Electronic Supplementary Information

for

Sustainable Electroorganic Synthesis of Lignin-derived Dicarboxylic Acids

Anna Lisa Rauen,[a] Frank Weinelt,[b] Siegfried R. Waldvogel*[a]

[a] Department of Chemistry, Johannes Gutenberg University Mainz, Duesbergweg 10-14, 55128 Mainz, Germany. E-Mail: waldvogel@uni-mainz.de

[b] Evonik Resource Efficiency GmbH, Postal Area 16, Building 1227, Office 213 Paul-Baumann-Straße 1, 45772 Marl, Germany

Table of Contents

1. General Information

All reagents were used in analytical grades. Solvents were purified by standard methods.[1] For electrochemical reactions, Ni/P foam electrodes (average pore size Ø 1.4 mm) were applied. The material was obtained from AQUA TITAN, Dortmund, Germany. As power source, a Z60-3.5 device (TDK Lambda, Achern, Germany) with an output of 0–60 V (± 0.01 V) and 0–3.5 A (± 1 mA) was used. The electrolysis was carried out with a two-electrode set-up under galvanostatic conditions. ^{1}H NMR and ^{13}C NMR spectra were recorded at 298 K using a Bruker Avance II 400 or Bruker Avance III 600 spectrometer (Analytische Messtechnik. Karlsruhe, Germany). Chemical shifts (δ) are reported in parts per million (ppm) relative to traces of $CHCl_3$ in the corresponding deuterated solvent. High performance liquid chromatography (HPLC) was performed on a Shimadzu HPLC–MS system using an autosampler SIL-20AHT, a column oven CTO-20AC, two pump modules LC-20AD for adjusting the solvent mixtures, a diode array detector SPD-M20A, a communication BUS module CBM-20A, and an Eurospher II 100-5 C18 column 150x4 mm (Knauer, Berlin, Germany). HPLC-MS measurements were carried out on a LCMS-2020 (Shimadzu, Kyoto, Japan).

2. Electrochemical Set-Up

Beaker-type cell (25 mL)

The beaker-type cell (25 mL) consists of a simple glass beaker with cooling jacket and is closed by a PTFE plug (Figure S1). This cap allows precise arrangement of the electrodes in a distance of 12 mm. Dimensions of the used Ni foam anodes were 2.0 x 6.0 x 0.6 cm. Dimensions of the used stainless-steel cathode were 2.0 x 6.0 x 0.2 cm. The immersed part of the Ni foam anode had dimensions of 2.0 x 3.0 x 0.6 cm. A current of 30 mA was applied, resulting in a geometrical current density of 5 mA/cm². Terminal voltage in 25 mL beaker-type cells typically was in the range of 2-3 V.

Figure S 1: View of an undivided beaker-type cell of 25 mL volume with cooling/heating jacket.

Flow cell

The flow cell used was developed by the Waldvogel Lab and is now commercially available by IKA Werke GmbH & Co. KG, Staufen, Germany (ElectraSyn flow).[2] It consists of two Teflon-half cells, equipped with a stainless-steel cathode and a nickel anode. The system is modified by a Teflon spacer with a size of 10.0 x 4.0 x 0.7 cm and a cavity of 6.0 x 2.0 x 0.6 cm for the Ni/P foam. The backside of this cavity is formed like a grid, so that the electrolyte can flow through. The spacer has eight holes, so that the eight screws of the flow cell can go through and fix the spacer between the two half cells (Figure S 2). For pumping the electrolyte through the inside of the flow cell, a precision dosing pump (Ritmo® 05, Fink Chem+Tec GmbH & Co. KG, Staufen, Germany) is applied.

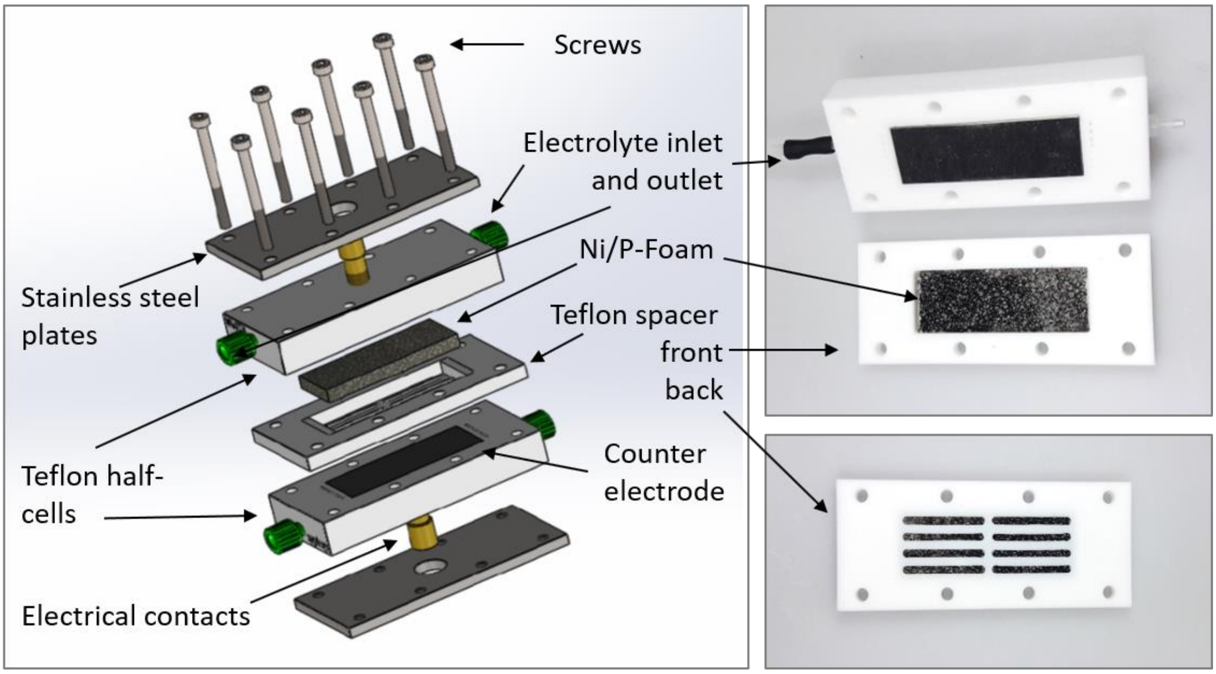


Figure S 2: Exploded view of all the parts of the flow cell with the Teflon spacer (left); Teflon spacer with foam electrode front and back view (right).

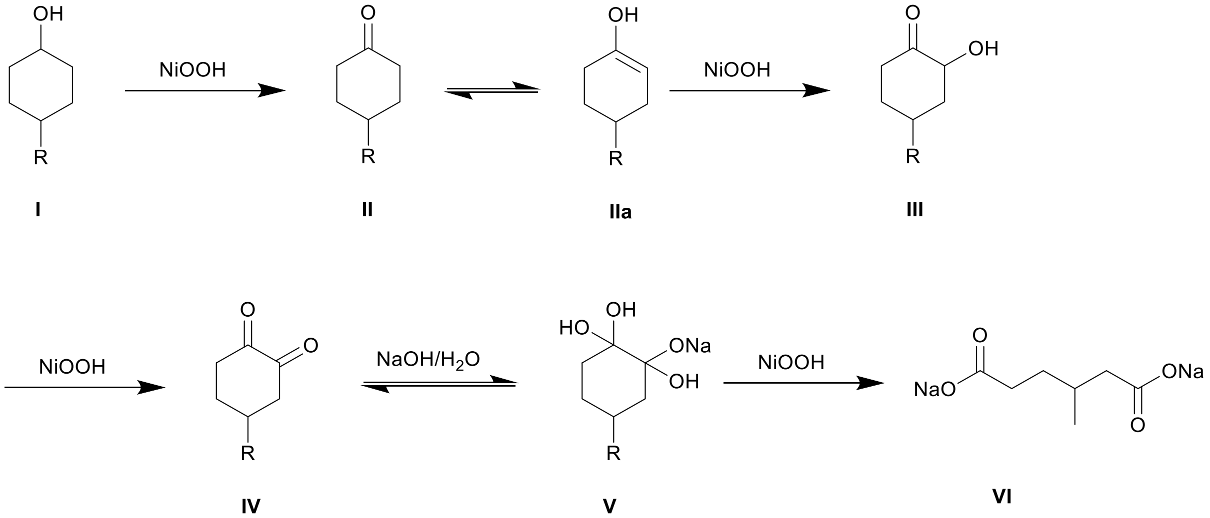
3. Activation of the Ni Electrode

The anodic deposition of nickel oxide hydroxide on Ni foam was carried out in an aqueous solution containing 0.05 M $NiSO_4 \cdot 6\ H_2O$, 0.1 M NaOAc, and 0.005 M NaOH. By reversal of electric polarity (0.1 s^{-1}), 200 C were applied with a current density of 3.5 mA/cm^2. The devices for the reversal of electric polarity were built in our workshop. With the use of a timer controlled reversing relay, the electrodes are reversed in polarity at adjustable intervals. After the activation, the electrodes were rinsed with water and dried at room temperature.

4. Electrochemical Reactions

4.1 Mechanism

The mechanistic concourse will most likely follow the work of Lyalin and Petrosyan.[3] Noteworthy, most of the intermediates were not unequivocally identified but follow the rationale known from this particular anode material NiOOH. The initial step for the sequence is the oxidation to the cyclohexanone (**II**) which is observed and can be used as alternative starting material as well. Most likely, the enol is oxidized at the NiOOH anode and subsequently further oxidized to dienone (**IV**). At alkaline conditions, this will readily add caustic soda and the vicinal alcohols and **V** will undergo the C-C bond cleavage to the target molecules. The formation of by-products like succinic and glutaric acid can occur via an additional enolisation and subsequent oxidation step starting from **III** or **IV,** which leads to two C-C bond cleavages. The species being involved in the initial and last steps are clearly identified, whereas the other ones can be rated as plausible.



4.2 Parameter Screening: Anodic Oxidation of 4-Methylcyclohexanol

Several essential reaction parameters were systematically studied in the batch approach with regard to their influence onto product yield: (i) electrode material, (ii) current density, (iii) amount of applied charge, (iv) temperature, and (v) electrolyte composition. The results are shown in the main manuscript. As an example, the screening of temperature is given here:

4-Methylcyclohexanol (2.5 mmol) and sodium hydroxide (1000 mg, 25.0 mmol) were dissolved in 25.0 mL H_2O and transferred to an undivided beaker-type cell (25 mL) equipped with a Ni anode and stainless-steel cathode (Figure S1). Under vigorous stirring, a constant current of 5 mA/cm^2 was applied until a charge of 8. F (1929 C) had passed. The alkaline solution was extracted three times with methyl *tert*-butyl ether (60 mL). The remaining aqueous layer was adjusted to pH 1 by addition of dilute H_2SO_4 (50 vol%). Then, the aqueous solution was extracted four times with EtOAc (80 mL). The combined organic layers from the EtOAc extraction steps were washed with brine and dried over Na_2SO_4. The product can be quantified by 1H NMR by comparing the integrals of the methyl group of 3-methyladipic acid. The reaction was carried out under 20 °C, 30 °C, 50 °C and 60 °C. The results are shown in Figure S 3. Raising the reaction temperature from 20 °C to 50 °C showed no significant influence on the conversion of the starting material. Higher temperatures than 50 °C decreased the conversion due to the volatility of the starting material.

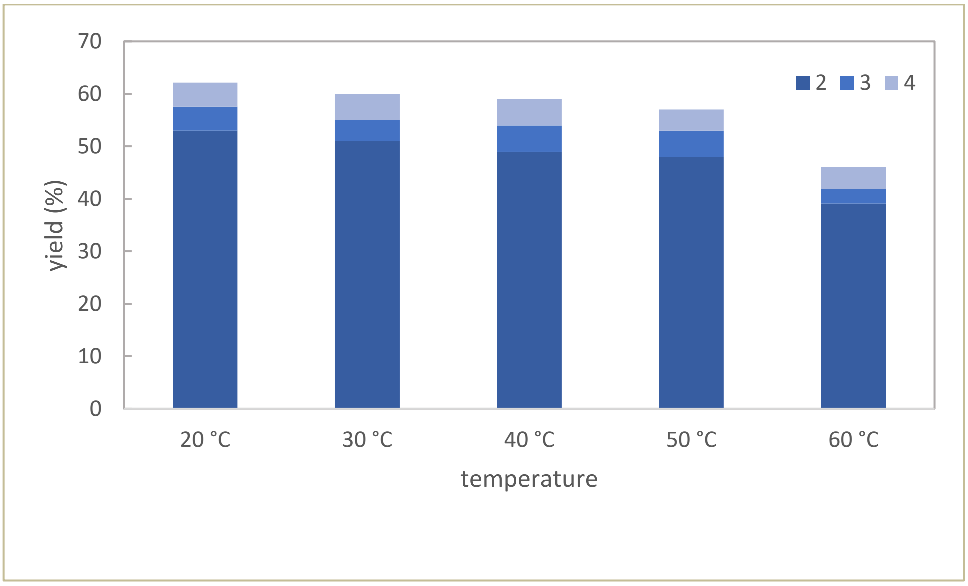
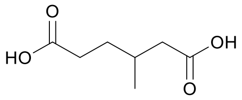


Figure S 3: Effect of temperature into the electrochemical synthesis of 3-Methyladipic acid (2).

4.3 General Procedure: Anodic Oxidation of Cyclohexanol in a Beaker-type Cell

Cyclohexanol (2.5 mmol) and sodium hydroxide (1000 mg, 25.0 mmol) were dissolved in 25.0 mL H_2O and transferred to an undivided beaker-type cell (25 mL) equipped with a Ni anode and stainless-steel cathode (Figure S 1). Under vigorous stirring, a current of 15 mA was applied until a charge of 8.5 F (2050 C) had passed. The alkaline solution was extracted three times with methyl *tert*-butyl ether (60 mL). The remaining aqueous phase was adjusted to pH 1 by addition of dilute H_2SO_4 (50 vol%). Then, the aqueous solution was extracted four times with EtOAc (80 mL). The combined organic layers from the EtOAc extraction steps were washed with brine and dried over Na_2SO_4. Concentration under reduced pressure gave the crude product. An aliquot of the crude product and an aliquot of 1,3,5-trimethoxybenzene as internal standard were dissolved in $CDCl_3$ to obtain a sample for ^{1}H and ^{13}C NMR characterization, inverse gated with a delay of 30 s. The amount of the formed dicarboxylic acid was determined by the integration ratio of the methoxy group of the standard and the carbonyl group of the product in the ^{13}C NMR spectrum.

3-Methyladipic acid

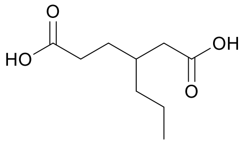


According to the general procedure, 285 mg (2.5 mmol) 4-methylcyclohexanol was added to 25 ml 1 M caustic soda. The reaction mixture was stirred, heated to 20 °C, and electrolysed until 8.5 F (2050 C) were applied at 5 mA/cm^2 (15 mA/6 cm^2). After the extraction procedure, 244 mg of the crude product were obtained. The NMR analysis with internal standard gave a yield of 53% 3-methyladipic acid. HRMS for $C_7H_{12}O_4$ (ESI$^-$) [M-H]$^-$: calc.: 159.0663, found: 159.0660.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 11.0 (bs, 2H). 2.52–2.16 (m, 4H), 2.05–1.97 (m, 1H), 1.78–1.69 (m, 1H), 1.59–1.50 (m, 1H), 1.00 (d, *J* = 6.7 Hz, 3H).

^{13}C (101 MHz, $CDCl_3$): δ [ppm] = 180.9, 179.6, 42.6, 31.8, 31.2, 26.7, 19.4.

3-Propyladipic acid

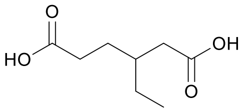


According to the general procedure, 355 mg (2.5 mmol) 4-propylcyclohexanol were added to 25 ml 1 M caustic soda. The reaction mixture was stirred, heated to 50 °C, and electrolysed until 8.5 F (2050 C) were applied at 2.5 mA/cm^2 (15 mA/6 cm^2). After the extraction procedure, 262 mg of the crude product were obtained. The NMR analysis with internal standard gave a yield of 36% 3-propyladipic acid. HRMS for $C_9H_{16}O_4$ (ESI$^-$) [M-H]$^-$: calc.: 187.0976, found: 187.0973.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 10.69 (bs, 2H), 2.42–2.22 (m, 4H), 1.95–1.88 (m, 1H), 1.72–1.65 (m, 2H), 1.33–1.29 (m, 4H), 0.96–0.83 (m, 3H).

^{13}C (101 MHz, $CDCl_3$): δ [ppm] = 180.3, 179.9, 38.64, 35.9, 34.1, 31.5, 29.1, 19.7, 15.1.

3-Ethyladipic acid

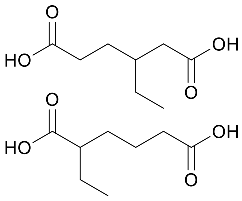


According to the general procedure, 320 mg (2.5 mmol) 4-ethylcyclohexanol were added to 25 ml 1 M caustic soda. The reaction mixture was stirred, heated to 50 °C, and electrolysed until 8.5 F (2050 C) were applied at 2.5 mA/cm^2 (15 mA/6 cm^2). After the extraction procedure, 264 mg of the crude product were obtained. The NMR analysis with internal standard gave a yield of 44% 3-ethyladipic acid. HRMS for $C_8H_{14}O_4$ (ESI$^-$) [M-H]$^-$: calc.: 173.0819, found: 173.0818.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] =10.56 (bs, 2H), 2.48–2.20 (m, 3H), 1.91–1.85 (m, 1H), 1.74–1.67 (m, 2H), 1.51–1.33 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H).

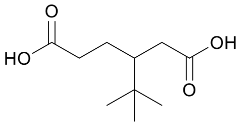
^{13}C (101 MHz, $CDCl_3$): δ [ppm] = 180.3, 179.9, 38.2, 35.7, 31.6, 28.1, 26.1, 9.9.

3-Ethyladipic acid/ 2-Ethyladipic acid mixture



According to the general procedure, 320 mg (2.5 mmol) 3-ethylcyclohexanol were added to 25 ml 1 M caustic soda. The reaction mixture was stirred, heated to 50 °C, and electrolysed until 8.5 F (2050 C) were applied at 2.5 mA/cm^2 (15 mA/6 cm^2). After the extraction procedure, 148 mg of the crude product were obtained. The NMR analysis with internal standard gave a yield of 12% 3-ethyladipic acid and 6% 2-ethyladipic acid. HRMS for $C_8H_{14}O_4$ (ESI$^-$) [M-H]$^-$: calc.: 173.0819, found: 173.0818.

3-*tert*-Butyladipic acid



According to the general procedure, 390 mg (2.5 mmol) 4-tertbutylcyclohexanol were added to 25 ml 1 M caustic soda. The reaction mixture was stirred, heated to 50 °C, and electrolysed until 8.5 F (2050 C) were applied at 2.5 mA/cm^2 (15 mA/6 cm^2). After the extraction procedure, 279 mg of the crude product were obtained. The NMR analysis with internal standard gave a yield of 30% 3-*tert*-butyladipic acid. HRMS for $C_{10}H_{18}O_4$ (ESI$^-$) [M-H]$^-$: calc.: 201.1132, found: 201.1132.

^{1}H NMR (400 MHz, $CDCl_3$): δ [ppm] = 11.03 (bs, 2H), 2.58–2.34 (m, 3H), 2.14–2.08 (m, 7.4 Hz, 1H), 2.00–1.92 (m, 1H), 1.80–1.64 (m, 1H), 1.52–1.36 (m, 1H), 0.92 (s, 9H).

^{13}C (101 MHz, $CDCl_3$): δ [ppm] = 181.1, 180.4, 43.9, 36.0, 33.8, 33.6, 27.4, 26.1.

4.4 Anodic Oxidation of 4-Methylcyclohexanol in a Flow Cell

4.4.1 Continuous Flow

For a continuous flow electrolysis, the activation of the nickel foam was carried out in the flow cell (Figure S 2). Afterwards the cell was rinsed with water. The electrolyte was prepared as a solution of 1 M NaOH and 0.1 M 4-methylcyclohexanol in water. Vigorous stirring was necessary for a properly mixed electrolyte. The electrolyte was pumped through the flow cell with 47 µL/min. Electric current was applied to the cell with 5 mA/cm^2 (geometrical current density), so that a charge amount of 8 F was reached after collecting 25 mL of electrolyte. The first 9 mL of electrolyte pumped through the cell under current flow were discarded, the following 25 mL were collected, and processed according to the work-up procedure for the batch electrolysis. The NMR analysis with internal standard gave a yield of 51% 3-methyladipic acid.

4.4.2 Circular Flow

For a circular flow electrolysis, the activation of the nickel foam was carried out in the flow cell. Afterwards the cell was rinsed with water. Cyclohexanol (2.5 mmol) and sodium hydroxide (1000 mg, 25.0 mmol) were dissolved in 25.0 mL H_2O and transferred to a temperature-controlled reservoir. Vigorous stirring was necessary for a properly mixed electrolyte. The electrolyte was pumped through the flow cell with 10 mL/min. The outlet of the flow cell went back to the reservoir. A charge amount of 8 F was applied with 5 mA/cm^2 (geometrical current density). After the electrolysis, the electrolyte was processed according to the work-up procedure for the batch electrolysis. The NMR analysis with internal standard gave a yield of 64% 3-methyladipic acid.

5. NMR Spectra

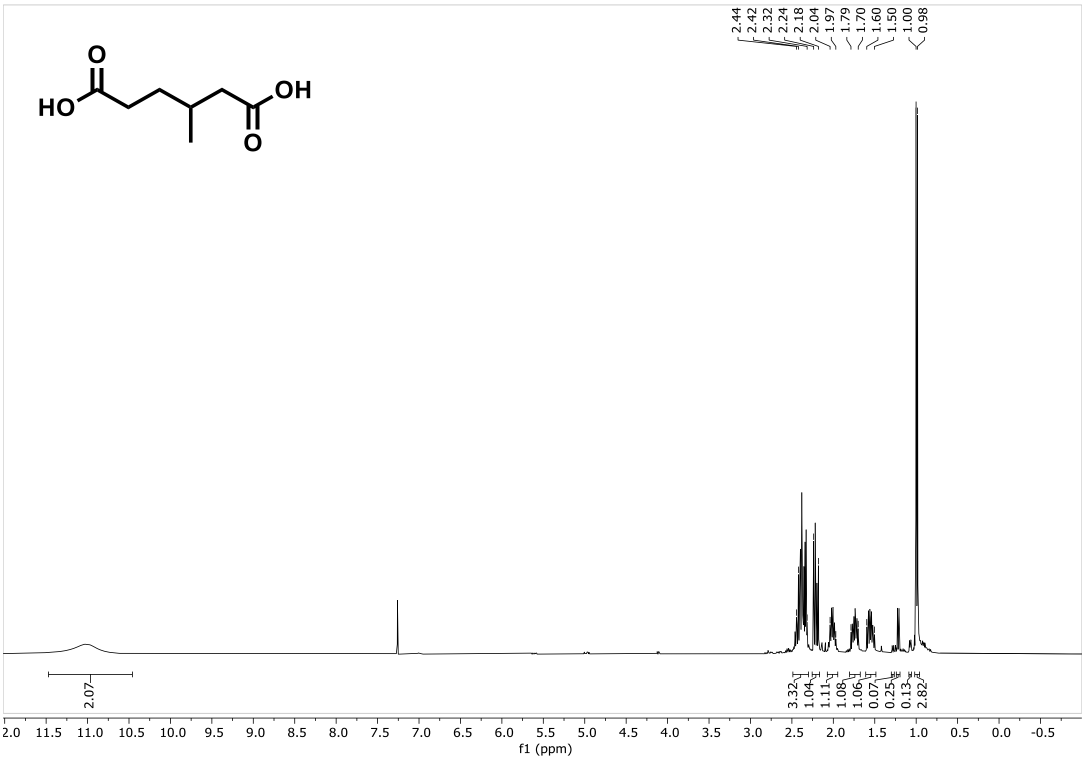


Figure S4: 400 MHz ^{1}H NMR spectra of 3-methyladipic acid in $CDCl_3$.

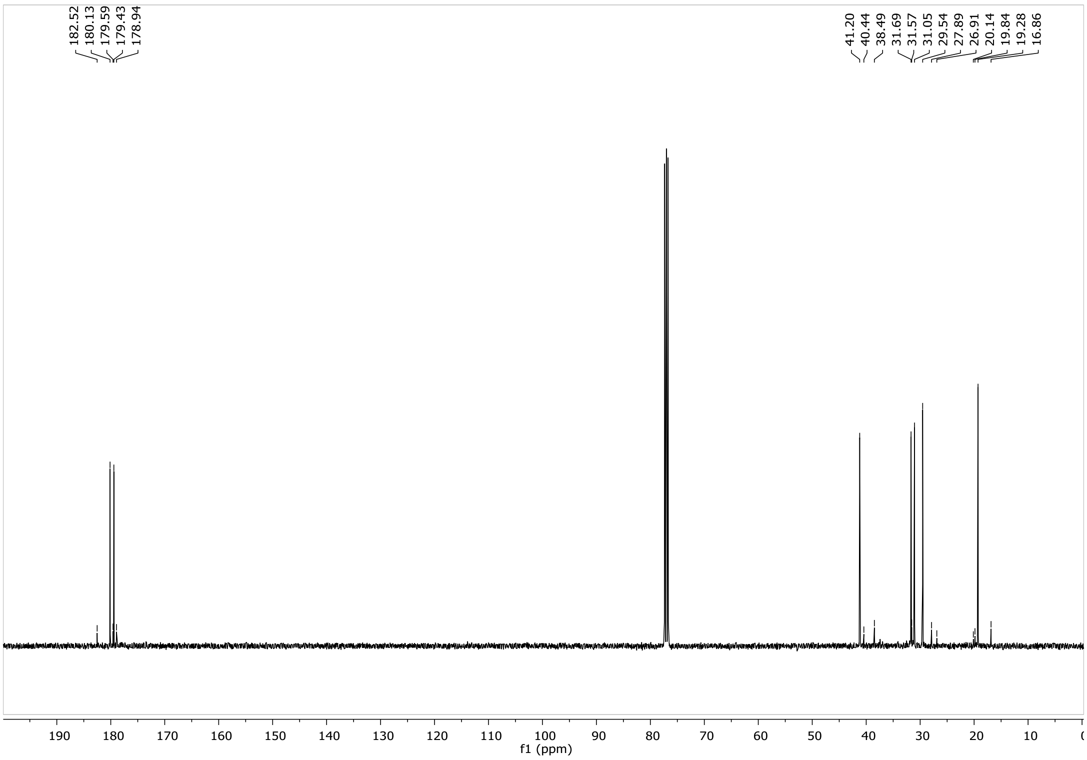


Figure S5 101 MHz ^{13}C NMR spectra of 3-methyladipic acid in $CDCl_3$.

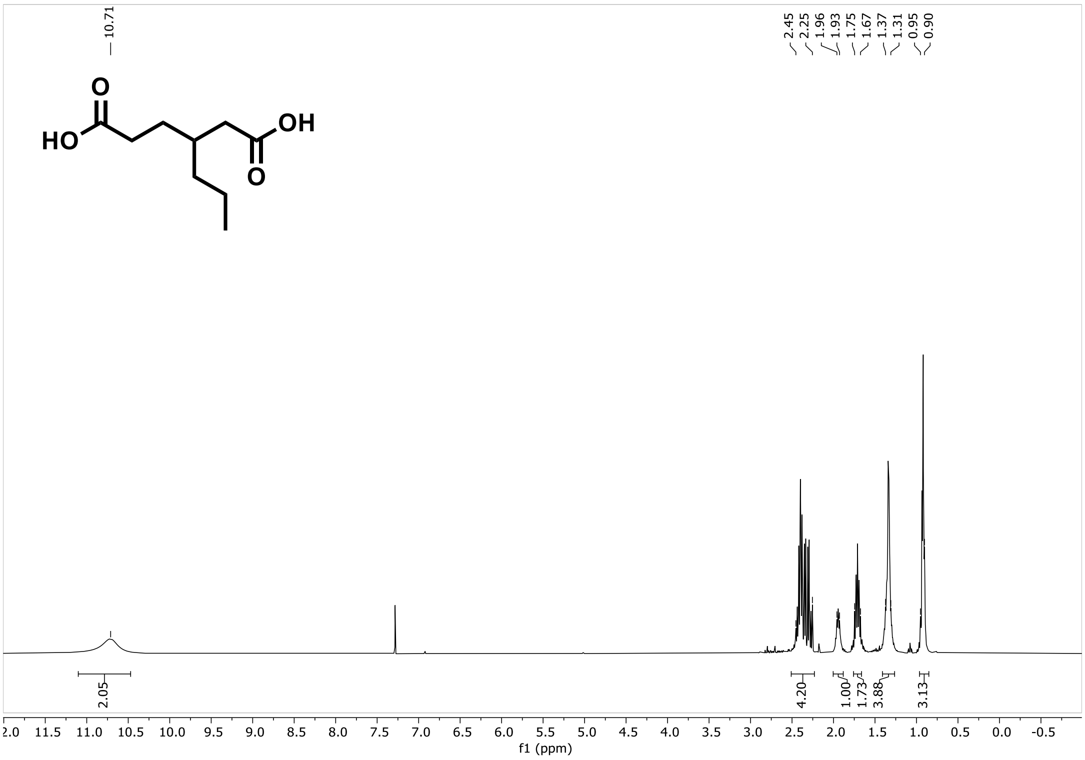


Figure S6: 400 MHz ^{1}H NMR spectra of 3-propyladipic acid in $CDCl_3$.

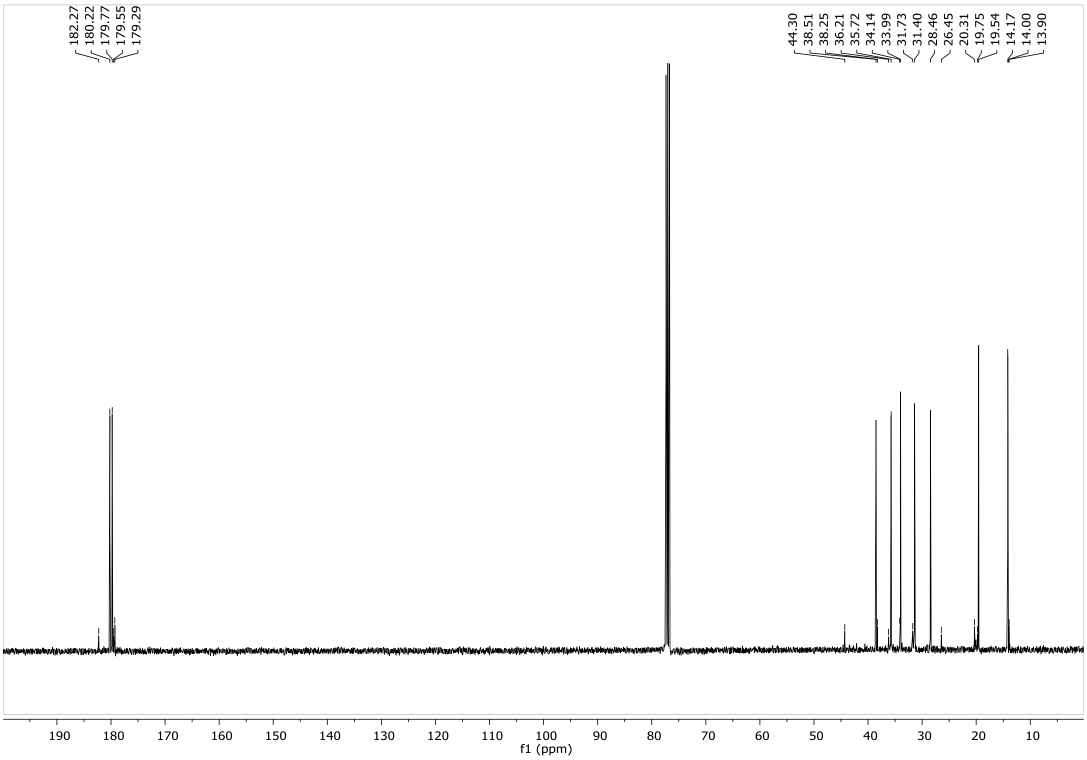


Figure S7: 101 MHz ^{13}C NMR spectra of 3-propyladipic acid in $CDCl_3$.

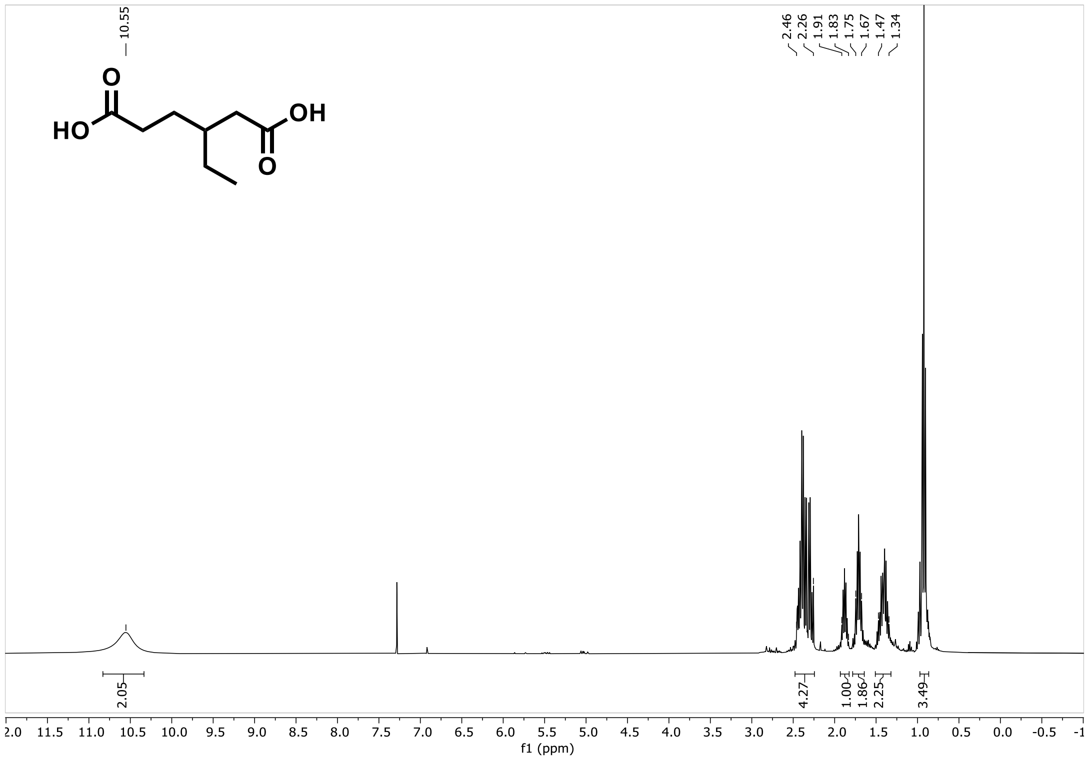


Figure S8: 400 MHz ^1H NMR spectra of 3-ethyladipic acid in $CDCl_3$.

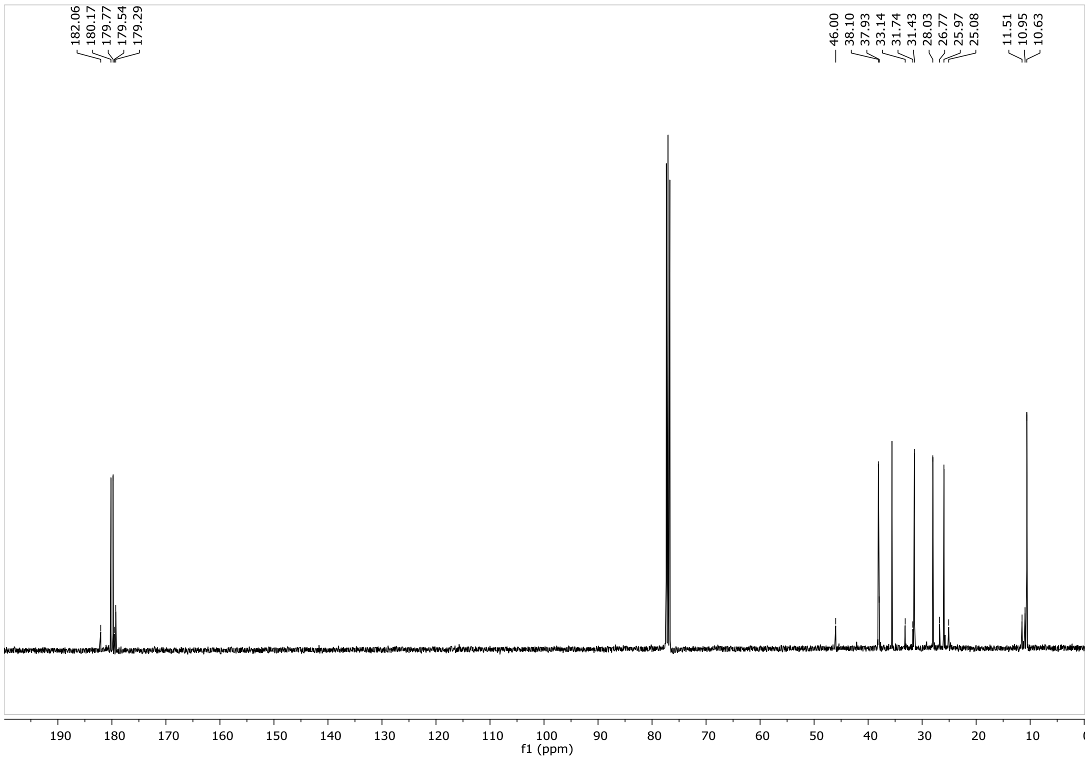


Figure S9: 101 MHz ^{13}C NMR spectra of 3-ethyladipic acid in $CDCl_3$.

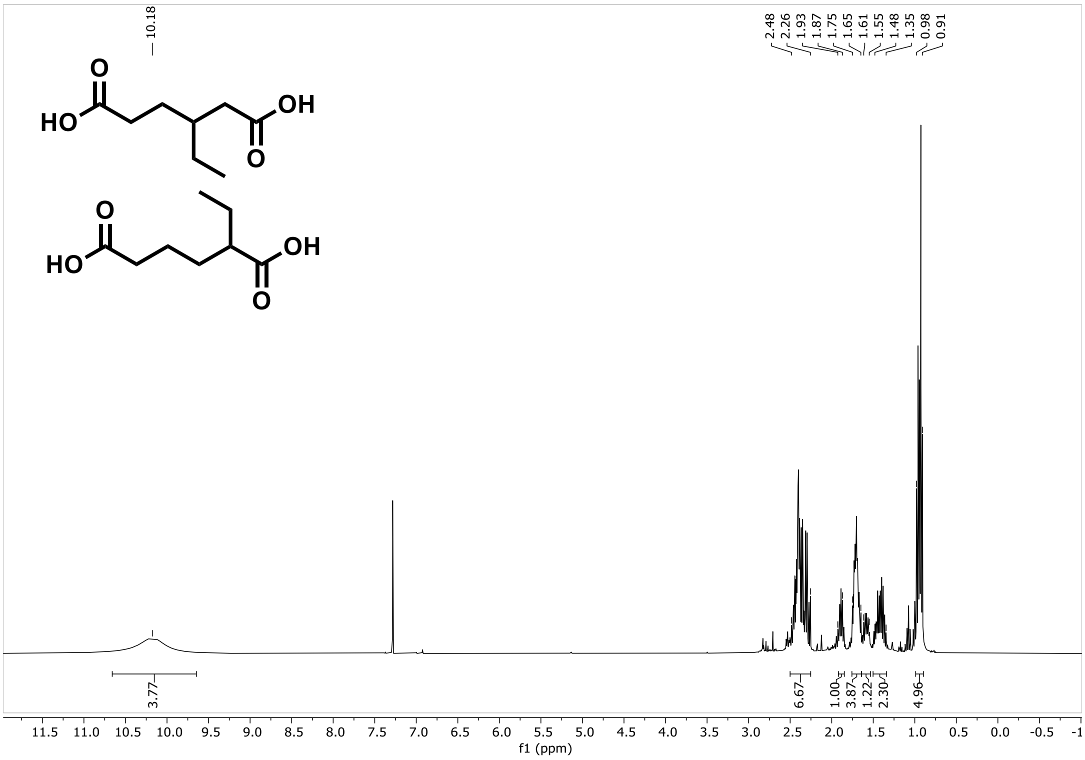


Figure S10: 400 MHz ^{1}H NMR spectra of 2-ethyladipic and 3-ethyladipic acid in $CDCl_3$.

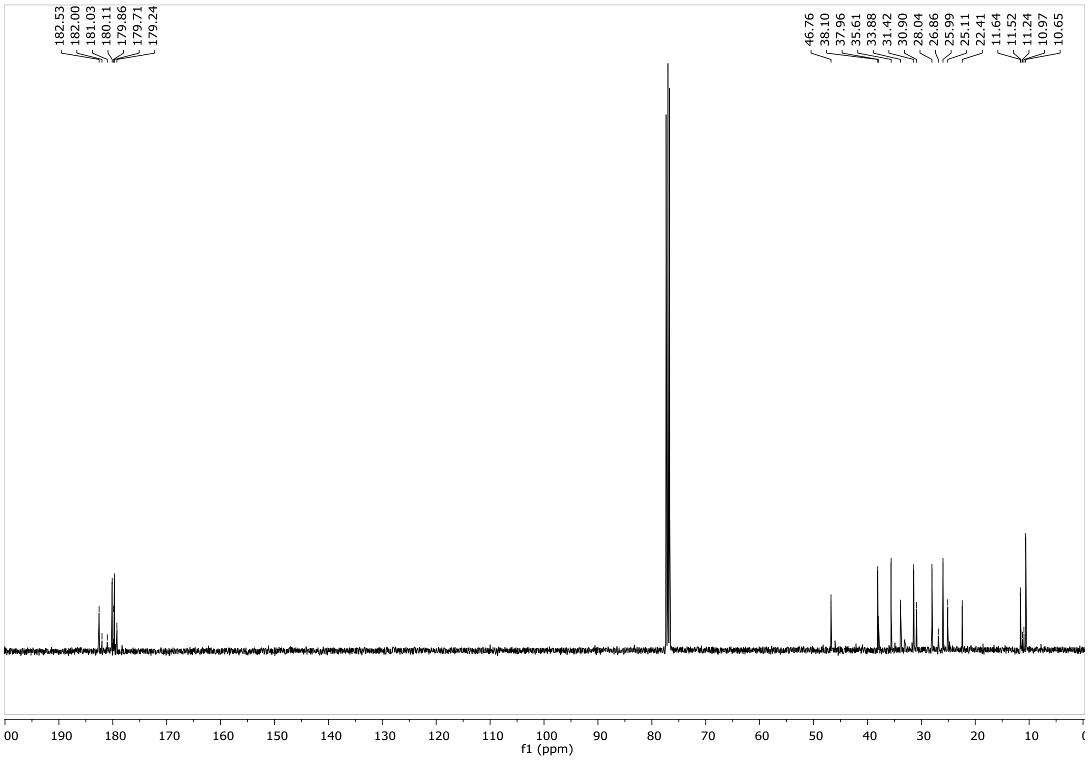


Figure S11: 101 MHz ^{13}C NMR spectra of 2-ethyladipic acid and 3-ethyladipic acid in $CDCl_3$.

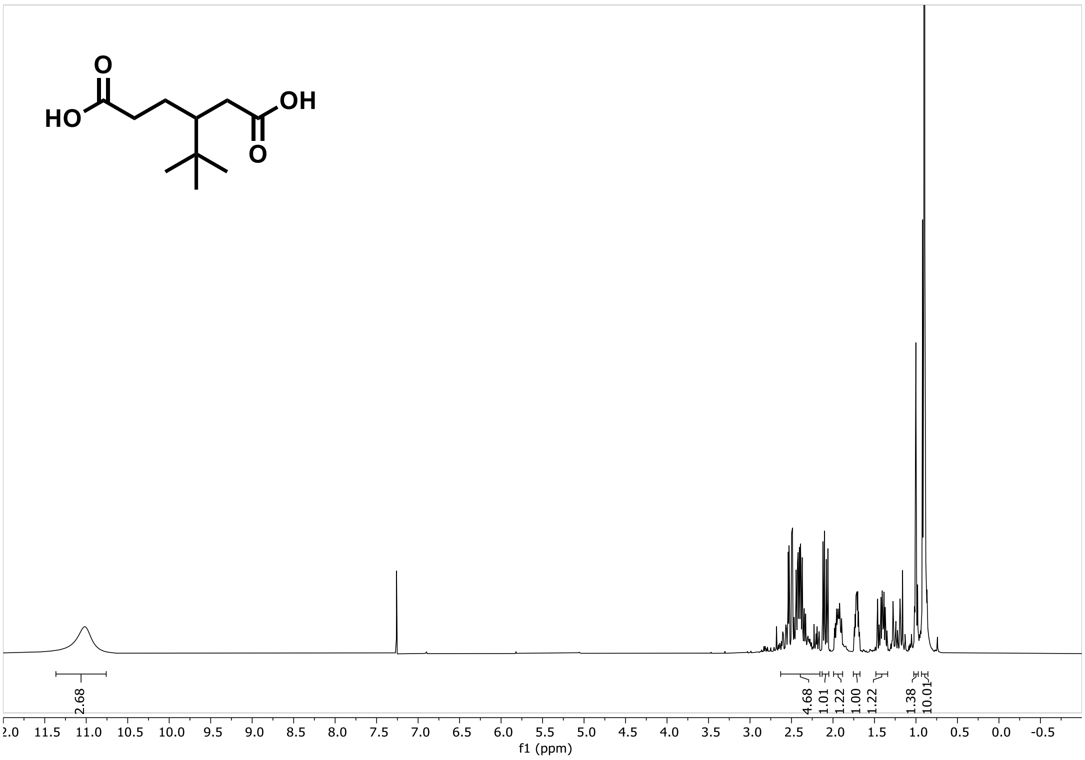


Figure S12: 400 MHz ^{1}H NMR spectra of 3-butyladipic acid in $CDCl_3$.

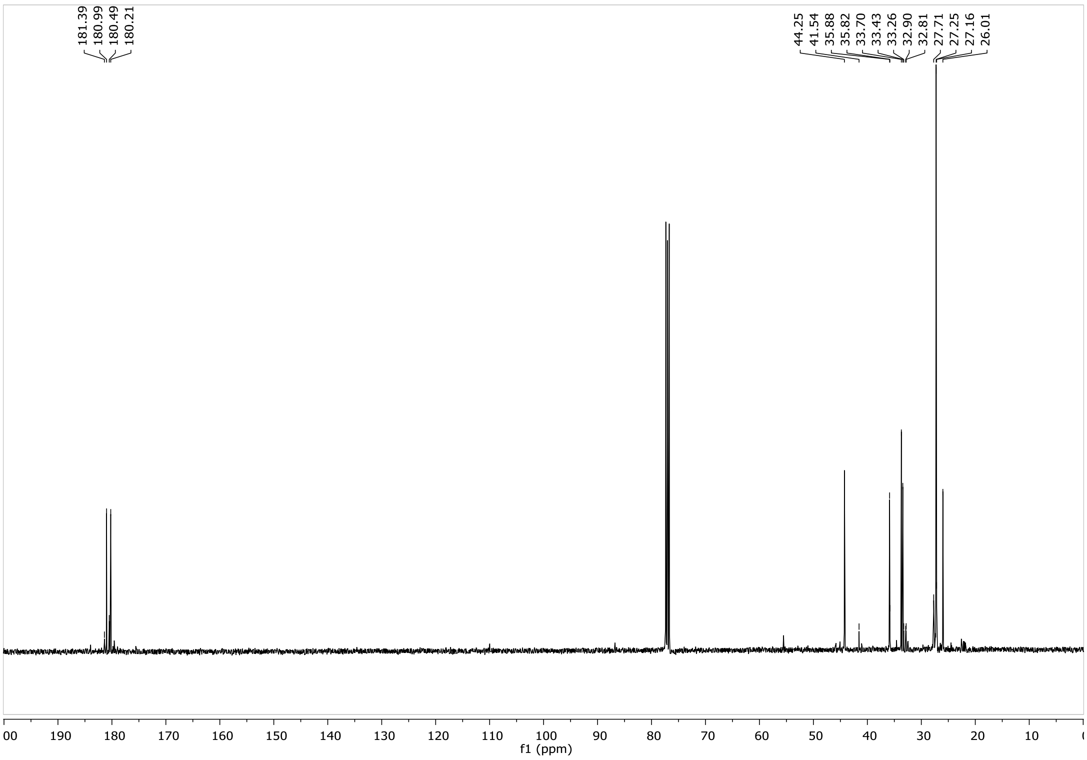


Figure S13: 101 MHz ^{13}C NMR spectra of 3-butyladipic acid in $CDCl_3$.

6. References

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2 a) C. Gütz, A. Stenglein, S. R. Waldvogel, *Org. Process Res Der.* 2017, **21**, 771; b) B. Gleede, M. Selt, C. Gütz, A. Stenglein, S. R. Waldvogel, *Org. Process Res. Dev*. 2020, **24**, in press.

3 B. V. Lyalin and V. A. Petrosyan, *Russ. J. Electrochem.*, 2010, **46**, 1199–1214.