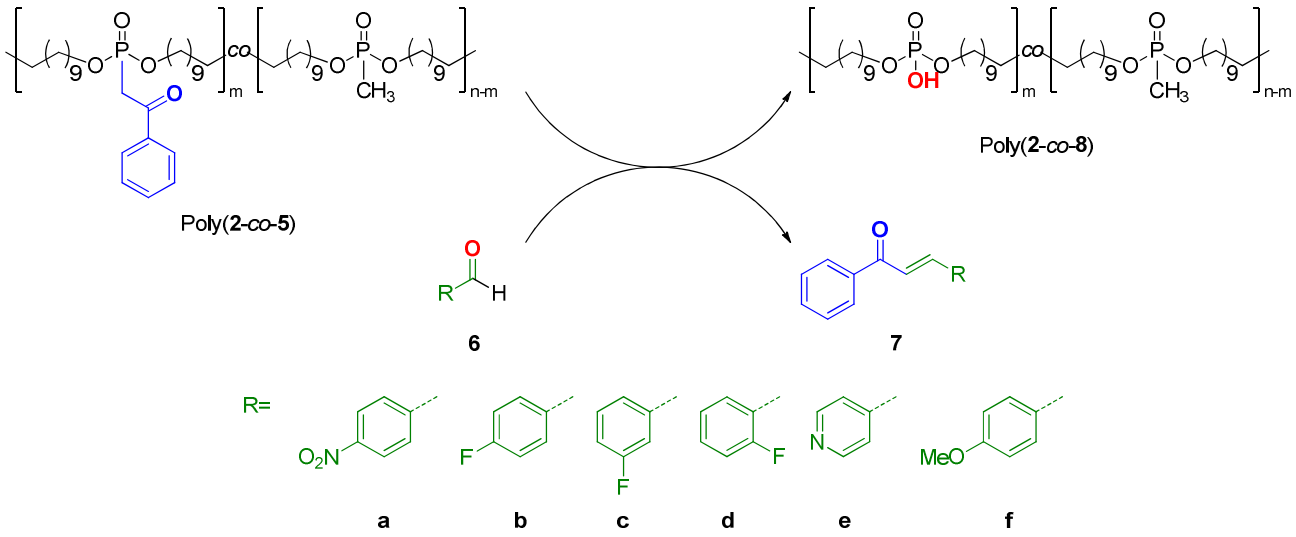
The deprotonation and subsequent HWE reaction with poly(**2**-*co*-**5**)**a** was studied with different bases and 4-nitrobenzaldehyde (**6a**) as a highly electrophilic reaction partner (compare Table S1). *n*-Butyllithium did not produce any reaction product, despite the fact, that lithium cations are well known to facilitate the HWE reaction by stabilization of the transition state. Low conversion was

observed when sodium hydride was used as the respective base, but the HWE reaction remained unsatisfactory.

Satisfying conversion to **7a** was observed if the Barton's base (*N*-tert-Butyl-*N*',*N*',*N*'',*N*''-tetramethylguanidine) was employed.[44] This base has already been used for the HWE reaction.[14]

The polymer, poly(**2**-*co*-**8**)**a**, was precipitated in *n*-pentane from the reaction mixture directly. The desired product **7a** was obtained as slightly yellow crystals after the solvent was removed at reduced pressure. ^{1}H and ^{13}C{H} NMR analyses as well as ESI mass spectrometry confirmed the successful formation of **7a** and the absence of any by-products, polymeric residues or degradation products (Figures S17-S19, ESI).

Barton base was therefore used to screen the HWE reaction with different aromatic aldehydes (Scheme 7). ^{1}H and ^{13}C{H} NMR spectroscopy revealed that for the aldehydes **6a-e** the HWE reaction with poly(**2**-*co*-**5**)**b** produced the desired chalcones **7a-e** in very high yield without side products (Table 4). Investigation of the stereochemistry of the α,β-unsaturated chalcones by ^{1}H NMR spectroscopy revealed *trans* geometry in all cases as expected for HWE reactions with phosphonate partners carrying sterically demanding esters.



Scheme 7. HWE reaction with different aldehydes **6a-f** yielding the corresponding chalcones **7a-f**.

Table 4. HWE reaction of aldehydes **6a-f** to **7a-f** with poly(**2**-*co*-**5**)**b** employing Barton's base for deprotonation in THF.

Run	Aldehyde **6**	Time / h	Chalcone **7**	Yield **7**[a]	Conversion to phosphate[b]
1	**6a** 4-O_2N-C_6H_4CHO	2	**7a**	88%	>99%
2	**6b** 4-F-C_6H_4CHO	2	**7b**	92%	97%
3	**6c** 3-F-C_6H_4CHO	2.5	**7c**	95%	95%
4	**6d** 2-F-C_6H_4CHO	2	**7d**	90%	97%
5	**6e** 4-pyr-CHO	1	**7e**	87%	>99%
6	**6f** 4-MeO-C_6H_4CHO	245	**7f**	82%	90%

[a] Determined gravimetrically. [b] Determined via $^{31}P\{H\}$ NMR.

The spectra of the products "as obtained" after solvent evaporation further prove the complete removal of the polymer after precipitation: no signals in $^{31}P\{H\}$ NMR were detectable for the raw products **7a-f** (Figure S17-S37, ESI).

The progress of the HWE reaction was investigated by $^{31}P\{H\}$ NMR spectroscopy (Figure S38, ESI). After addition of Barton's base, the signal of the phosphorus atom connected to a phenacyl group in the $^{31}P\{H\}$ NMR spectrum at 19.94 ppm broadened significantly, indicating the deprotonation of the methylene group. The signal of the phosphorus atom connected to a methyl group at 30.67 ppm is untouched, as the acidity of the methyl protons is negligible in comparison to the activated methylene protons next to the electron withdrawing group. After addition of the aldehyde (**6f**), the integral of the phenacyl phosphonate signal decreases while a new signal at -0.8 to -1.0 ppm appears and increases over time. Both integrals can be compared as they are normalized to the methyl phosphonate signal which does not take part in the HWE reaction. The reaction kinetics can be followed by plotting the ratio of the normalized integrals versus the reaction time (Figure S39, ESI). Also the conversion of the reaction can be calculated from this ratio allowing terminating the reaction after the conversion reached the maximum.

The reaction was also followed by ^{1}H NMR spectroscopy (Figure S40, ESI). The doublet at 3.62 ppm transforms into one broad signal after addition of the base, indicating deprotonation of the methylene group adjacent to phosphorus. Subsequent addition of the aldehyde (**6f**) is indicated by the strong resonances at 9.84 (aldehyde proton), two doublets at 7.82 and 7.05 and a singlet at 3.86 ppm. These resonances decrease over time as the aldehyde is consumed in the HWE

reaction, while new signals at 8.06 – 7.97, 7.79– 7.42, 7.00 – 6.89 and 3.83 ppm increase due to the progressing formation of the chalcone **7f**.

Further, the ^{1}H NMR spectra of the reaction mixtures prove the stability of the polyester backbone under these conditions as no degradation products can be detected. Also, a single resonance in the ^{31}P{H} NMR spectrum corresponding to a diester of phosphoric acid at -0.8 ppm proves that the formation of any monoesters or triesters can be excluded, which would appear at much lower respectively higher field (Figure S41, ESI). Therefore, transesterification reactions or hydrolysis did not take place during the HWE reaction. The charged nature of polyanion poly(**2**-*co*-**8**)**b** decreased the solubility in THF dramatically, resulting in SEC elution of the polymer as a broad peak indicating interaction with the SEC columns (Figure S42, ESI). In order to finally prove the stability of the polymeric phosphonate, the reaction mixture and the polymer were analyzed via ^{1}H-DOSY NMR spectroscopy (Figure 4).

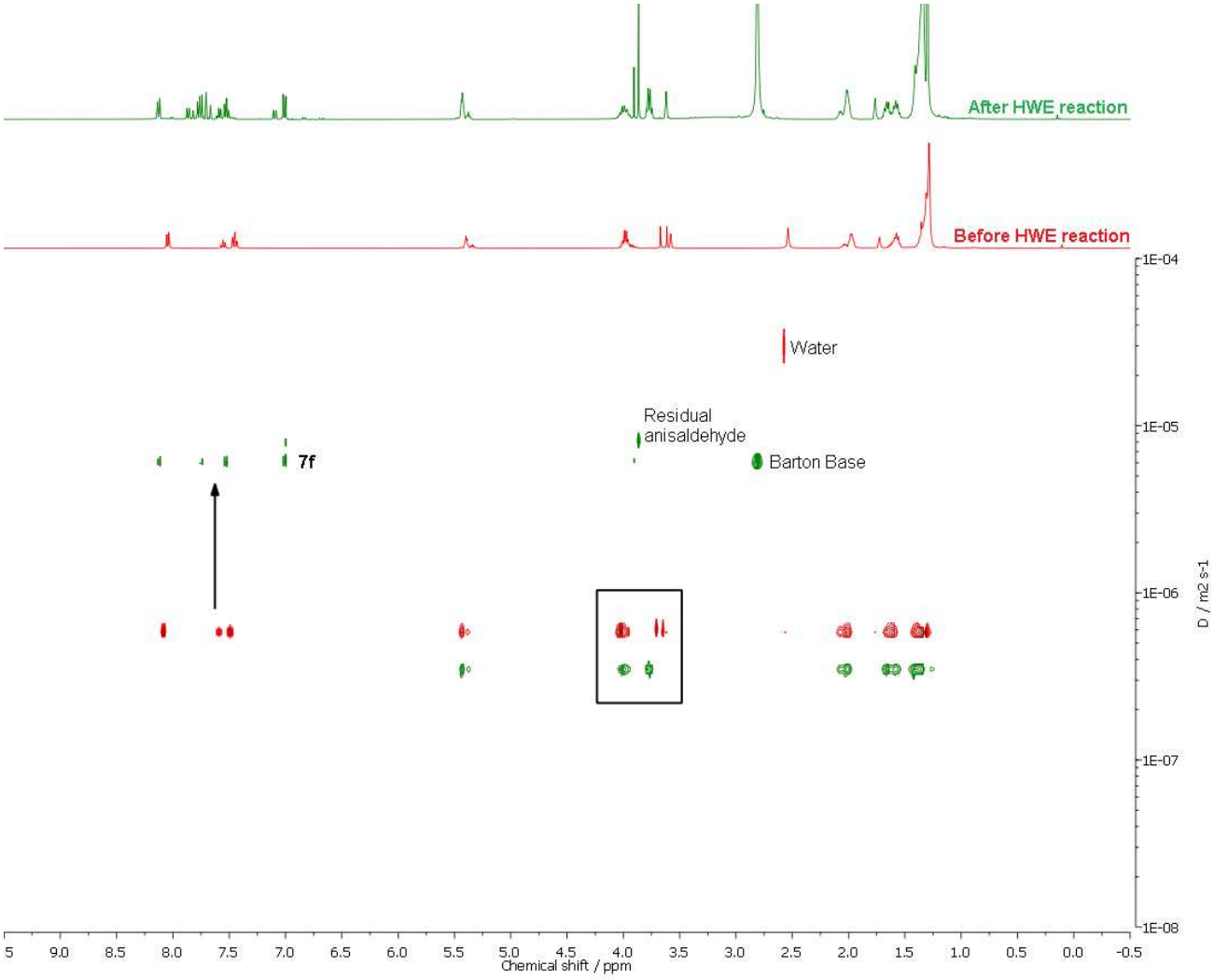


Figure 4. ^{1}H-DOSY NMR spectra of the reaction run 6 before (*red*) and after (*green*) the HWE reaction in THF-d_8 at 20°C. The higher diffusivity of product **7f** is indicated with the arrow. A magnification of the resonances from 4.30 to 3.40 ppm is shown in Figure S43, ESI.

The superimposed DOSY spectra in Figure 4 clearly show that the diffusion coefficients of the polymers before (red, $6 \cdot 10^{-7}$ m^2 s^{-1}) and after the reaction (green, $4 \cdot 10^{-7}$ m^2 s^{-1}) are similar proving the presence of a polymeric species. In addition to the polymer signals, the ^{1}H-DOSY also shows the formation of the reaction product with a much higher diffusion coefficient ($6 \cdot 10^{-6}$

m^2 s^{-1}). A slight decrease of the diffusion values of poly(**2**-*co*-**8**) compared with the value calculated for poly(**2**-*co*-**5**) might be due to ionic interactions and the formation of small aggregates in THF-d_8 and a resulting decreased solubility of the polymer after the formation of the phosphoric acid. The observations made from ^{1}H-DOSY and ^{31}P{H} NMR clearly prove that the polymer backbone is not degraded during the HWE reaction. This observation is not only true for the HWE reactions with highly electrophilic aldehydes (and thus short reaction times), but also for less electrophilic reaction partners, e.g. anisaldehyde **6f**. The polymer backbone is conserved even if the reaction is conducted for several weeks at room temperature which was the case for run 6 of the polymer supported HWE reactions.

It is important to note that the depleted polymeric support, like any phosphonate compound used in a HWE reaction, cannot be regenerated in an economic way, limiting its application to single use only. Nevertheless, application of this reactive and easy to use polymer is beneficial if time-consuming and expensive purification efforts need to be minimized, as the phosphate byproduct can be removed efficiently by precipitation or filtration as shown above.

Summary

A novel general platform for the generation of polymeric reagents for the Horner-Wadsworth-Emmons (HWE) reaction has been developed. ADMET polymerization was used to synthesize various polyphosphonates. Either homopolymer of **2** or copolymers with a phenacyl phosphonate monomer (**5**) were produced. As an alternative, the HWE-reactive phenacyl phosphonate groups were also introduced into the homopolymers of methyl phosphonate by postmodification after hydrogenation. This postmodification route might be advantageous when a prefunctionalized monomer is not accessible or not tolerated during metathesis polymerization.

The HWE-reactive polyphosphonates carrying a model-phenacyl group along the backbone were used in reactions with several aromatic aldehydes. Deprotonation of the phosphonate side chains was accomplished using the Barton base. After the addition of the electrophile, a homogenous reaction was possible. The products were obtained in high yields from solution after precipitation of the polymeric carrier without any further purification. Moreover, it was shown that the polyester backbone is not degraded during the reaction, yielding a poly(phosphate) from a poly(alkyl phosphonate) which is herein reported for the first time.

In conclusion, we believe that the poly(phosphonate) platform in combination with tailorable solubility profiles achieved by ADMET polymerization makes the polymer-supported HWE reaction very interesting for the production of various olefins. Purification efforts are minimized and reaction products are obtained in high yield in a homogenous and fast reaction. In contrast to other polymer supported HWE reagents, the system reported herein is adjustable to the individual needs by choosing an appropriate monomer depending on the hydrophobicity/hydrophilicity of the desired main product. Since degradation of the polyester, even under the strong nucleophilic conditions employed during the HWE reaction, is negligible, the reaction can be carried out homogenously which is an advantage over all other methods reported so far using modified polystyrene beads or cross-linked polymer gels. Purification efforts are reduced to a minimum and we therefore expect our system to facilitate the preparation of unsaturated compounds via the HWE reaction in industry and academia.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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