

Supporting Information

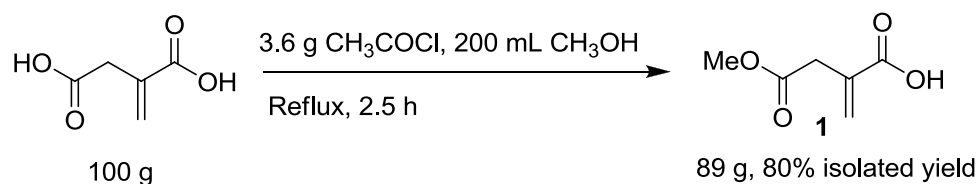
Greener synthesis of β -methyl- α -methylene- γ -butyrolactone from biorenewable itaconic acid

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Methods and Reagents. All syntheses and manipulations of required for air- and moisture-sensitive materials were carried out in flamed Schlenk-type glassware on a dual-manifold Schlenk line, on a high-vacuum line, or in an inert gas (Ar or N₂)-filled glovebox. THF was dried using the sodium and benzophenone method and distilled under dry nitrogen atmosphere prior to use. DMF was stirred with CaH₂ for 24 h, filtered and vacuum-distilled under dry nitrogen atmosphere at 30–40 °C; this process was repeated twice/thrice prior to use to reproduce the large scale polymerizations. NMR solvents CDCl₃ and D₂O were used as received. NMR spectra were recorded on a Varian Inova 300 (300 MHz, ¹H; 75 MHz, ¹³C) or a 400 MHz spectrometer. Chemical shifts for ¹H and ¹³C spectra were referenced to internal solvent resonances and are reported as parts per million relative to SiMe₄.

Itaconic acid, ammonium formate, 5 Wt. % Pd on carbon wet support, diethyl oxalate, 30% w/w sodium methoxide in methanol, ruthenium(III) 2,4-pentanedionate, and 1,4-bis(diphenylphosphino)butane were purchased from Alfa Aesar Chemical Co. Acetyl chloride, 10 Wt. % Pd on carbon wet support, BH₃•SMe₂ complex, *p*-TsOH•H₂O, aqueous formaldehyde (37 wt. % in water), and potassium carbonate were purchased from Sigma-Aldrich Chemical Co and used as received. The monomer γ -Methyl- α -methylene- γ -butyrolactone (γ MMBL) and the N-heterocyclic carbene 1,3-di-*tert*-butylimidazol-2-ylidene (tBu) were purchased from TCI America. Monomers γ MMBL and β -methyl- α -methylene- γ -butyrolactone (β MMBL) synthesized from this work were first degassed with dry nitrogen and stirred with CaH₂ overnight, and vacuum-distilled under dry nitrogen atmosphere at 40–50 °C (100 mTorr) prior to use; the purified monomers were stored in brown bottles inside a glovebox freezer at –30 °C. Butylated hydroxytoluene (BHT-H, 2,6-di-*tert*-butyl-4-methylphenol) was purchased from Alfa Aesar Chemical Co. BHT-H was recrystallized from hexanes prior to use.



4-Methoxy-2-methylene-4-oxobutanoic acid (1). In a 1000 mL single-necked round-bottomed flask, itaconic acid (100.0 g, 768.6 mmol) was added in methanol (200 mL). Acetyl chloride (3.60 g, 22.9 mmol) was slowly added over 2 min and the reaction mixture was brought to reflux and stirred for additional 2.5 h. After cooling to room temperature, methanol was evaporated under reduced pressure, and the crude product was dissolved in a minimum amount of hot toluene (200 mL) followed by layering with 300 mL hexanes. The mixture was cooled at 0 °C for 24 h, and the resulting white crystals were filtered off, washed with cold hexanes and dried in high vacuum to give 89.0 g of **1** (80% yield) as a white solid. ¹H NMR (CDCl₃): δ 11.88 (br s, 1H), 6.47 (s, 1H), 5.84 (s, 1H), 3.71 (s, 3H), 3.35 (s, 2H). The above ¹H NMR spectral data are consistent with those reported in the literature.^{1a,1b}

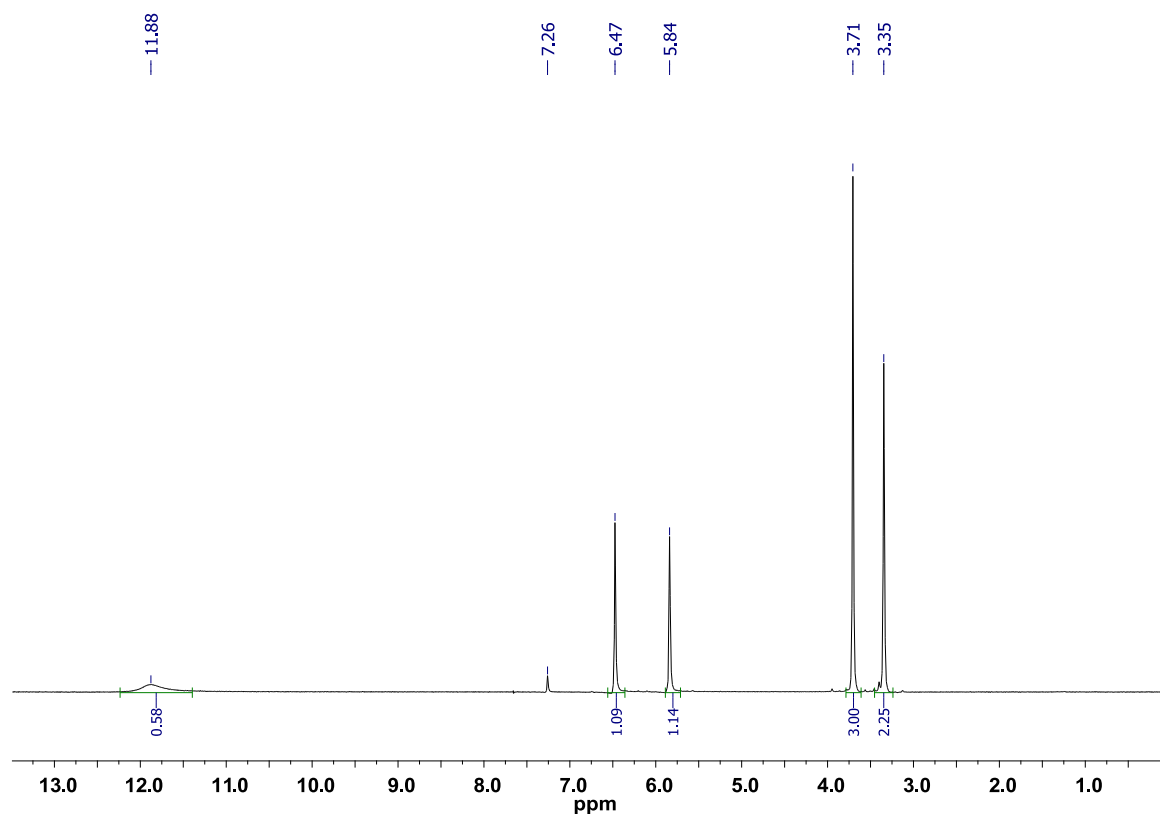
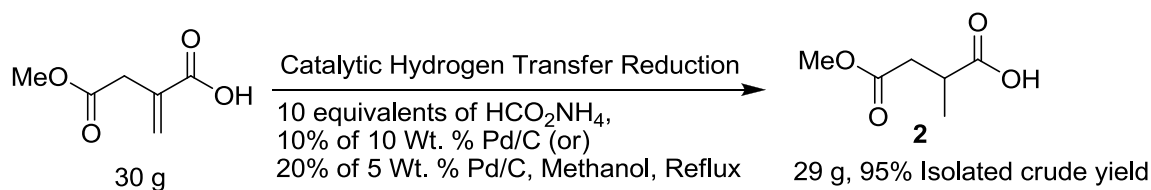


Figure S1. ¹H NMR (CDCl₃) spectrum of **1**.



4-Methoxy-2-methyl-4-oxobutanoic acid (2). In a 1000 mL single-necked round-bottomed flask, **1** (29.0 g, 0.208 mol) and ammonium formate (131 g, 2.08 mol) was added in methanol (300 mL). Pd/C (10 wt. %, 10 mol% of olefin by weight, 2.21 g, 20.8 mmol, or 5 wt. %, 20 mol% of olefin by weight, 4.43 g, 41.6 mmol) was added, and the reaction mixture was brought to reflux and stirred for 16 h. After cooling the mixture to room temperature, the Pd/C catalyst was removed by filtration and methanol was evaporated under reduced pressure. The excess ammonium formate present in the crude product was precipitated with 300 mL chloroform and removed by filtration. The chloroform solution was further passed through 30 g short silica gel column to remove the dissolved ammonium formate in chloroform. The chloroform was evaporated under reduced pressure, resulted in a viscous oil. This oil was dried in high vacuum to give 29.0 g of **2** (95% crude yield) as a viscous oil. ^1H NMR (CDCl_3): δ 6.97 (br s, 1H), 3.64 (s, 3H), 2.72 (m, 2H), 2.38 (dd, 1H); 1.16 (d, 3H). The above ^1H NMR spectral data are consistent with those reported in the literature.^{1a,1b,2a,2b}

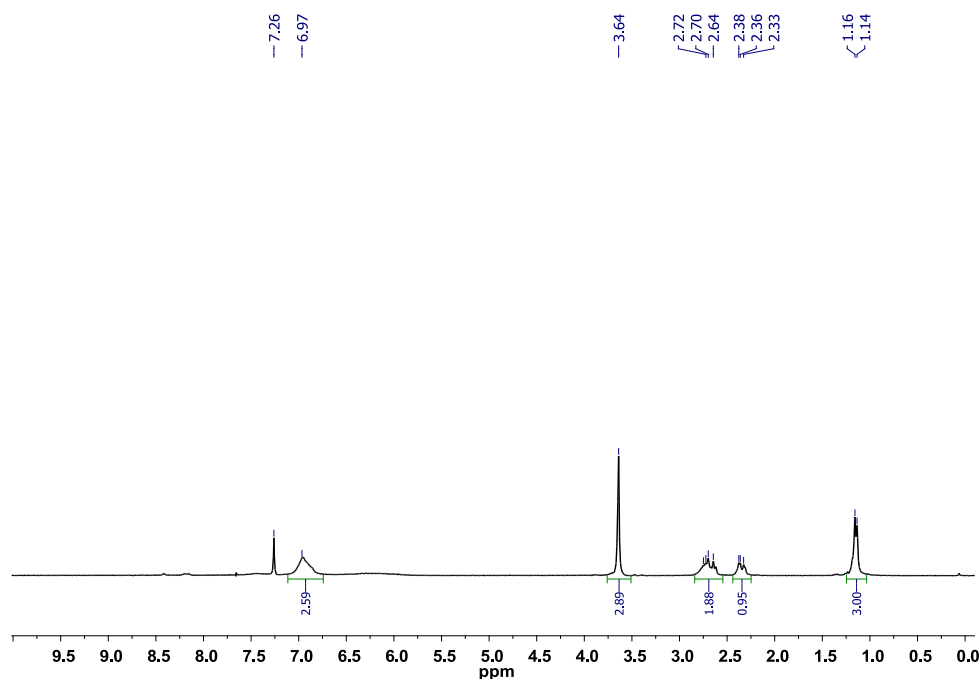
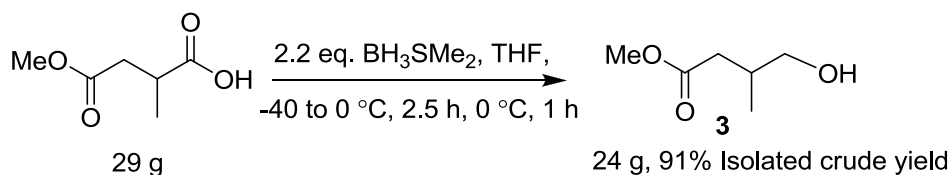


Figure S2. ^1H NMR (CDCl_3) spectrum of crude **2**.



Methyl 4-hydroxy-3-methylbutanoate (3). In a 250 mL Schlenk flask, under an atmosphere of nitrogen in a glove box, **2** (29.0 g, 198 mmol) was dissolved in dry THF (150 mL) and capped with a rubber septum. This flask was interfaced with a Schlenk line, purged with dry nitrogen gas and cooled to $-40 \text{ }^\circ\text{C}$. $\text{BH}_3 \cdot \text{SMe}_2$ complex (33.2 g, 41.4 mL, 437 mmol) taken in another Schlenk flask was added dropwise at this temperature through a cannula. The resulting mixture was warmed to $0 \text{ }^\circ\text{C}$ over a period of 2.5 h and stirred for additional 1 h at this temperature. Methanol (100 mL) was added and the volatiles were evaporated in vacuo. The last operation was repeated twice to give the desired compound as a colorless oil (24 g, 91% crude yield). This compound was used in the next step without any further purification. $^1\text{H NMR}$ (CDCl_3): δ 3.68 (s, 3H), 3.59-3.54 (m, 1H), 3.47-3.43 (m, 1H), 2.48-2.42 (dd, 1H), 2.26-2.13 (m, 2H), 1.95 (br s, 1H), 0.97-0.96 (d, 3H). $^1\text{H NMR}$ spectral data are consistent with those reported in the literature.^{1b,2b,3}

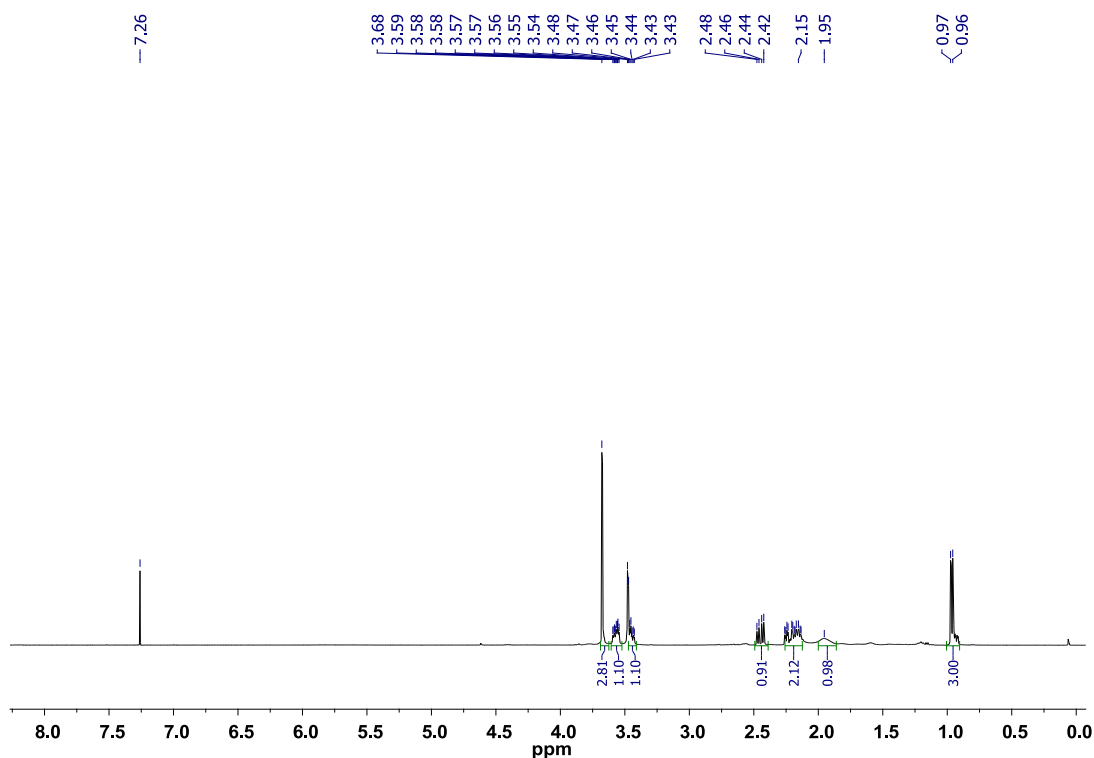
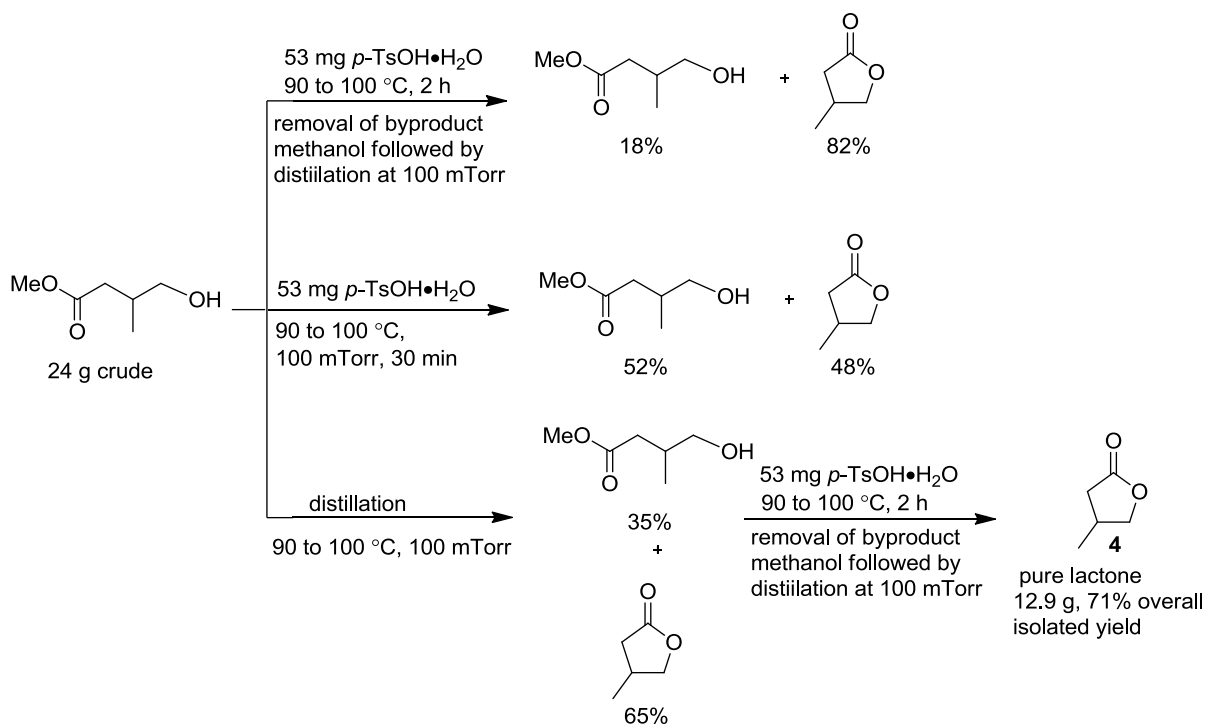


Figure S3. $^1\text{H NMR}$ (CDCl_3) spectrum of crude **3**.



β -Methyl- γ -butyrolactone (4). Distillation of crude compound **3** (24.0 g, 182 mmol) at 90-100 °C (100 mTorr) resulted in 35% of **3** and 65% of **4**, followed by removal of the by-product methanol under vacuum. This mixture was further treated with p -TsOH \cdot H₂O (53 mg, 0.27 mmol with respect to the crude compound **3**) and stirred for 2 h at 90 to 100 °C (or 24 h at RT), meanwhile the by-product methanol was removed (a complete removal of methanol is mandatory to achieve pure compound **4**, before distillation at 100 mTorr). The residue was distilled in vacuo (90-100 °C/100 mTorr) to give **4** (12.9 g, 71% overall isolated yield) as a colorless liquid. ¹H NMR (CDCl₃): δ 4.42-4.38 (m, 1H), 3.88-3.84 (m, 1H), 2.69-2.60 (m, 2H), 2.17-2.09 (m, 1H), 1.16-1.14 (d, 3H). ¹H NMR spectral data are consistent with those reported in the literature.^{2b}

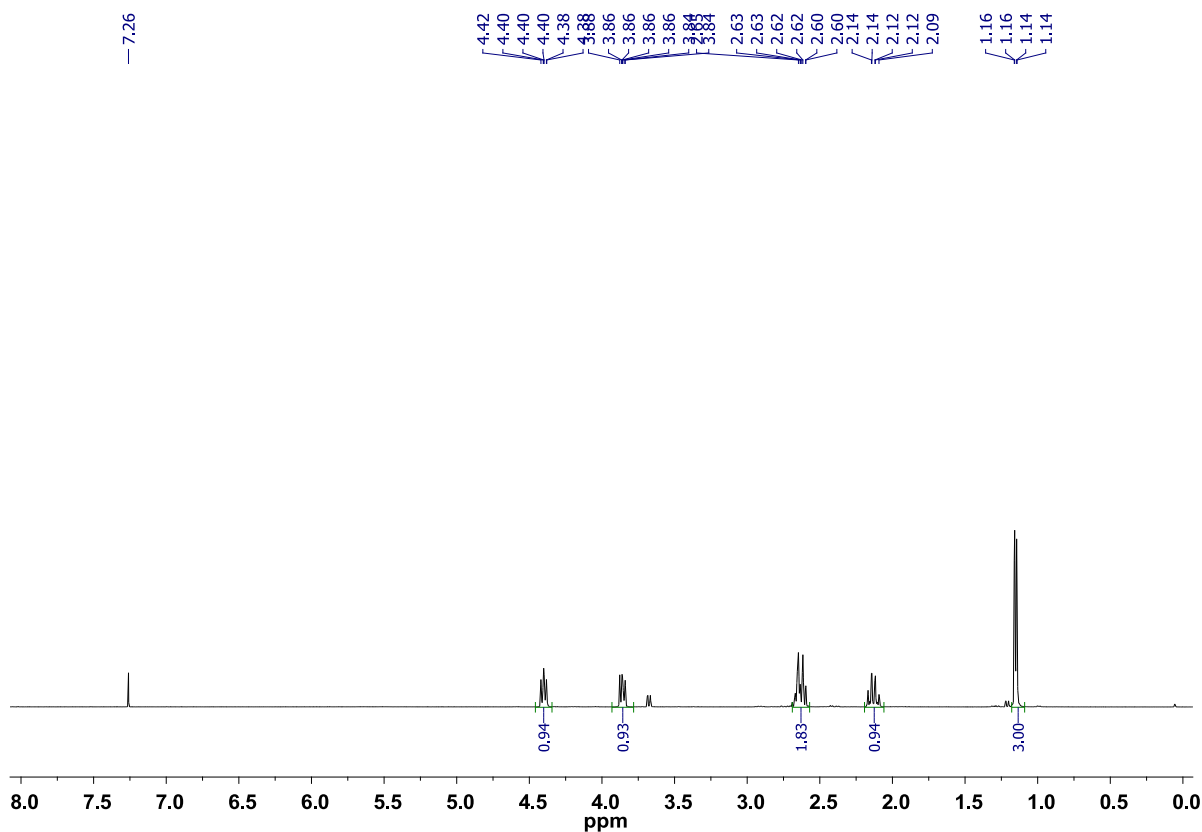
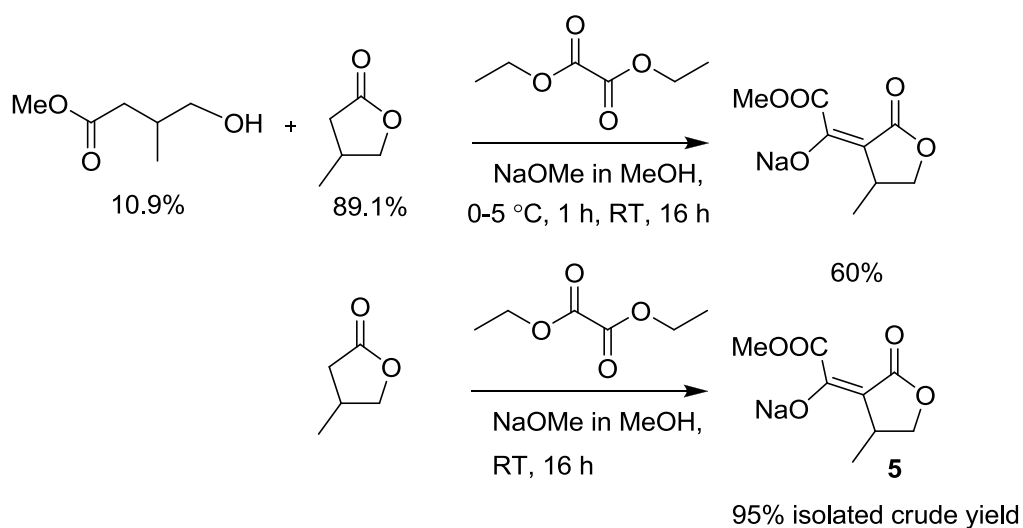


Figure S4. ^1H NMR (CDCl_3) spectrum of crude **4**.



Isolation of methyl oxalyl β -methyl- γ -butyrolactone sodium salt (5**).** In a 250 mL Schlenk flask, under an atmosphere of nitrogen in a glove box, sodium methoxide, 30% w/w in methanol (27 mL, 150 mmol) was added and capped with a rubber septum. This flask was interfaced with a Schlenk

line, purged with dry nitrogen gas at room temperature. Diethyl oxalate (20.7 g, 142 mmol) and **4** (12.9 g, 129 mmol) taken in another Schlenk flask was added dropwise at room temperature through a cannula. After complete addition, the mixture was stirred for 16 h, during which time a slurry was formed, affording a pale yellowish white cake (additional solvent is not required to perform this reaction). The solid cake was filtered and washed with either hexanes or ethanol (washing with hexanes resulted in more product as compared to ethanol, due to product solubility in ethanol). The cake was dried overnight under a vacuum to give 27.3 g, 95% yield with hexanes washing, or 16.6 g, 58% with the ethanol washing, of the desired product as a white to pale yellow solid. $^1\text{H NMR}$ (D_2O): δ 4.42-4.37 (t, 1H), 3.95-3.92 (dd, 1H), 3.84 (s, 3H), 3.27-3.22 (m, 1H), 1.19-1.18 (d, 3H).⁴

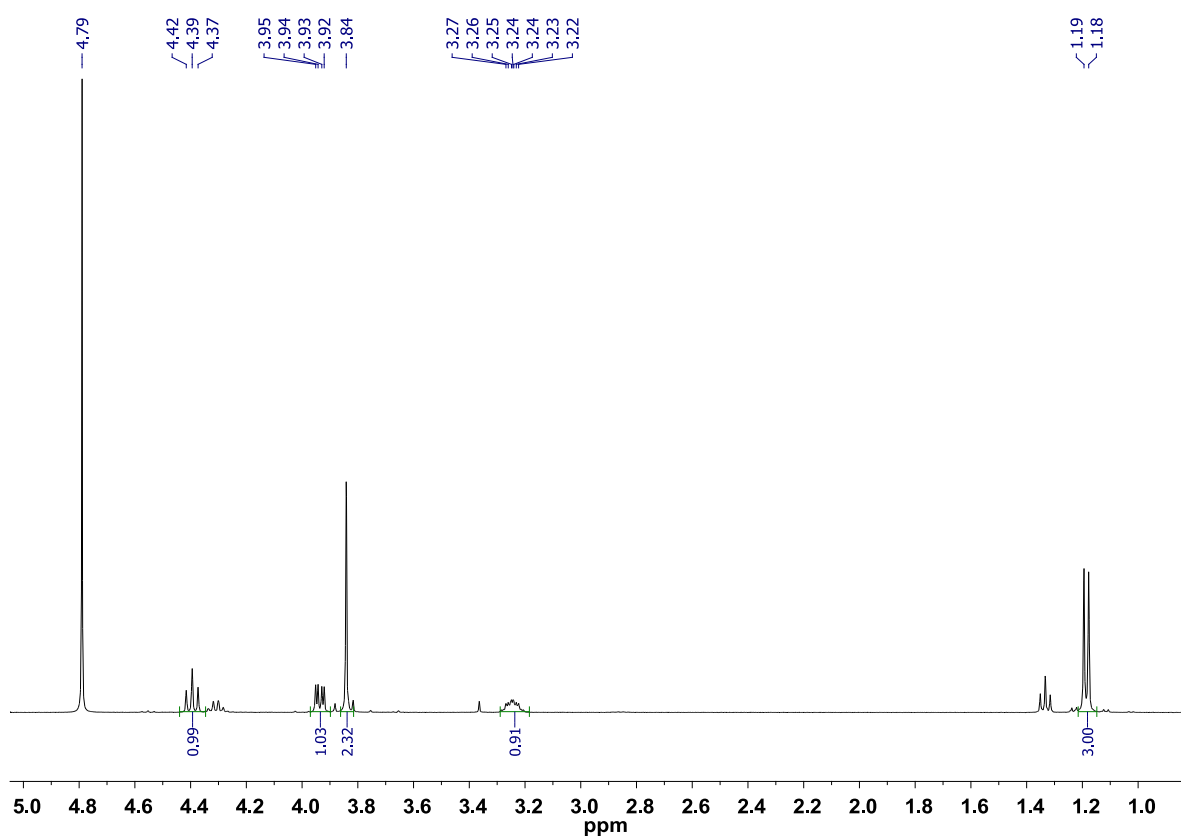
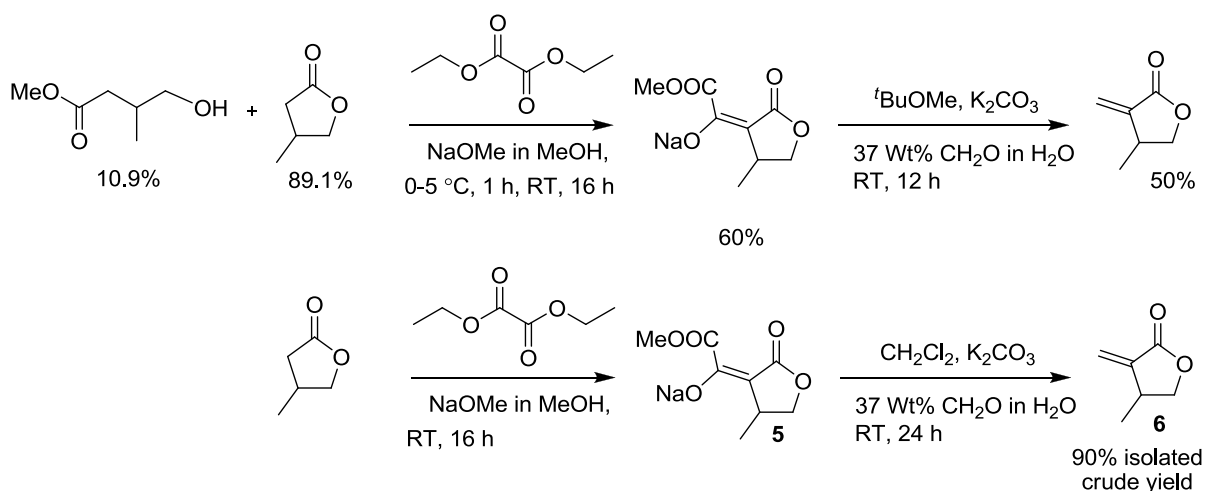


Figure S5. $^1\text{H NMR}$ (D_2O) spectrum of crude **5**.



β -Methyl- α -methylene- γ -butyrolactone (β -MMBL) (6**).** In a 1000 mL single-necked round-bottomed flask, **5** (27.3 g, 123 mmol) was added in 150 mL water and stirred at room temperature to obtain a homogeneous solution. This solution was cooled to below 10 °C with an ice/water bath followed by the addition of potassium carbonate (4.21 g, 30.5 mmol) and 250 mL of dichloromethane. After stabilization of temperature below 10 °C and complete mixing of both water and dichloromethane phases, aqueous formaldehyde (37 wt. % in water, 9.6 mL, 119 mmol) was added dropwise over 15 min and slowly warmed to room temperature over 24 h with stirring. The organic layer was separated from the aqueous layer and the aqueous layer was further extracted with dichloromethane (3×50 mL) (more water was added as needed to dissolve the byproduct salts, or the salts were filtered off before work up). All organic layers were combined and dried with sodium sulfate with the added polymerization inhibitor hydroquinone (20 mg). Dichloromethane was removed under reduced pressure and the residue was dried under vacuum to give 12.4 g (90%) of pure product **6** (spectroscopically pure with some small residual solvent peaks so further purification was not required) as a colorless liquid. 1H NMR ($CDCl_3$): δ 6.26-6.25 (d, 1H), 5.60-5.59 (d, 1H), 4.52-4.48 (t, 1H), 3.86-3.82 (m, 1H), 3.17-3.12 (m, 1H), 1.28-1.26 (d, 3H). 1H NMR spectral data are consistent with those reported in the literature.^{4,5}

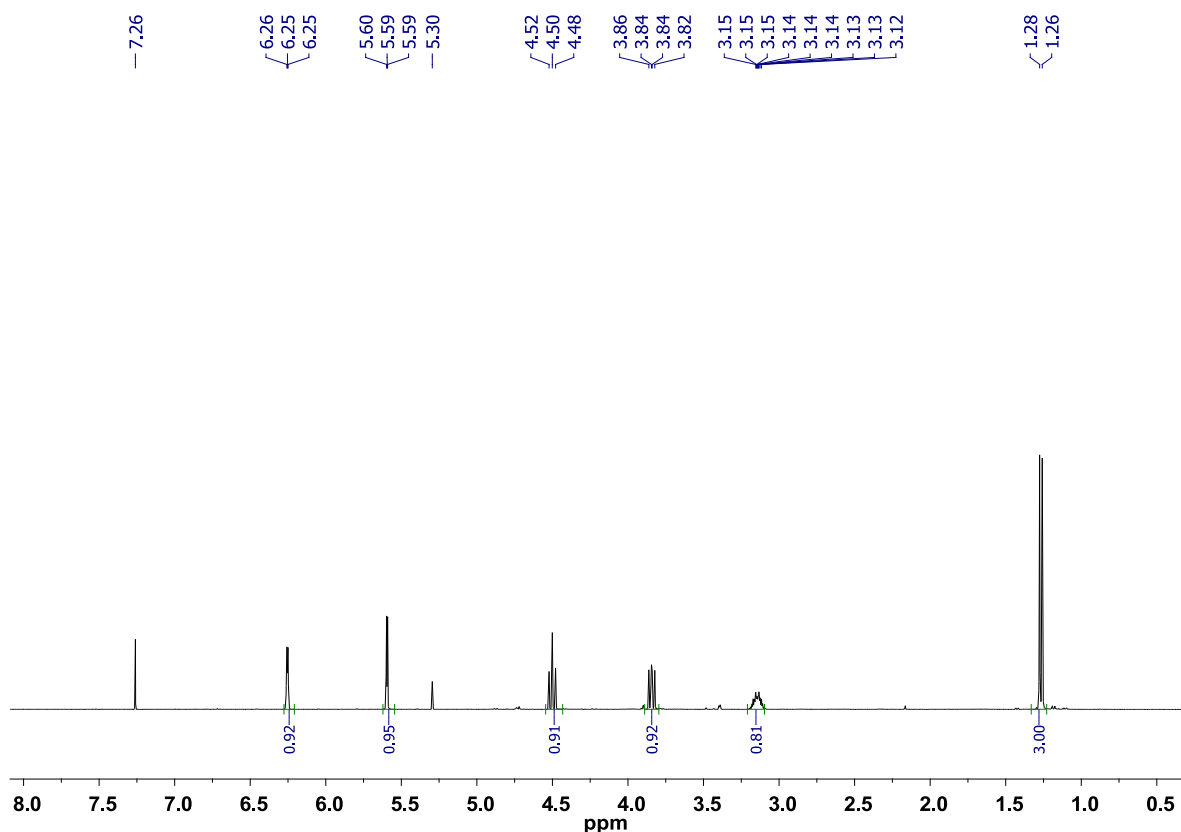


Figure S6. ^1H NMR (CDCl_3) spectrum of crude β -MMBL (**6**).

General Polymerization Procedures. Polymerizations were performed in 200 mL oven and flame-dried glass reactors inside the glovebox under ambient conditions (ca. 25 °C). In a typical procedure, a predetermined volume of $t\text{Bu}$ stock solution in DMF (8.91 mM, 1.0 mL, 8.91 μmol for a polymerization run with 10000 equiv. monomer relative to $t\text{Bu}$) was added to a solution of 45 mL of DMF and monomer (γ -MMBL or β -MMBL, 10.0 g, 89.2 mmol, 10000 equiv. relative to $t\text{Bu}$) under vigorous stirring. Likewise, for 30.00 g scale polymerization of γ -MMBL or β -MMBL (267.55 mmol), the $t\text{Bu}$ stock solution in DMF (26.75 mM, 3.0 mL, 26.75 μmol) and 70 mL DMF were used. For polymerizations of β -MMBL, toluene was first added to the reactor as an internal standard for measuring the monomer conversion. After the measured time interval, a 0.2 mL aliquot was taken from the reaction mixture via syringe and quickly quenched into a 1 mL vial containing 0.6 mL of undried “wet” CDCl_3 stabilized by 250 ppm of BHT-H; the quenched aliquots were later analyzed by

^1H NMR to obtain the percent monomer conversion data. The polymerization was quenched after completion by addition of 100 mL 5% HCl-acidified methanol for the 10 g scale run or 300 mL 5% HCl-methanol for the 30 g scale run. The quenched mixture was precipitated into 1000 mL of methanol for the 10 g scale run or 2500 mL of methanol for the 30 g scale run, stirred for 24 h, filtered, washed with methanol, and dried in a vacuum oven at 50 °C overnight to a constant weight.

Polymer characterizations. Polymer number-average molecular weights (M_n) and molecular weight distributions ($\text{MWD} = M_w/M_n$) were measured by gel permeation chromatography (GPC) analyses carried out at 40 °C and a flow rate of 1.0 mL/min, with DMF as the eluent, on a Waters University 1500 GPC instrument coupled with a Waters RI detector and equipped with four PLgel 5 μm mixed-C columns (Polymer Laboratories; linear range of molecular weight = 200–2,000,000). The instrument was calibrated with 10 poly(methyl methacrylate (PMMA) standards, and chromatograms were processed with Waters Empower software.

References

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