ChemistryOPEN

Supporting Information

Methyl Perillate as a Highly Functionalized Natural Starting Material for Terephthalic Acid

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Supporting Information

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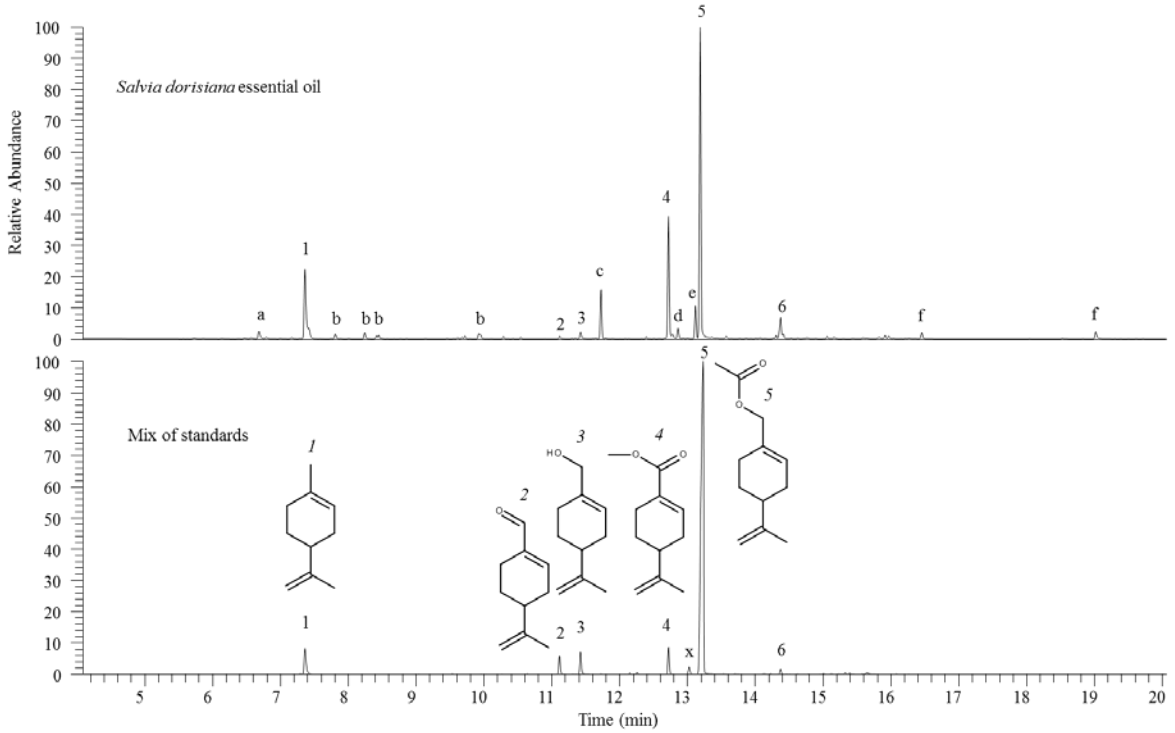


Figure S1 GC-MS chromatogram of *Salvia dorisiana* esssential oil and a mix of standards. Essential oil concentration was 53.2 µg/mL in pentane, with 4.66 µg/mL cis-nerolidol (internal standard). Shown is total ion count (TIC), 100% = 5.13E6. Standard mix consisted of limonene (1) 8.36 µg/mL, perillyl aldehyde (2) 5.36 µg/mL, perillyl alcohol (3) 5.27 µg/mL, methyl perillate (4) 6.68 µg/mL, perilla acetate (5) 4.62 µg/mL and cis-nerolidol (6) 4.66 µg/mL in pentane, shown is TIC, 100%=2.20E7. Identity of compounds a-f and x was determined by library hit: α-myrcene (a), some monoterpenes (b), myrtenyl acetate (c), a monoterpene acetate (d), caryophyllene (e), some sesquiterpenes (f), and in the standard mix there was a small contamination of cuminyl acetate (x).

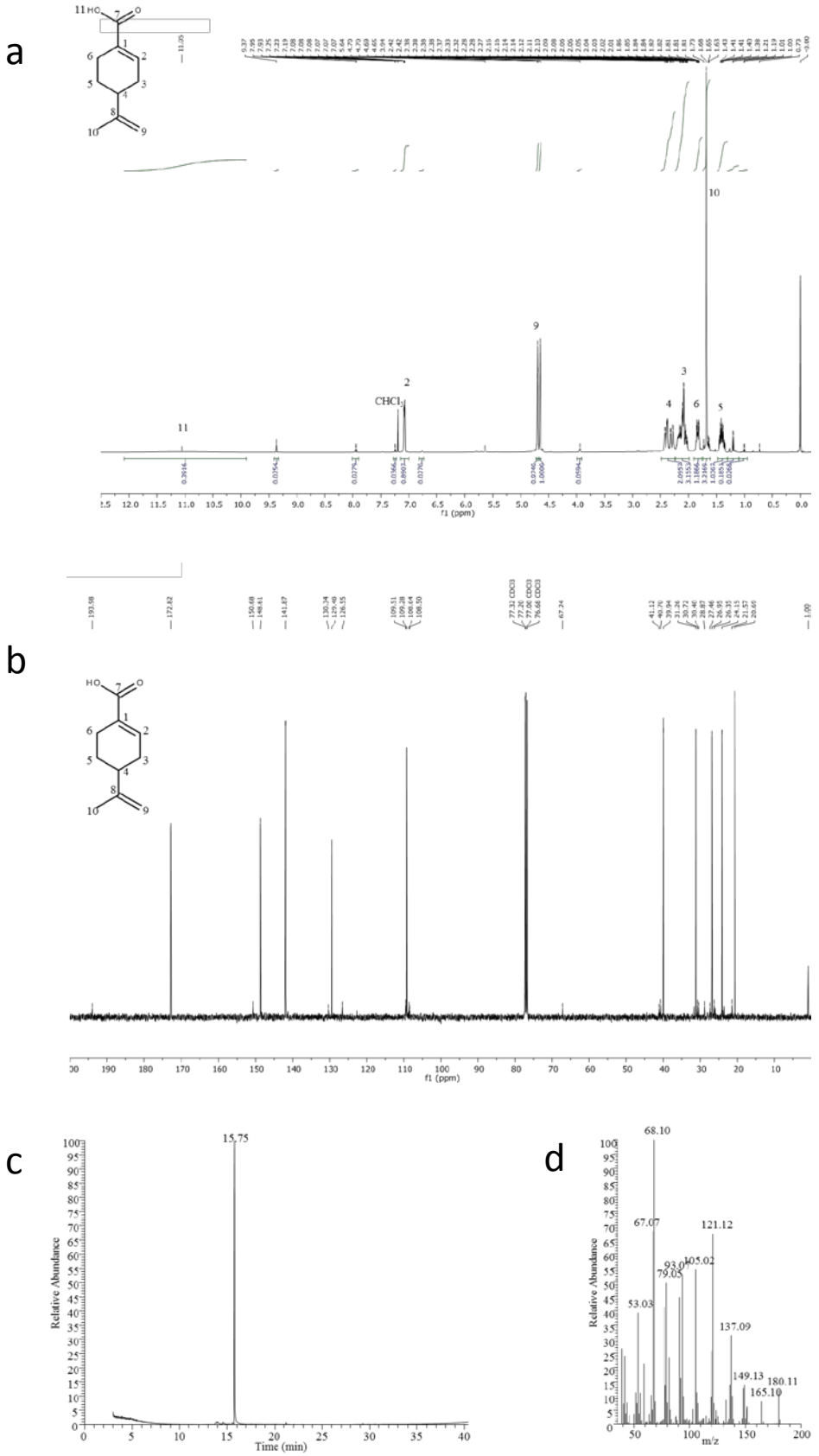


Figure S2 Oxidation of perillyl aldehyde with a silver oxide catalyst yielded near pure PA a. ^{1}H-NMR spectrum of product in $CDCl_3$, PA peak numbers are indicated, b. ^{13}C-NMR spectrum in $CDCl_3$, peak numbers indicated, c. GC-MS chromatogram (product in $CHCl_3$ methylated with TMSH), peak of methylperillate is visible at RT 15.75, d. Mass spectrum of the methylperillate peak at RT 15.75.

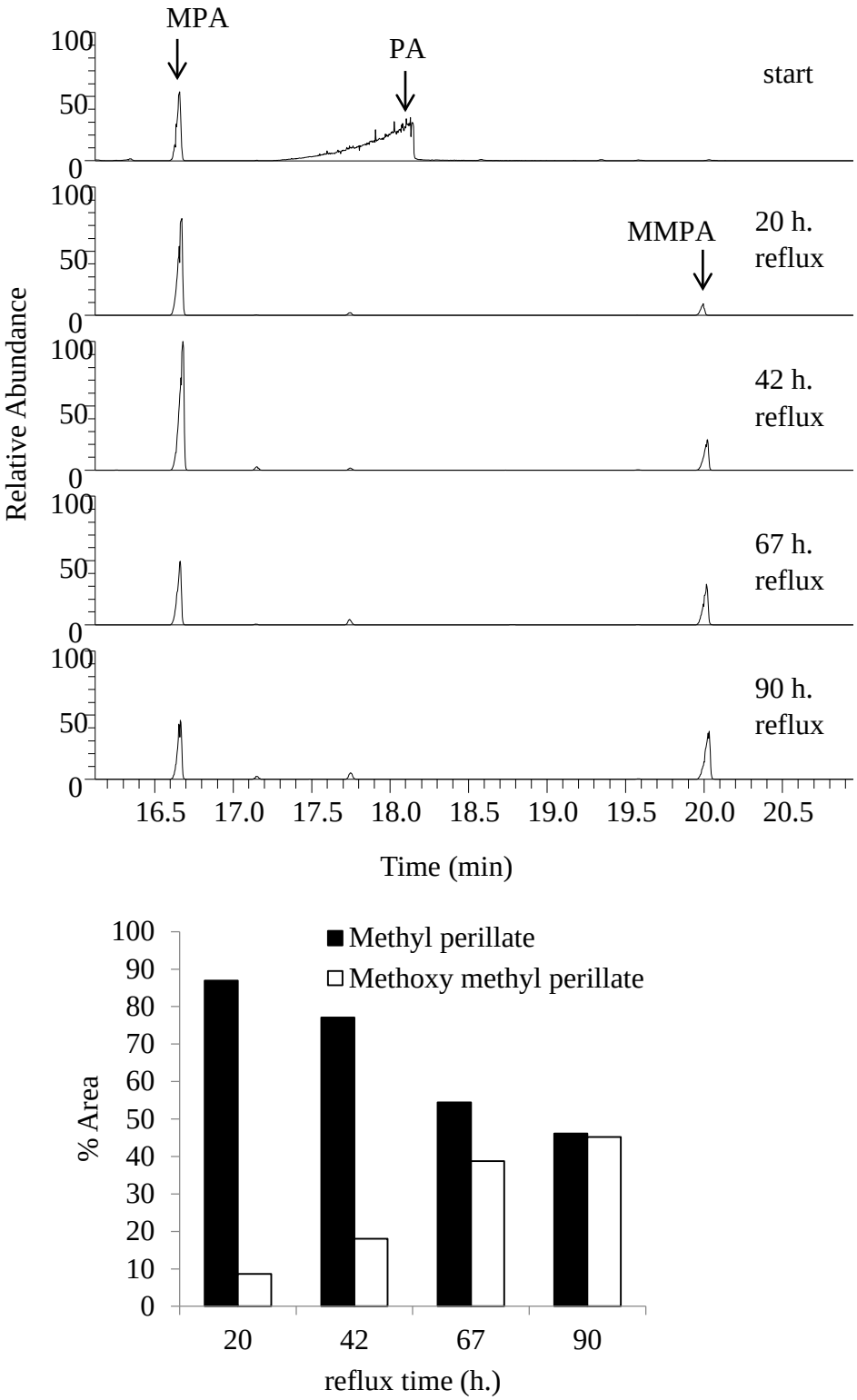
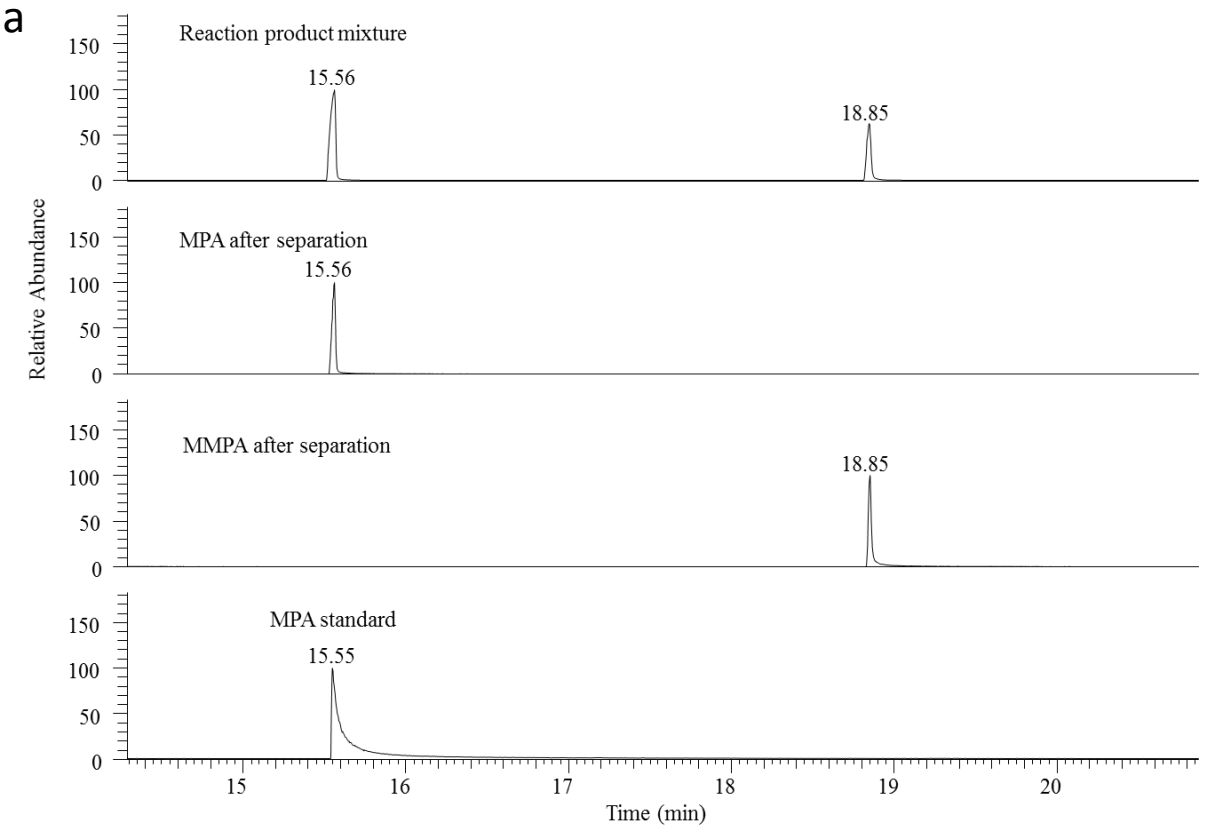
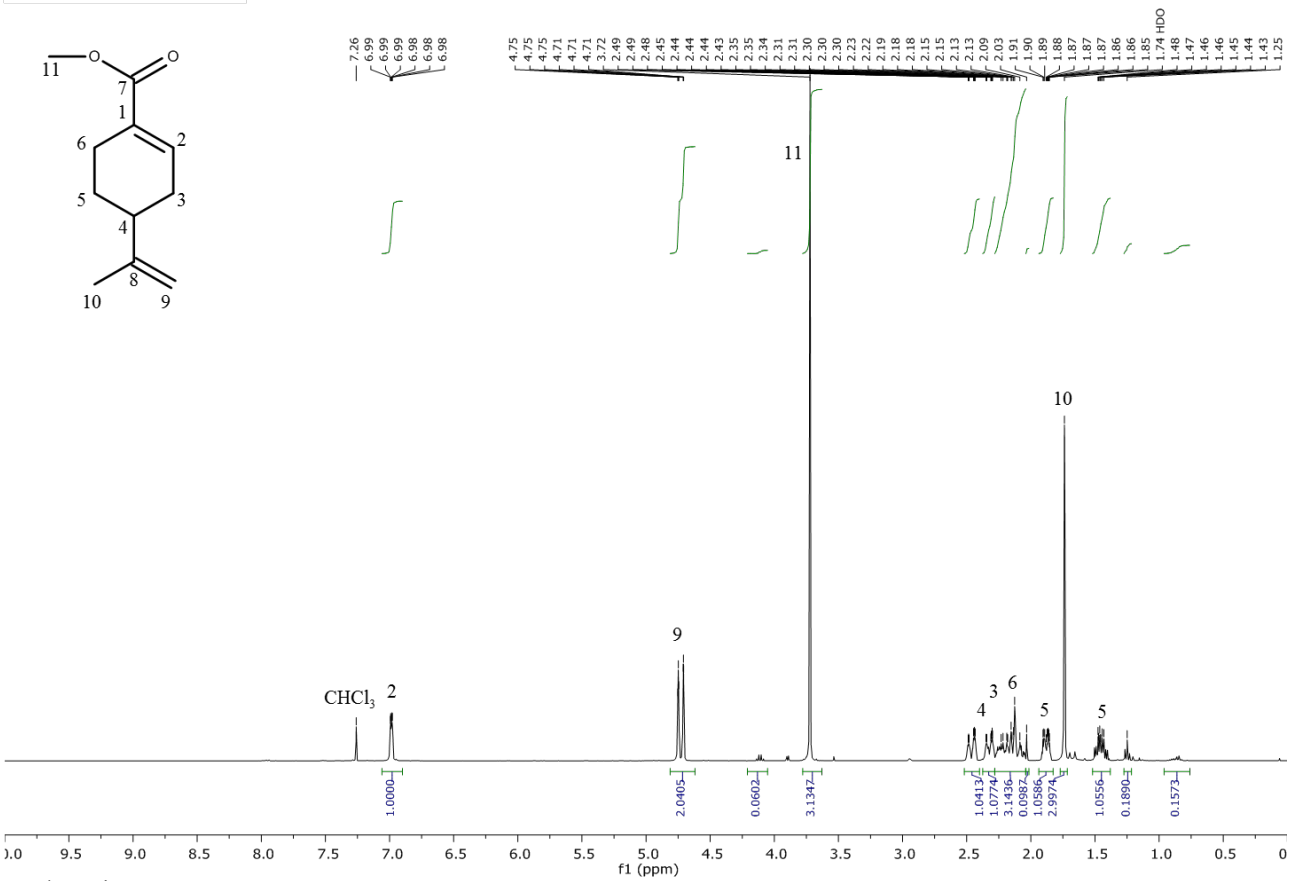


Fig. S3 GC-MS chromatograms of the methylation reaction of perillic acid (PA) to methylperillate (MPA) at different time-points, reaction samples diluted in chloroform and dried over MgSO4. The reaction yielded 8-methoxy-methyl perillate (MMPA) as a by-product. The longer the reaction time, the more MMPA was formed. At RT 17.75 a peak of another minor by-product is visible, the amount of this by-product increased with time as well. A short reaction time of 21 h ensured complete conversion of PA to MPA and small amount of the by-products, which could be readily separated by column-chromatography.

Fig. S4 Methylation of perillic acid with p-TSA yielded a mixture of methylperillate (MPA) and methoxymethylperillate (MMPA). The mixture could be readily separated with column chromatography or Kugelrohr distillation a. GC-MS chromatograms of the reaction product mixture, MPA and MMPA products after separation and an MPA reference standard, b-d. characterization of MPA after separation, b. ^{1}H-NMR in $CDCl_3$ of MPA, c. ^{13}C-NMR (100.62 MHz, $CDCl_3$) of MPA, d. FT-IR of MPA, e-j. characterization of MMPA after separation, e. MS spectrum of methoxy methyl perillate (GC peak at RT 18.85), f. ^{1}H-NMR ($CDCl_3$) of MMPA, g. ^{13}C-NMR (100.62 MHz, $CDCl_3$) of MMPA, h. FT-IR of MMPA, i. DEPT135 spectrum of MMPA, j. 2D-HSQC ($CDCl_3$) spectrum of MMPA





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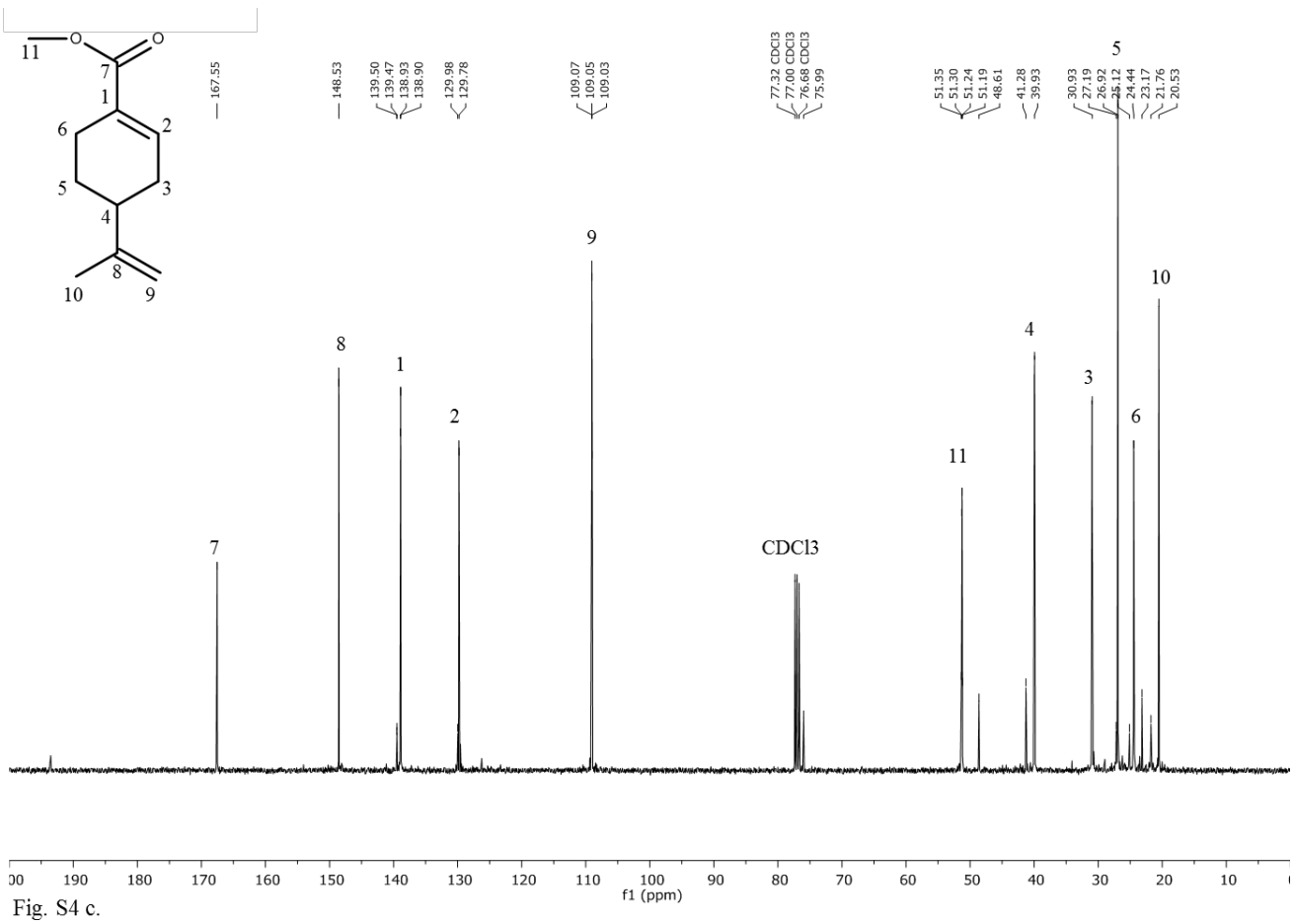

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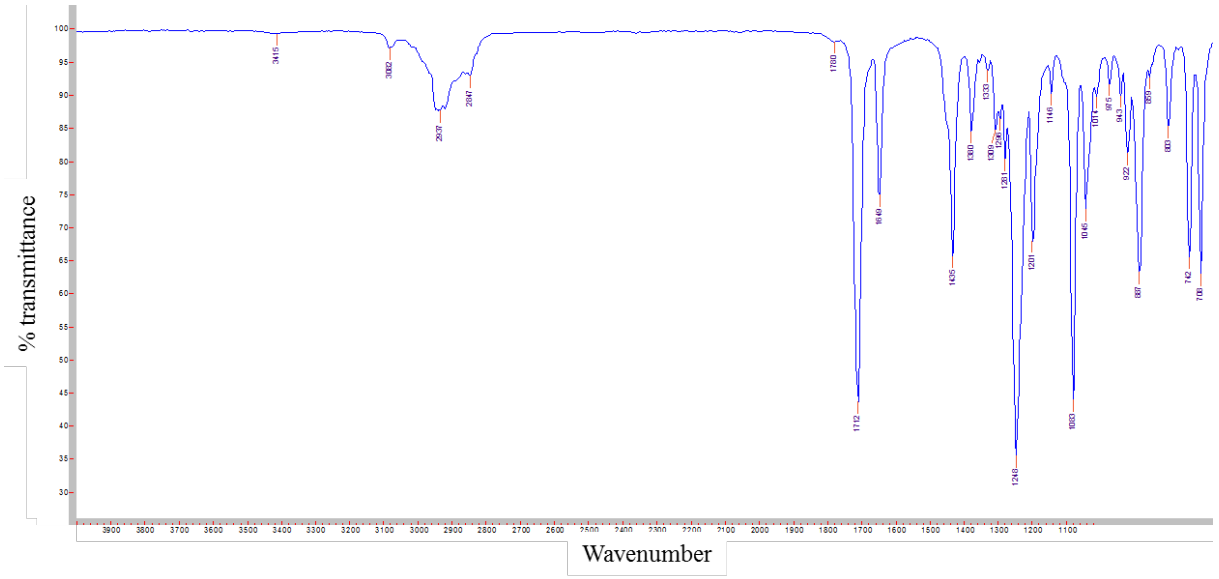

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Peak2	742	Peak8	1083	Peak14	1435
Peak3	803	Peak9	1146	Peak15	1649
Peak4	887	Peak10	1201	Peak16	1712
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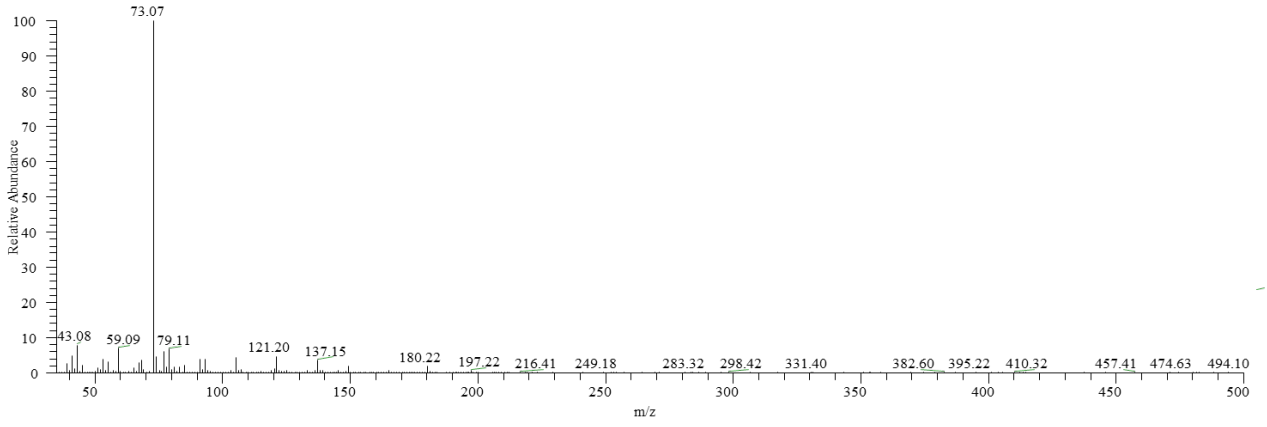
Peak6	975	Peak12	1309	Peak18	3082

Fig. S4 d.



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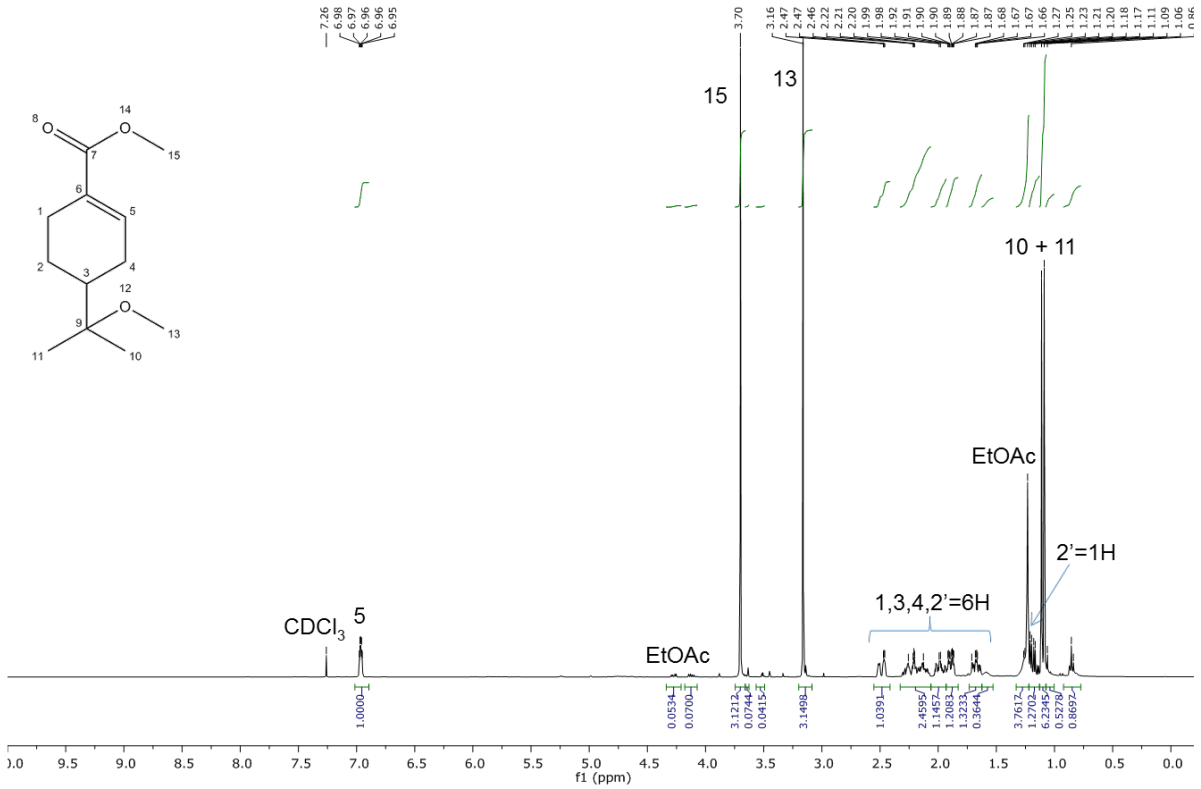

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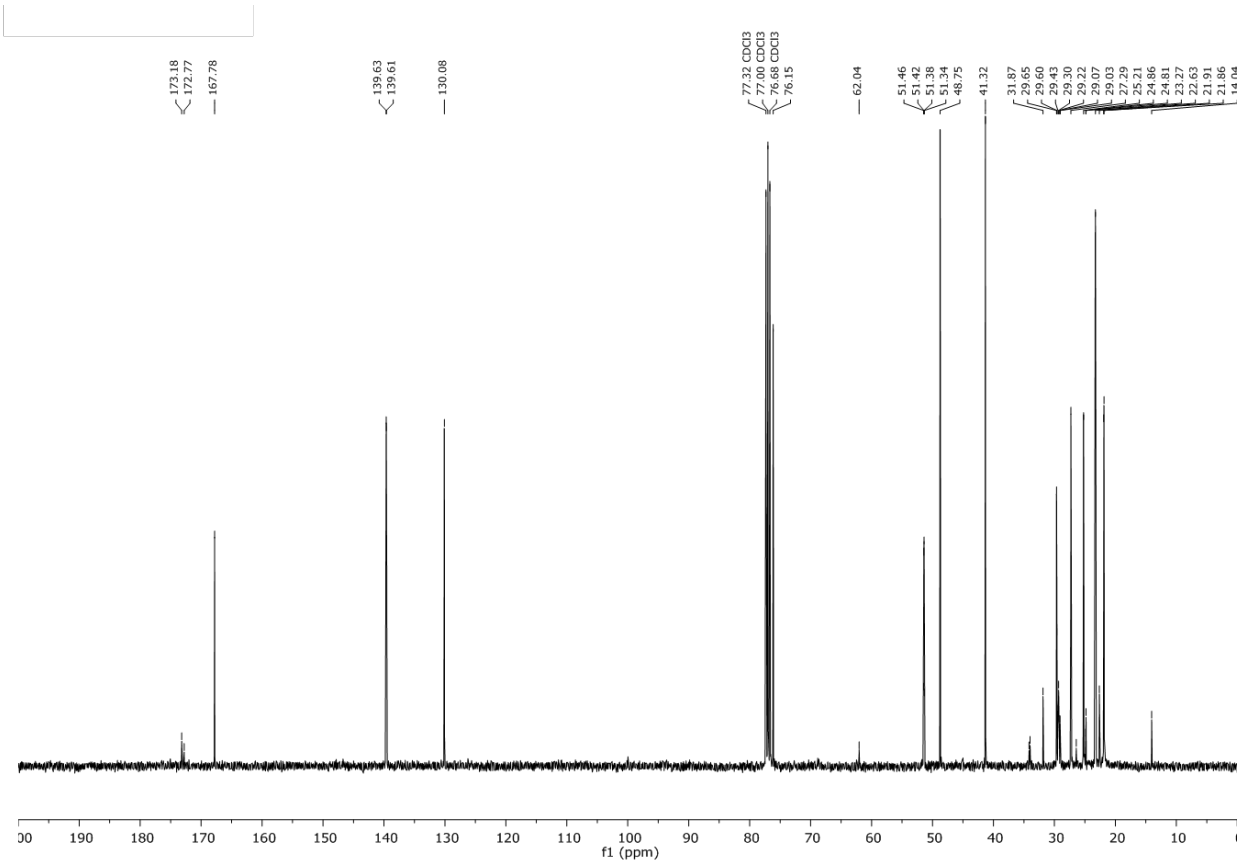

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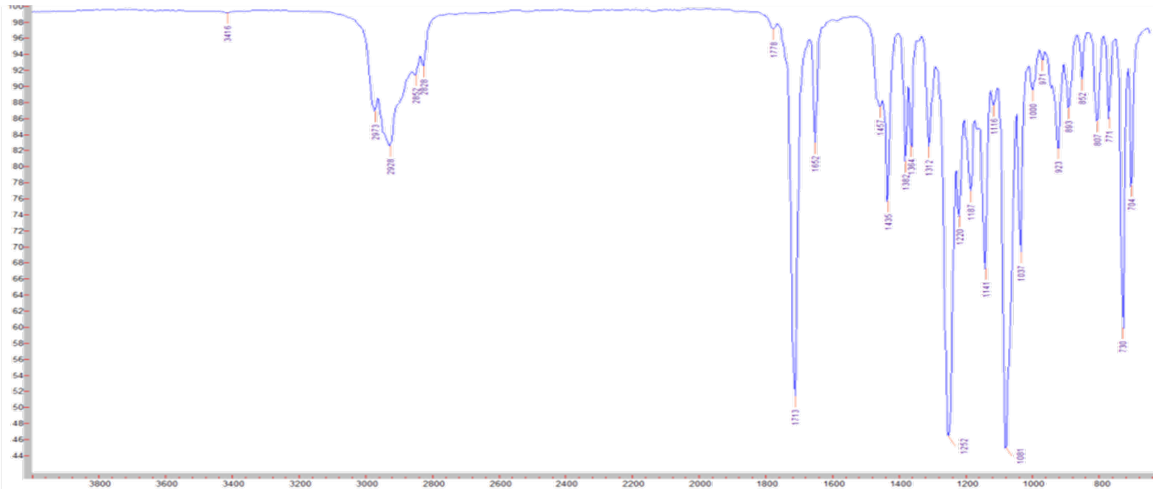

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Peak2	730	Peak10	1037	Peak18	1364	Peak26	2852
Peak3	771	Peak11	1081	Peak19	1382	Peak27	2928
Peak4	807	Peak12	1116	Peak20	1435	Peak28	2973
Peak5	852	Peak13	1141	Peak21	1457	Peak29	3416
Peak6	893	Peak14	1187	Peak22	1652		
Peak7	923	Peak15	1220	Peak23	1713		
Peak8	971	Peak16	1252	Peak24	1778		

Fig. S4 h.

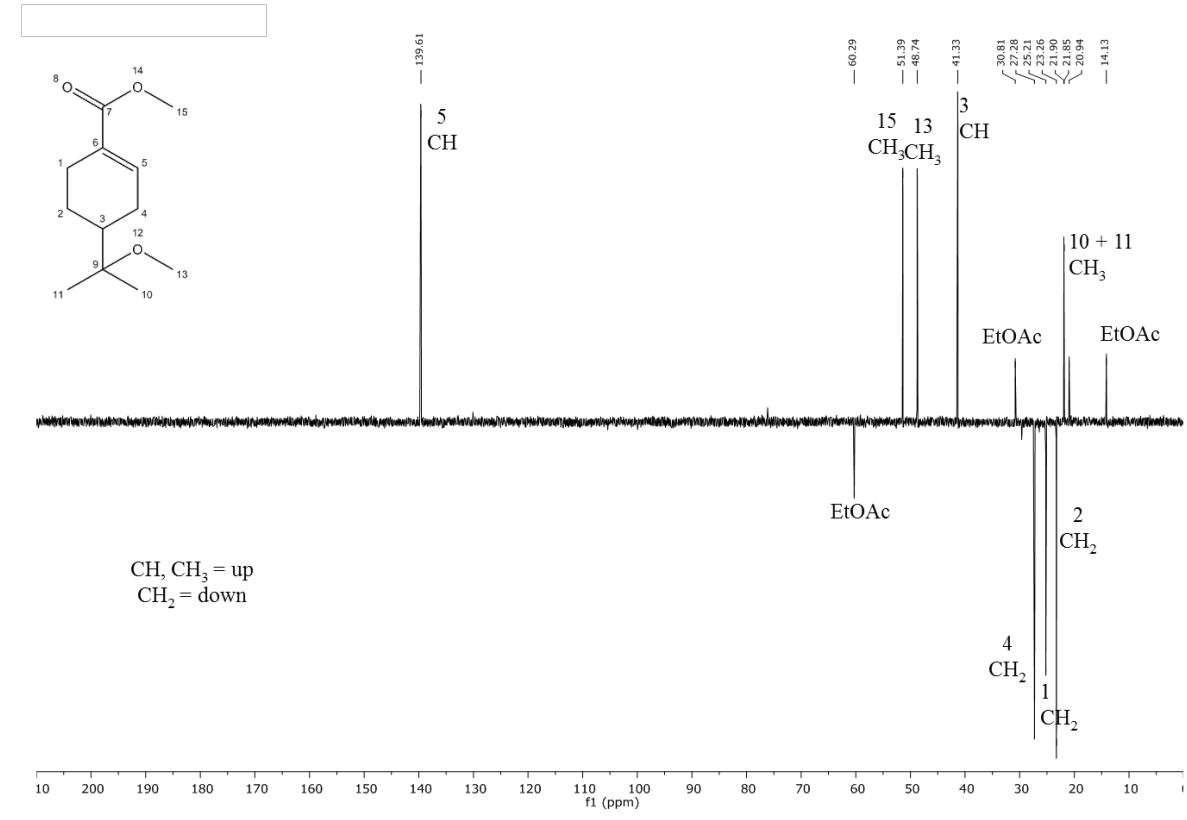


Fig. S4 i.

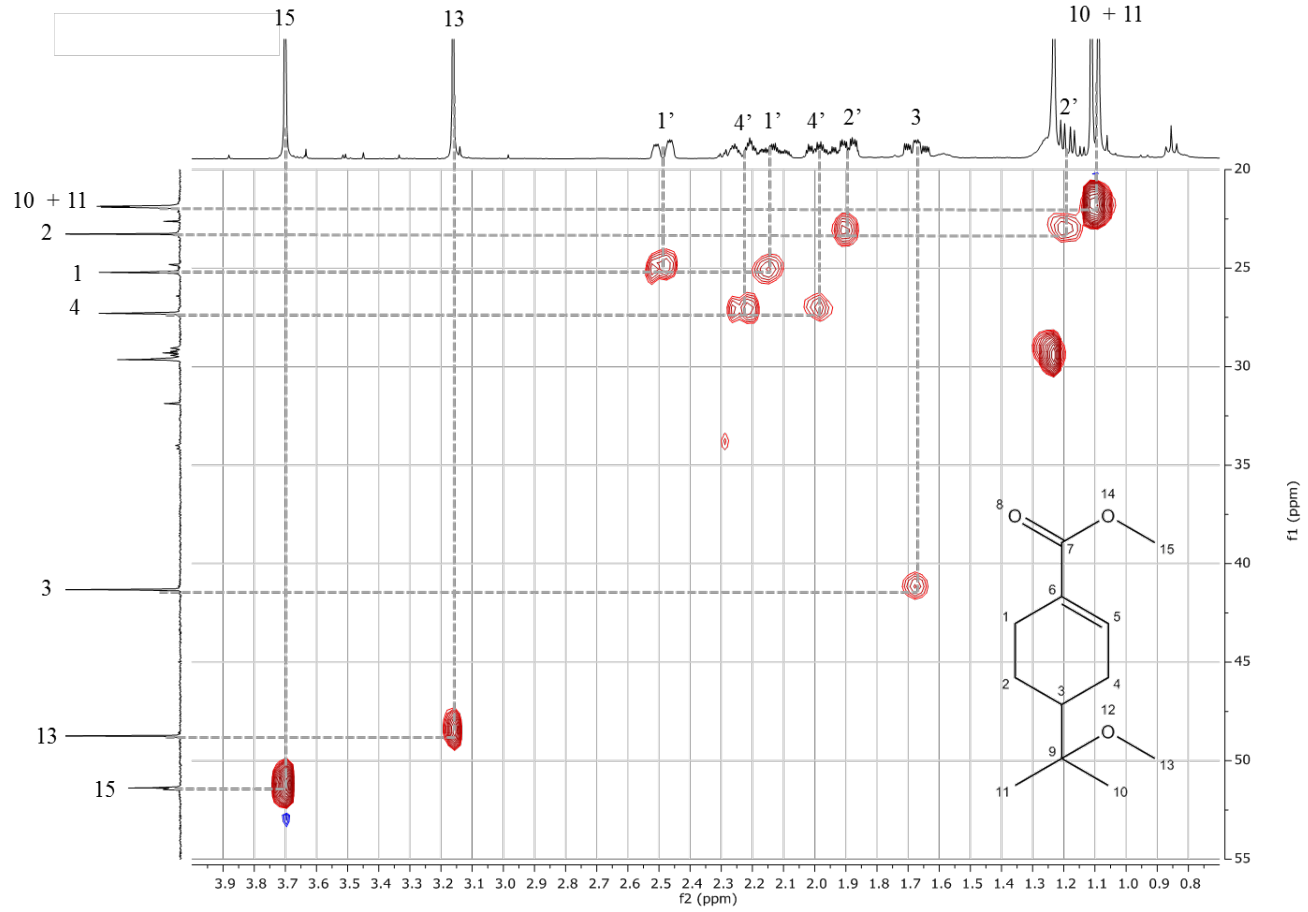
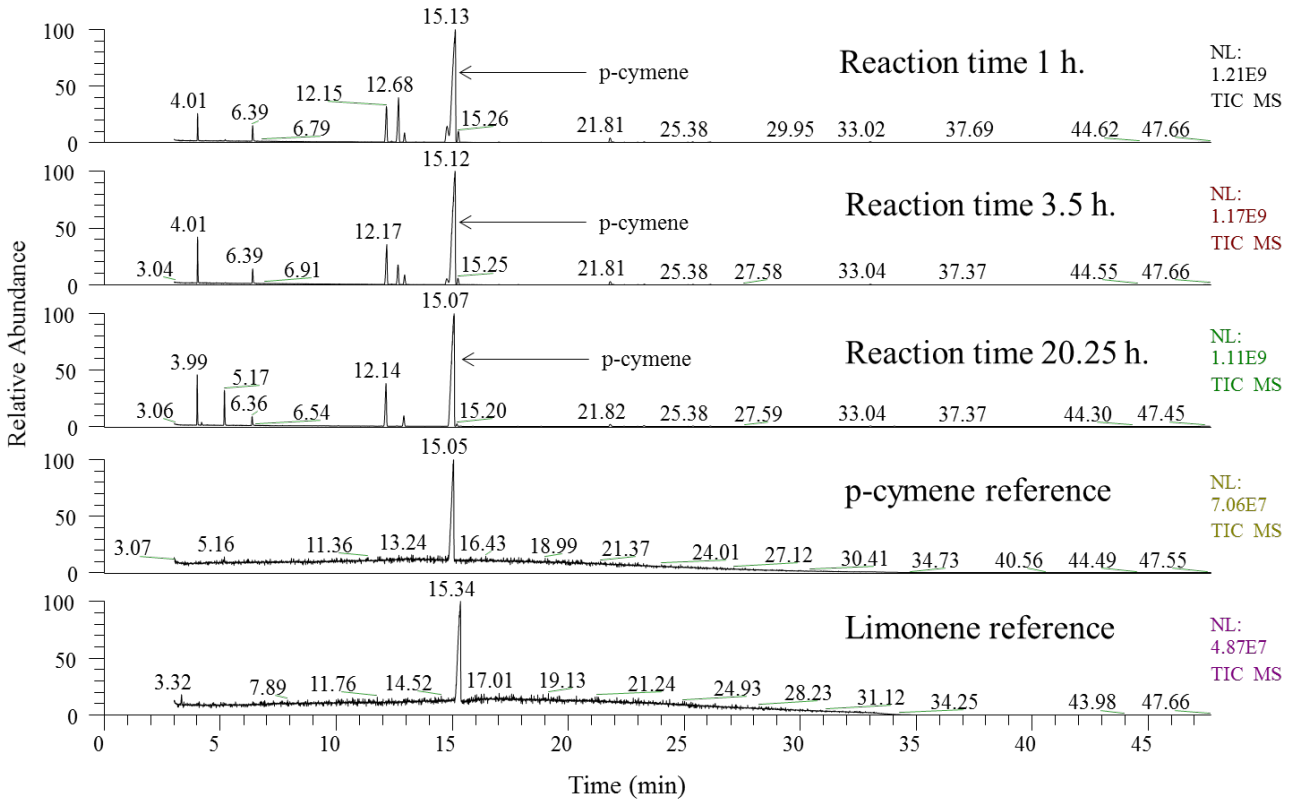


Fig. S4 j.

Fig. S5 Dehydrogenation reaction of limonene to p-cymene at different reaction times, presence of limonene, p-cymene, dehydrogenation intermediates and acetone aldol-addition products was analyzed. a. GC-MS of dehydrogenation product at different reaction times, b. 1H-NMR of time 1h, c. 13C-NMR of 1h, d. 1H-NMR 3.5h, e. 13C-NMR 3.5h, f. 1H-NMR 20.25h, g. 13C-NMR 20.25h



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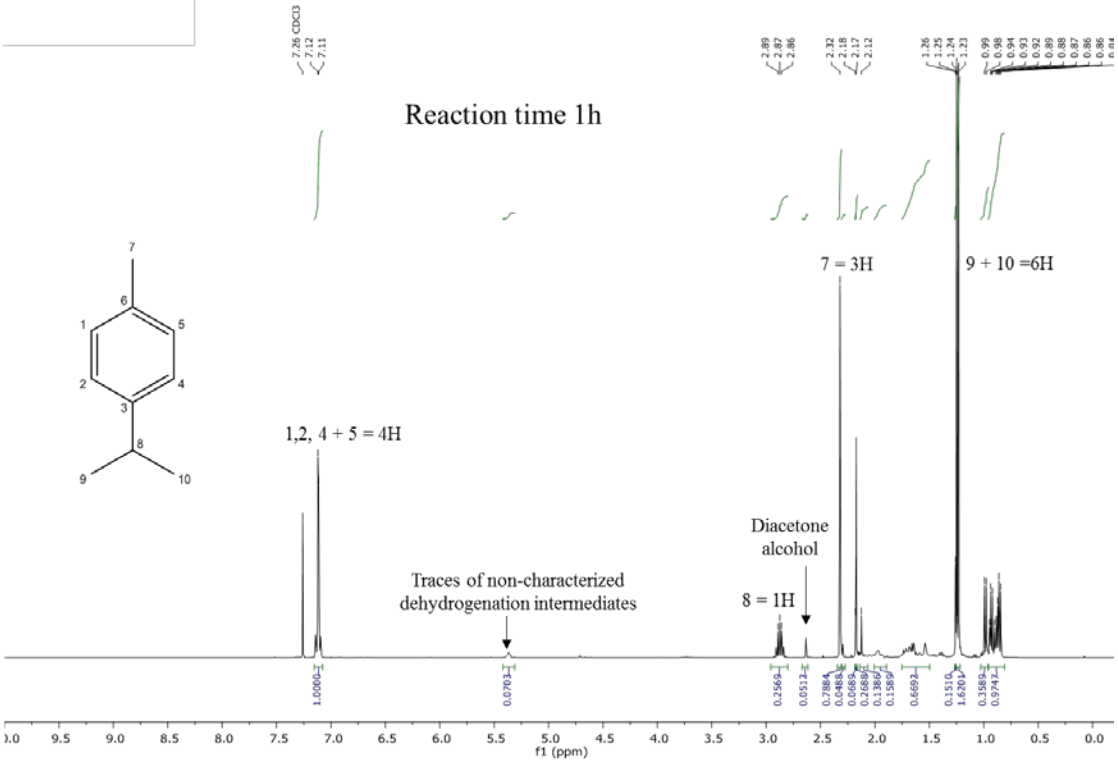
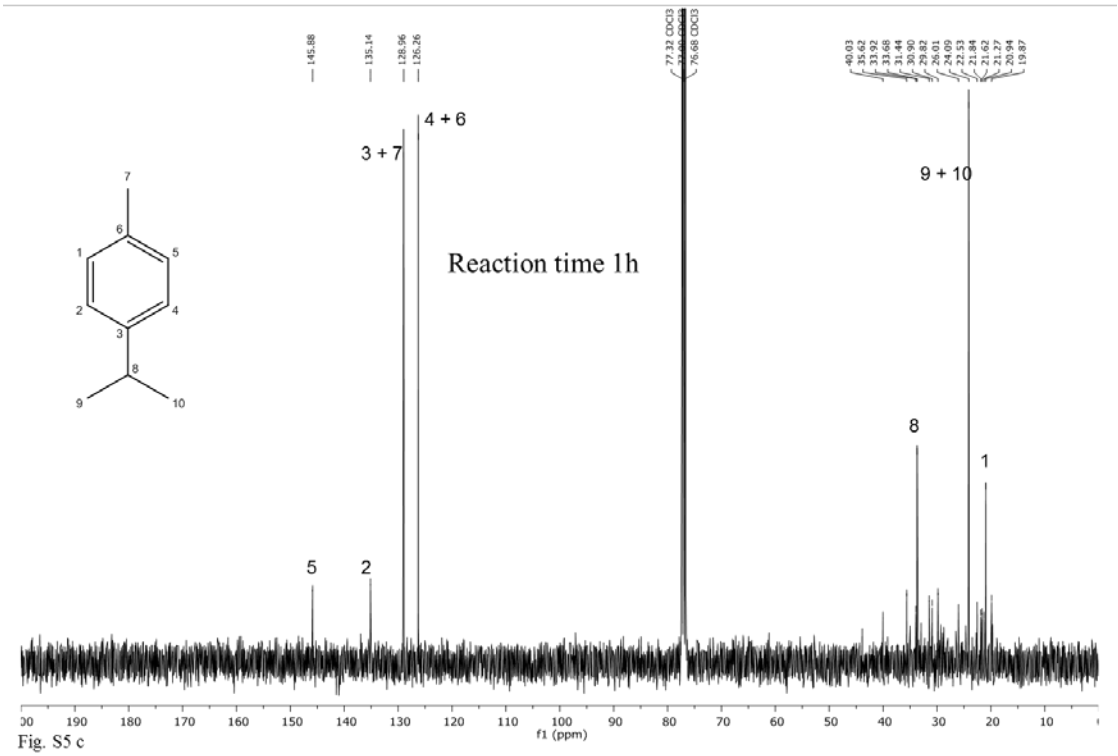


Fig. S5 b



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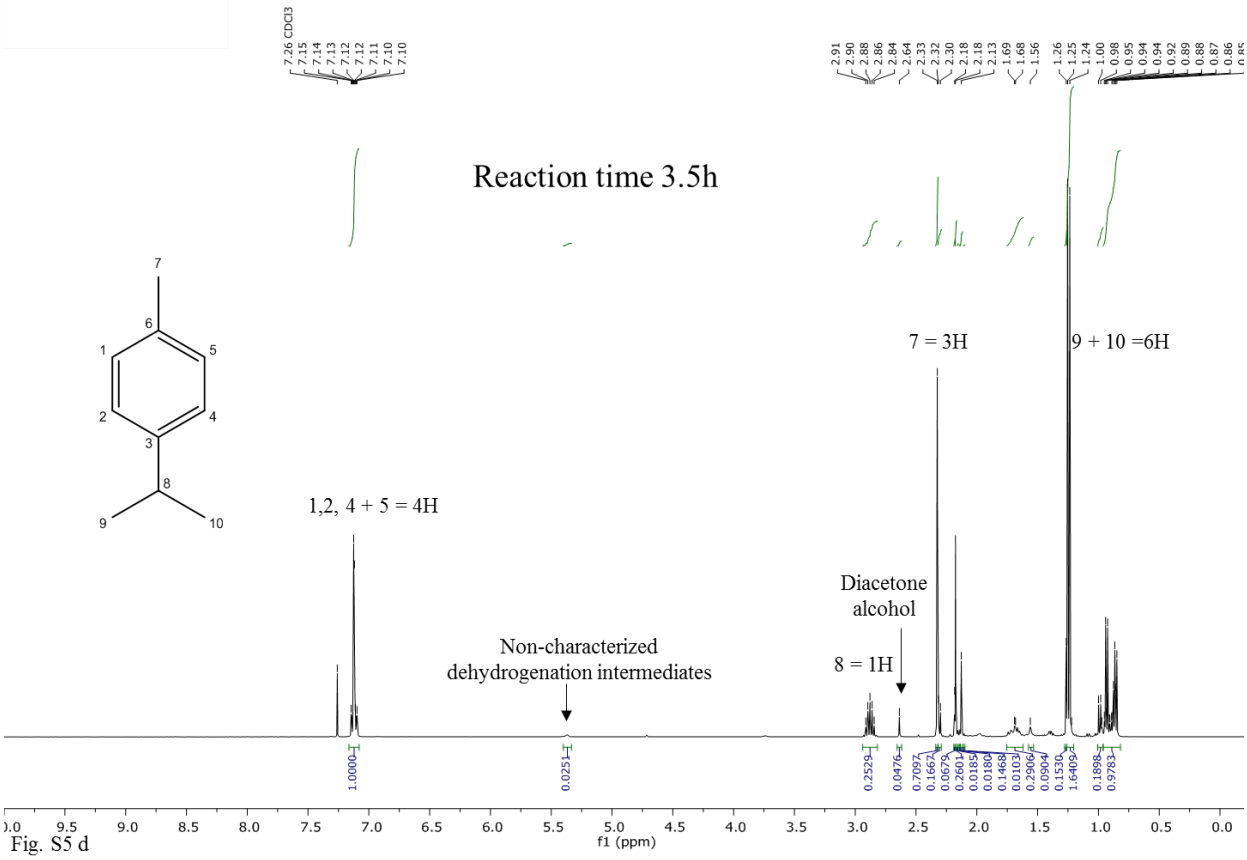

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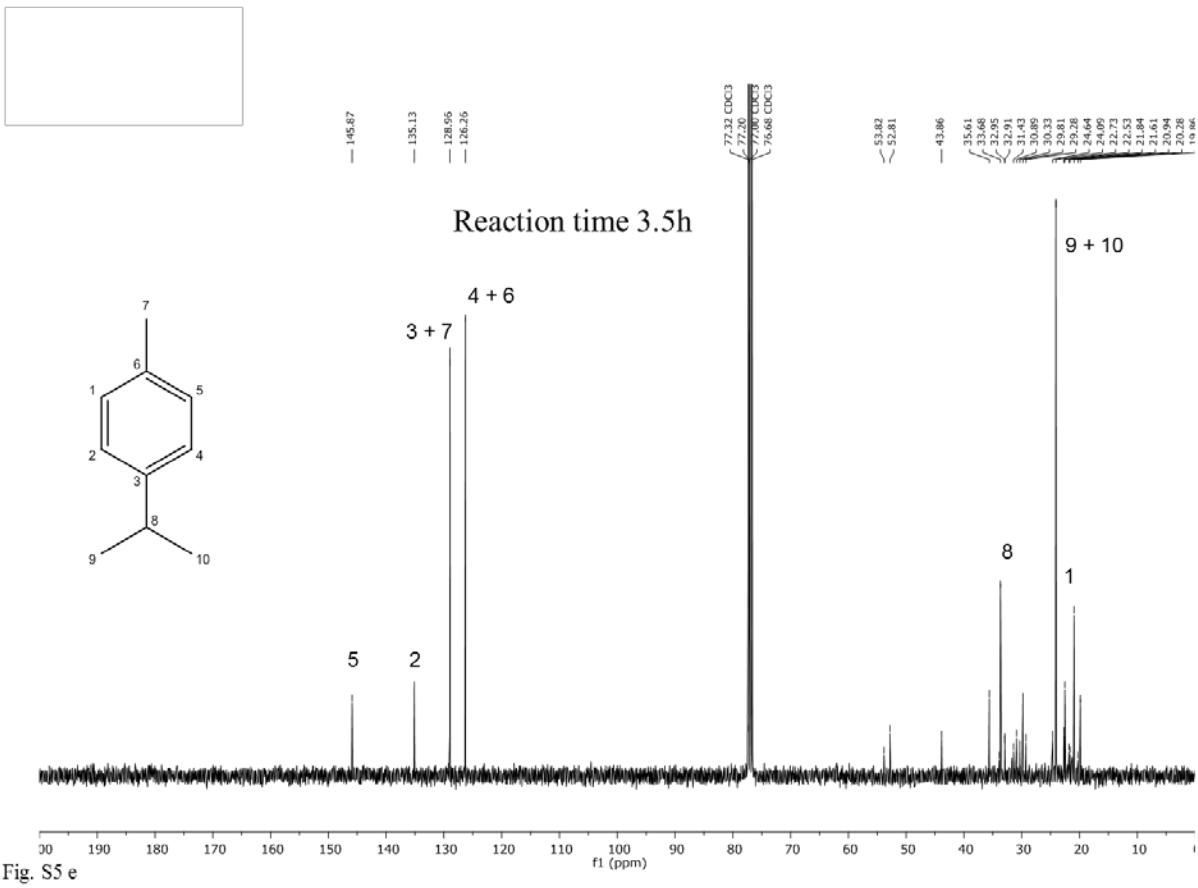

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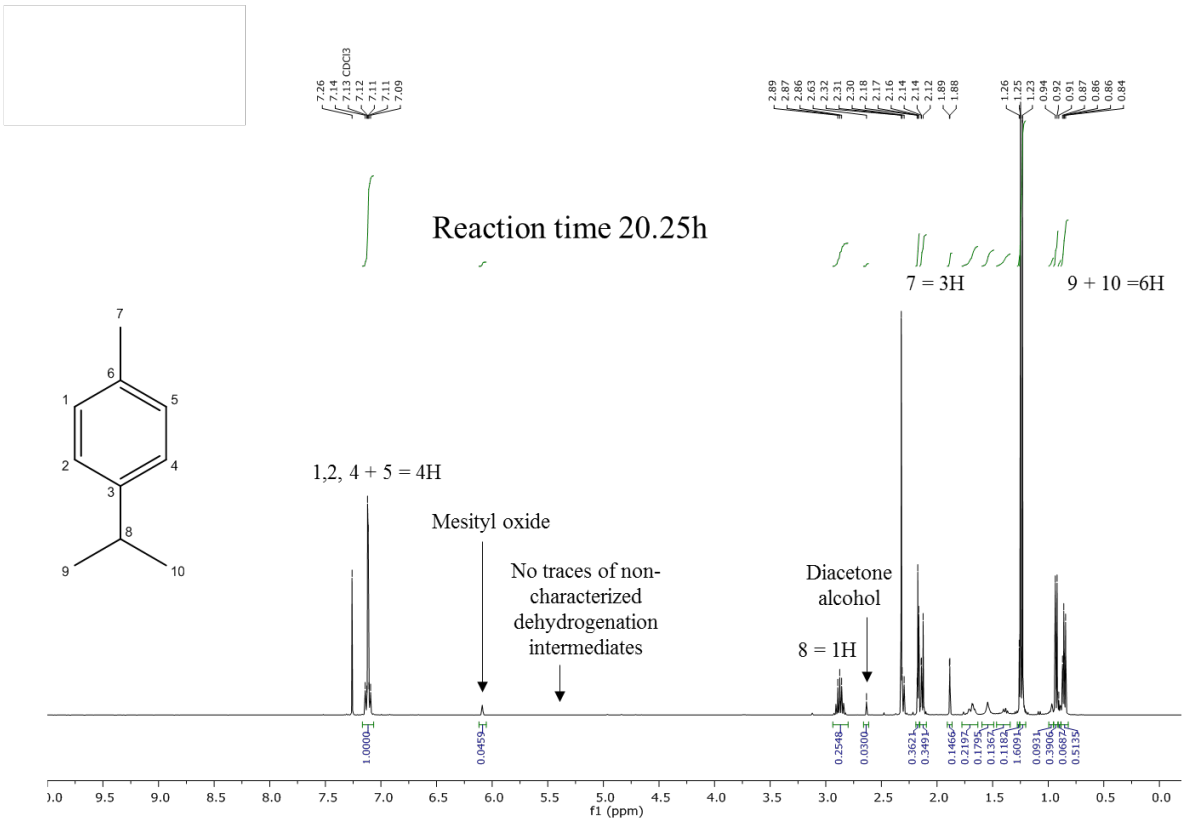

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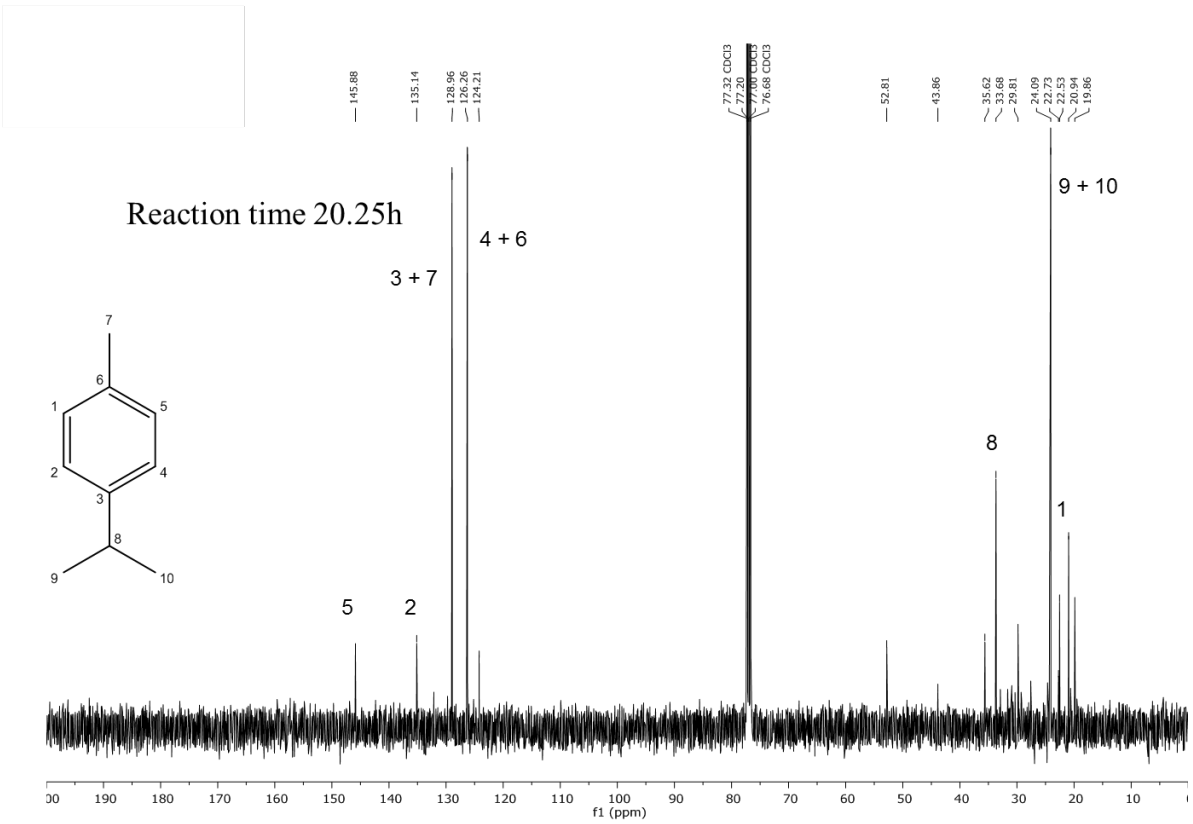


Fig. S5 g

Fig. S6. Methyl cumate, the product of dehydrogenation from MP. Byproducts related to acetone are detected, and some other byproducts are visible, b. ^{1}H-NMR (400.17 MHz, CDCl3), methyl cumate peaks are indicated, and that of the acetone related by-products diacetone alcohol and mesityl oxide, c.^{13}C-NMR (100.62 MHz, CDCl3)

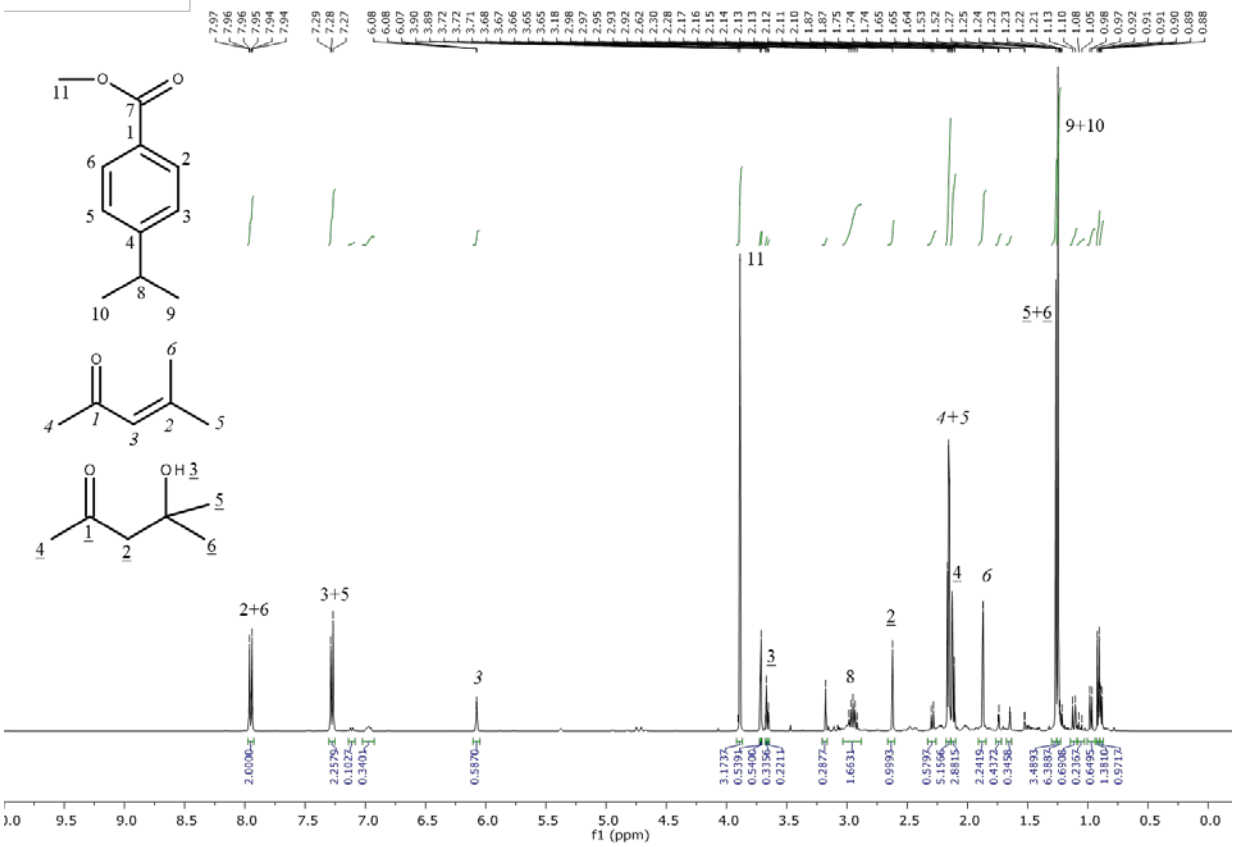
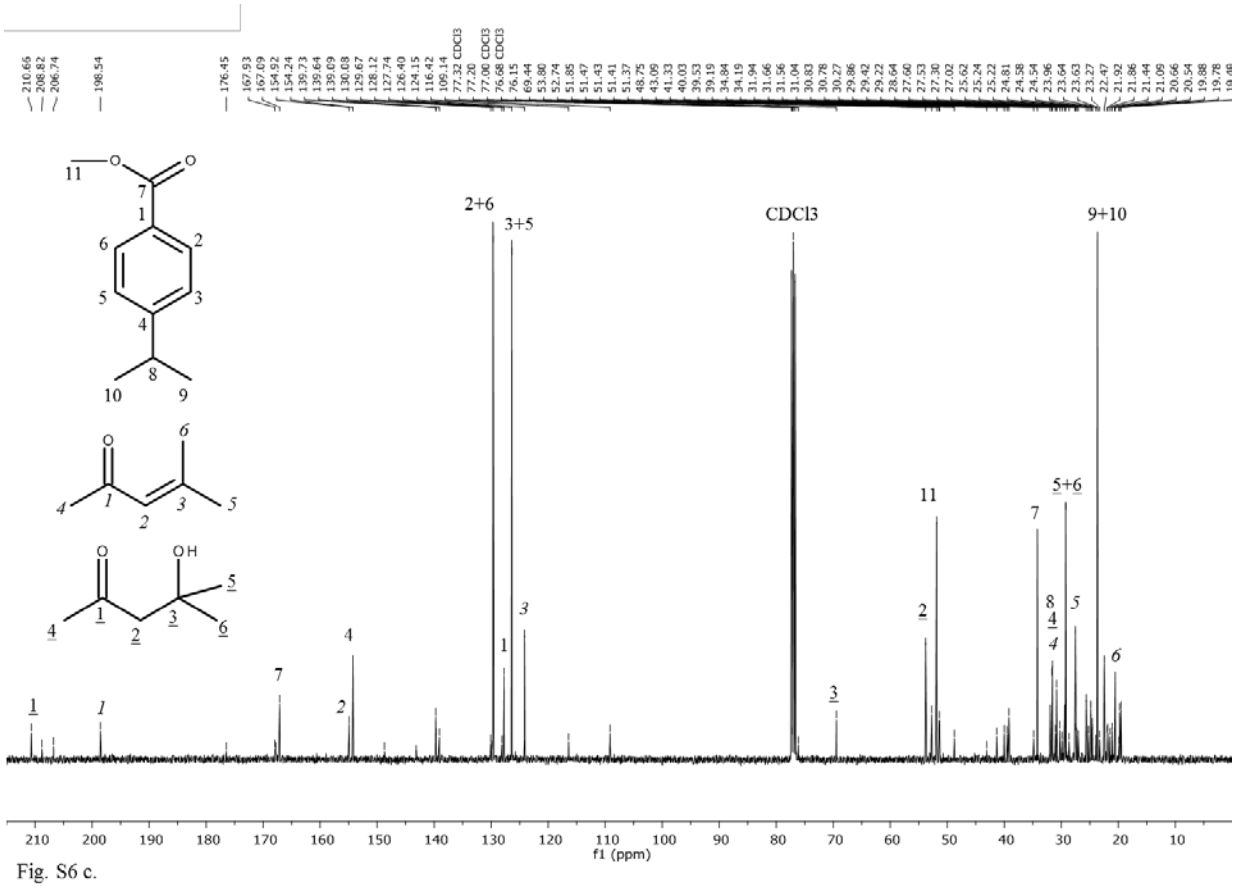


Fig. S6 b.



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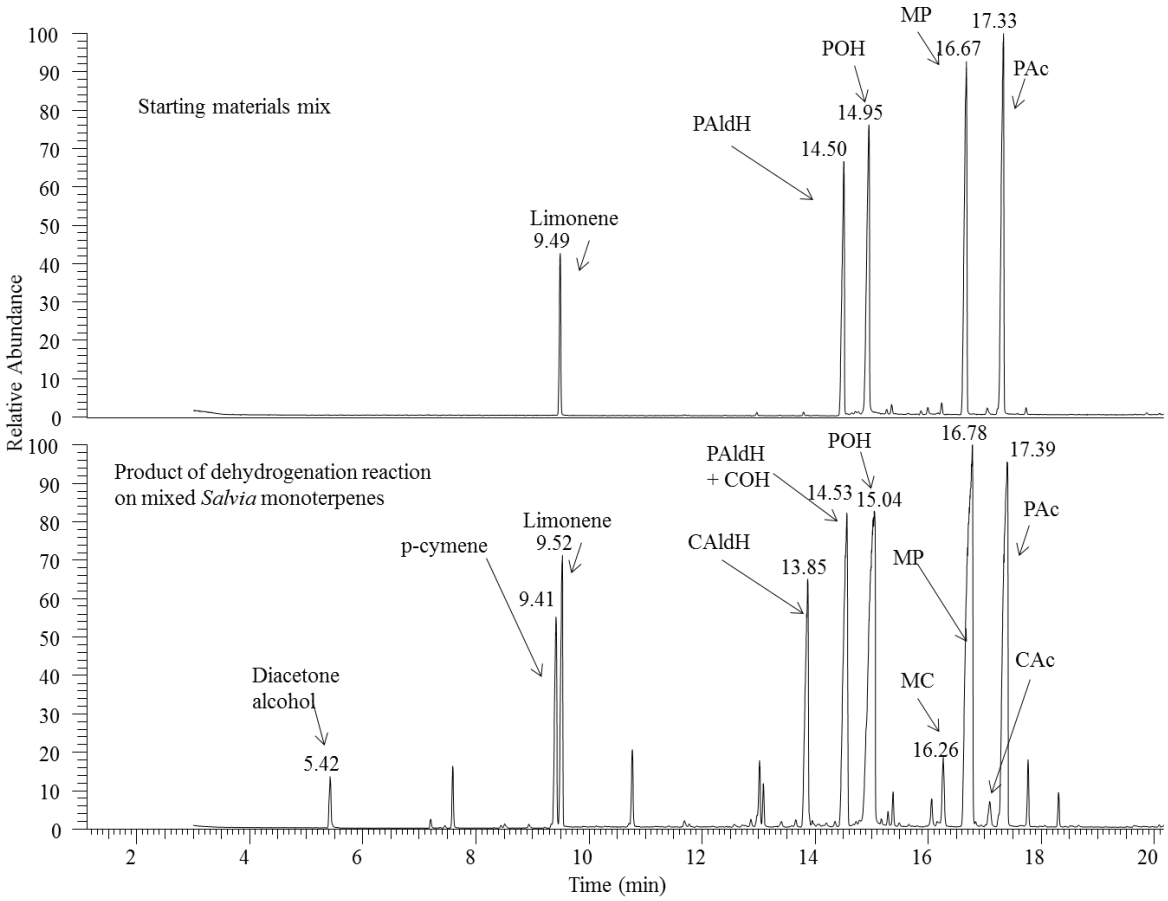
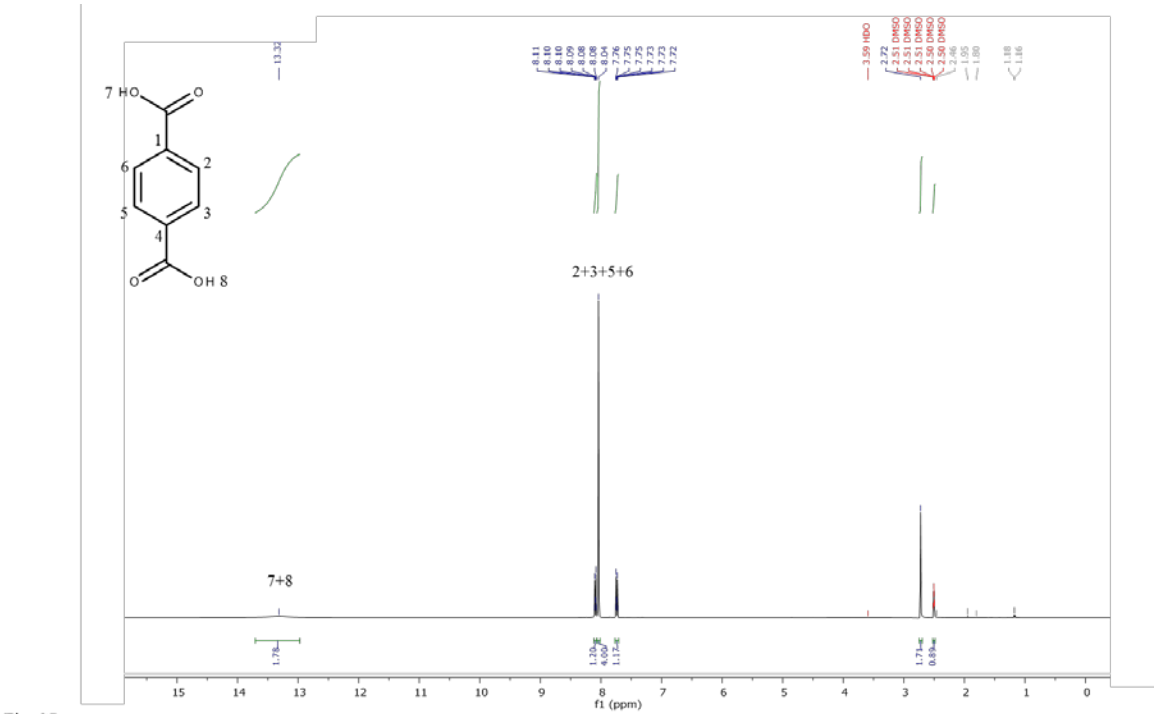


Fig. S7 GC-MS chromatograms of dehydrogenation reaction on mixed *Salvia* monoterpenes. The reaction yielded a mix of all the dehydrogenated forms, together with the starting materials, diacetone alcohol and some non-identified compounds.

Fig. S7 Oxidation of methyl cumic acid (MCA) with nitric acid yields terephthalic acid (TA) in one step a. ^{1}H-NMR of produced TA in DMSO, b. ^{13}C-NMR of produced TA in DMSO, c. DEPT135 of produced TA (DMSO-D6) d. FT-IR of produced TA and TA reference compound, e. LC-MS and LC-MS/MS chromatograms of produced TA and TA reference compound, f. quantification of TA in product 69.7%, g. MS and MS/MS spectra of TA, h. MS and MS/MS spectra of byproduct. i. GC-MS chromatogram of silylated product



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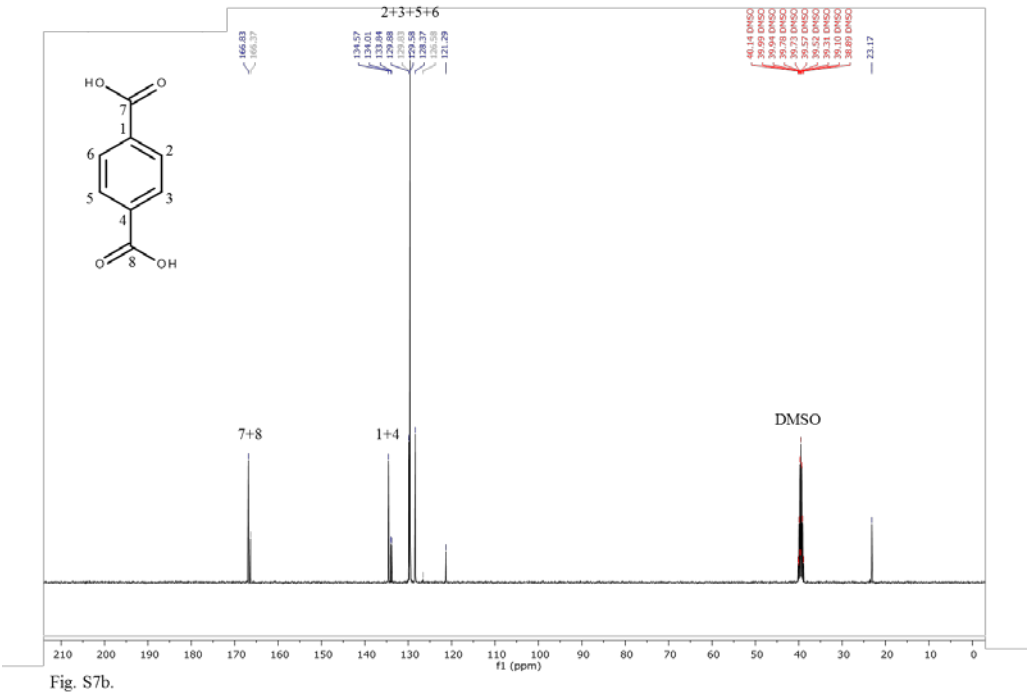

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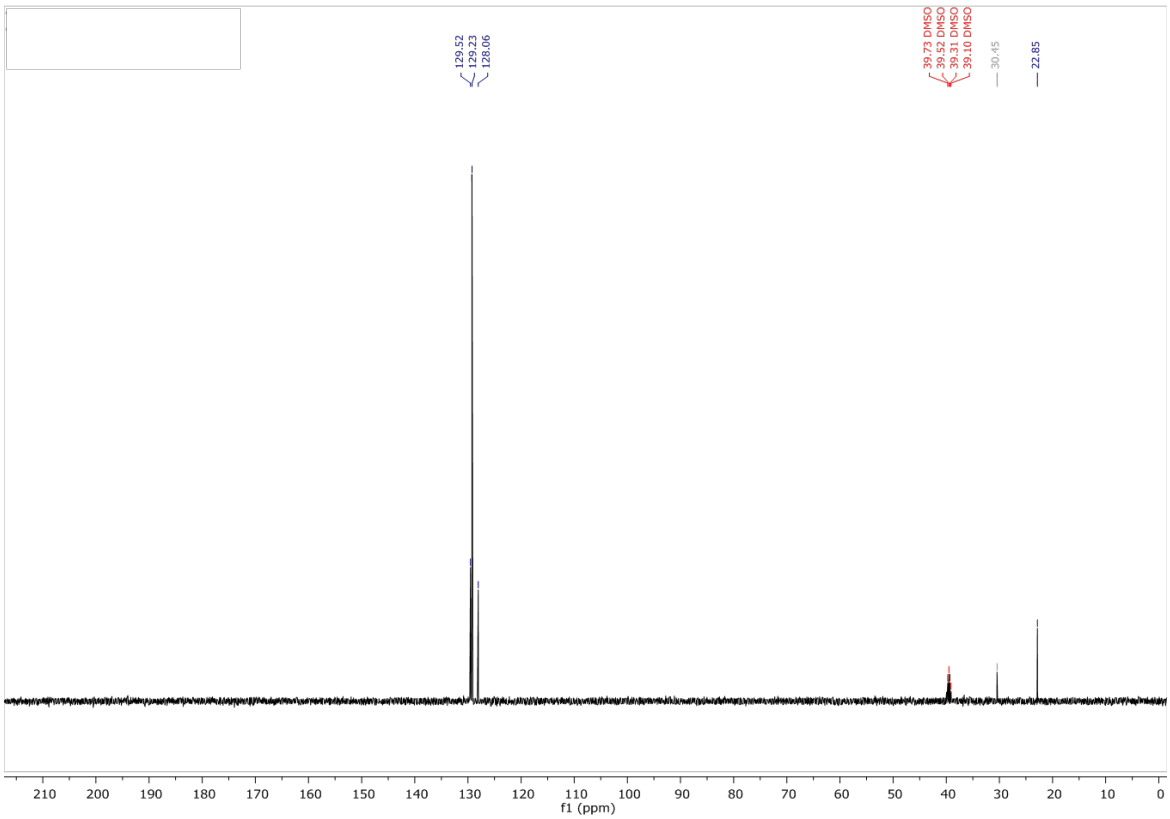

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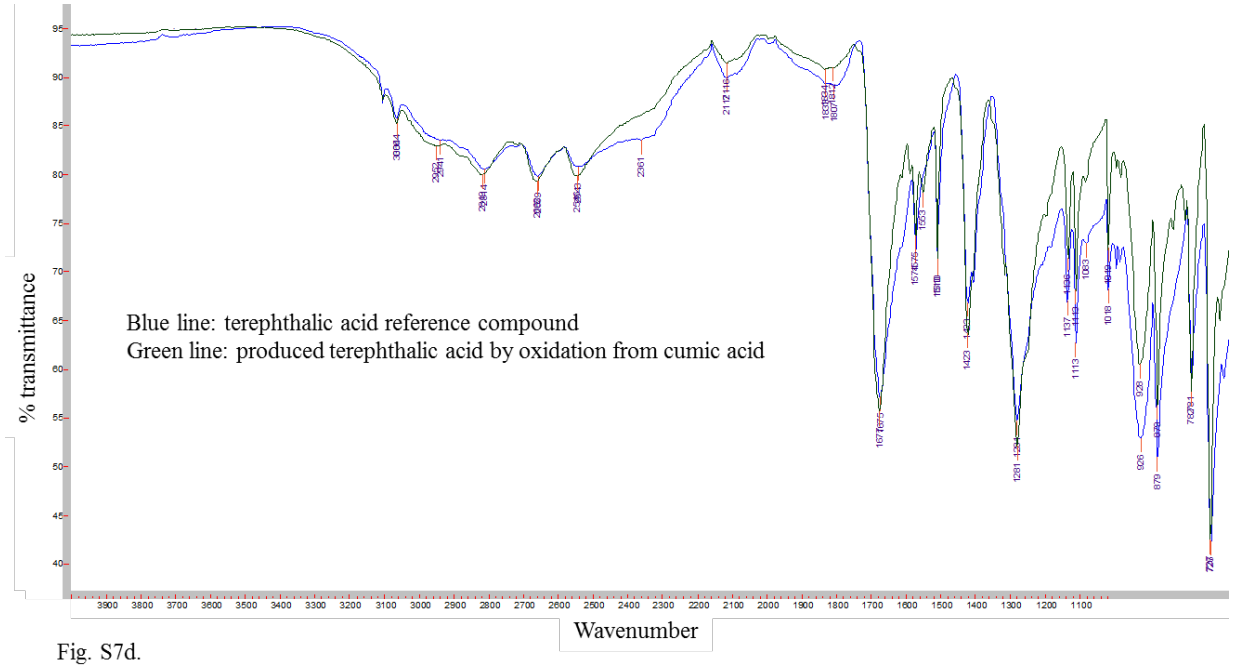

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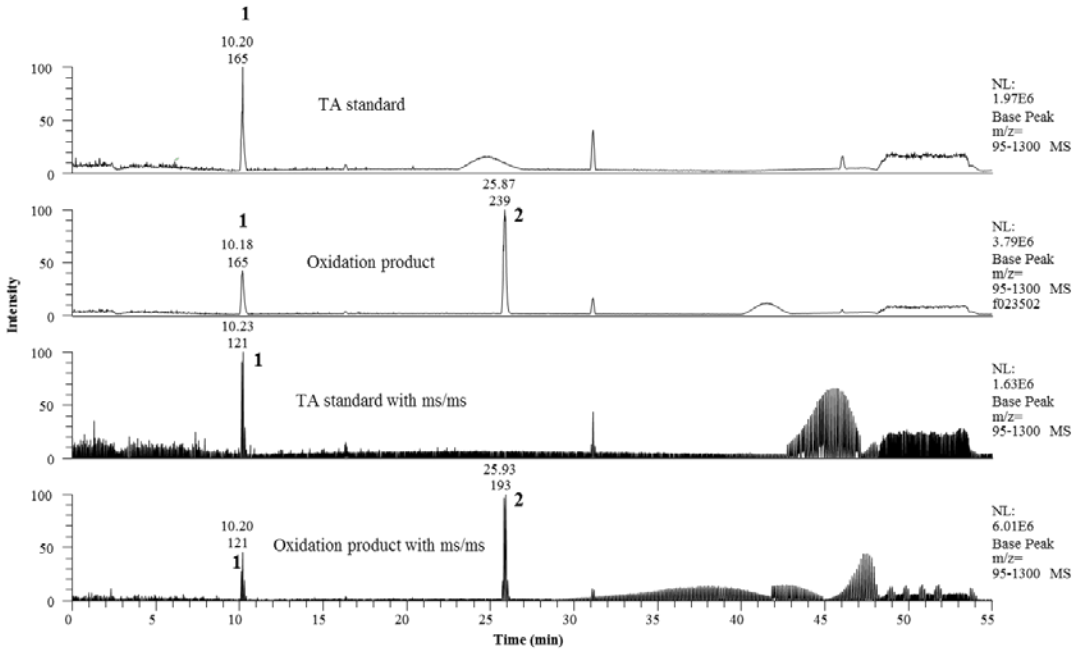

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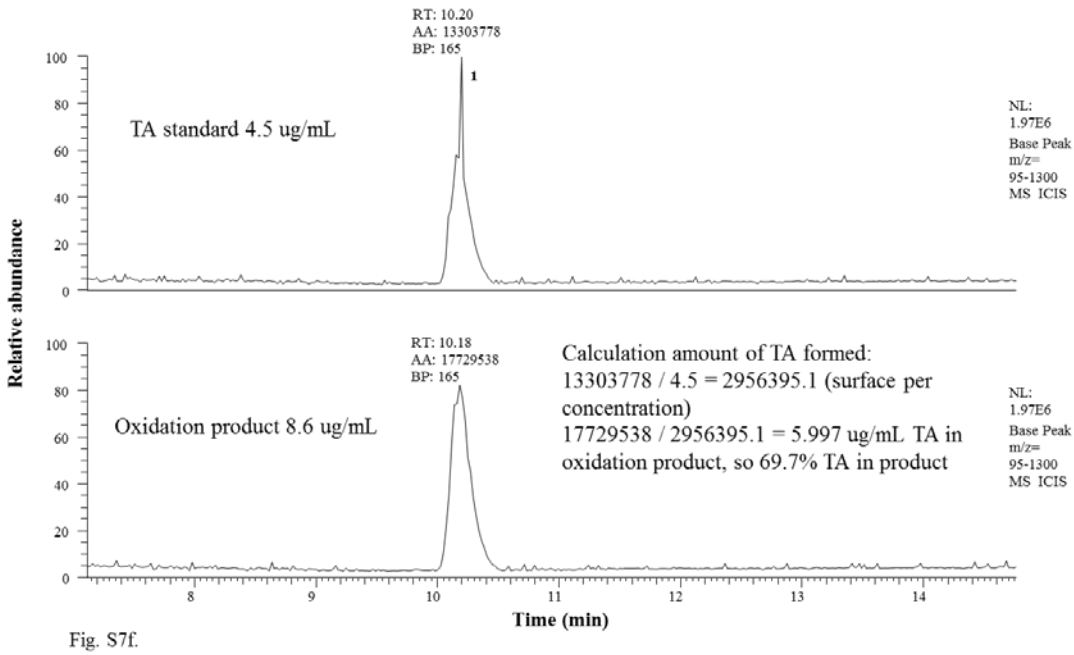

Fig. S7f.

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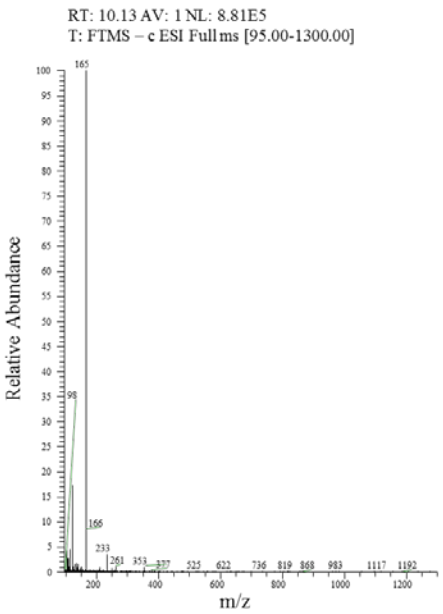
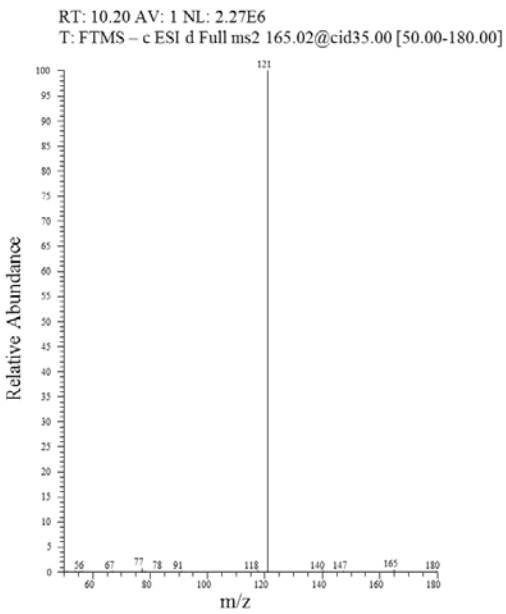


Fig. S7g.

MS/MS peak 1



MS peak 2

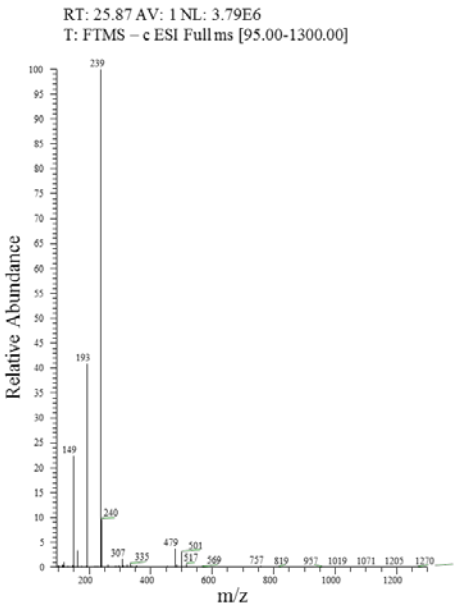
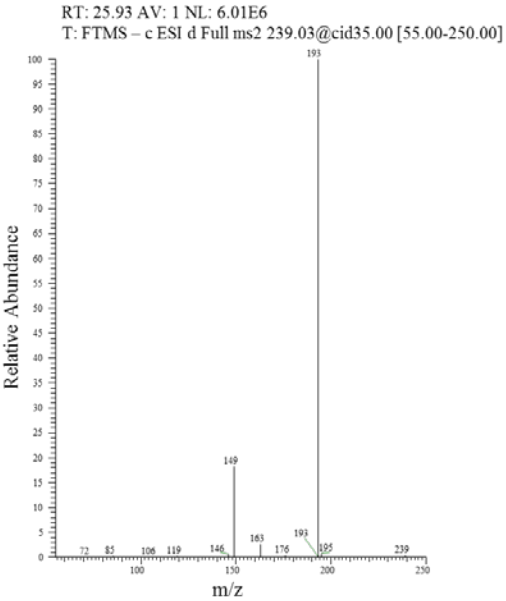


Fig. S7h.

MS/MS peak 2



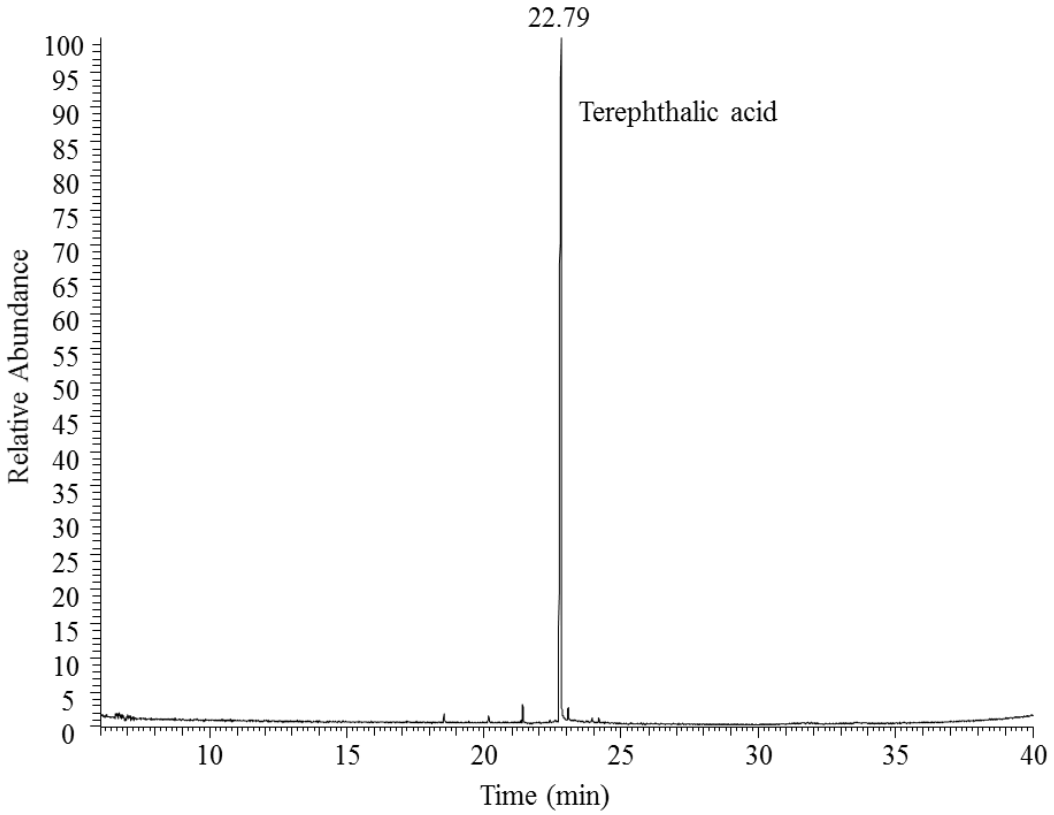

22.79
Terephthalic acid
Relative Abundance
Time (min)
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
10
15
20
25
30
35
40

Fig S7i

Supplemental Scheme S1: Reaction scheme from MPA to MCA

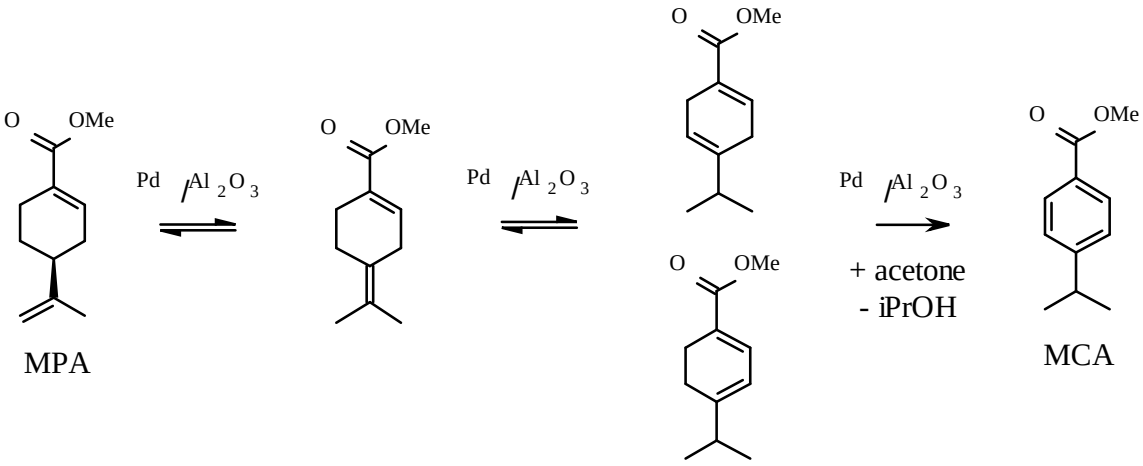


Table S1 Quantification of perillic acid related monoterpenes in *Salvia dorisiana* hydrodistilled essential oil

Compound	**g per kg essential oil**
(-)-Limonene	83 (±22)
Perillyl aldehyde	3.7 (±1.0)
Perillyl alcohol	11.9 (±4.8)
Methyl perillate	204 (±83)
Perilla acetate	4.2 (±0.6)

Quantification was done by linear fit to authentic reference compound standard curve. ± standard deviation, n=5. Oil yield was 1.26 g oil / 100 g DW biomass (± 0.94 g, n=7).

Table S2. Reactions of biobased starting materials towards TA

Compound[a]	Functional groups	Reactions needed	Natural source	Fermentative production
sugars	oxygenated ring	solubilization, hydrodeoxy-genation, oxidation (100-600 ^{o}C, 0.1-83 bar)	biomass (sugars)	n.a.
lignin and lignocellulose	aromatic ring	Grinding, drying, cooling, solubilizing, pyrolysis, separation, oxidation (50-1000° C)	biomass (lignin)	n.a.
isobutanol (via pX)	oxygenated carbohydrate	dehydration, dimerization, dehydrocyclization, oxidation (175–225° C, 15–30 bar) (existing infrastructure Amoco oxidation)	biomass (sugars)	Yes[1]
fructose (via DMF, pX)	oxygenated ring	dehydration, hydrodeoxygenation, Diels-Alder, dehydration, oxidation (100-300° C, 10-100 bar)	biomass (sugars)	n.a.
muconic acid	oxygenated carbohydrate	microbial synthesis, isomerization, Diels-Alder, catalytic dehydrogenation (150° C)	biomass (sugars)	Yes[2]
FDCA	2 acid groups	dehydration, oxidation, Diels-Alder, dehydration (100-200° C, 5-20 bar)	biomass (sugars)	Yes[3]
limonene, pinene	oxygenated ring, functionalized p-position	dehydrogenation, oxidation, oxidation	essential oil (Citrus)	Yes[4]
malic acid	oxygenated carbohydrate	dimerization/condensation, esterification, Diels–Alder/retro-Diels–Alder/elimination	biomass (sugars)	Yes[5]
methyl perillic acid	oxygenated ring, acid group, functionalized p-position	dehydrogenation, oxidation	essential oil (Perilla, Salvia)	Yes[6]

[a] Overview existing TA processes from Collias et al.[7]

1: E. N. Lamsen, S. Atsumi, Front Microbiol 2012, 3, 196.

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3: F. Koopman, N. Wierckx, J. H. de Winde, H. J. Ruijssenaars, Bioresour Technol 2010, 101, 6291-6296.

4: E. Jongedijk, K. Cankar, M. Buchhaupt, J. Schrader, H. Bouwmeester, J. Beekwilder, Appl Microbiol Biot 2016, 100, 2927-2938; E. Jongedijk, K. Cankar, J. Ranzijn, S. van der Krol, H. Bouwmeester, J. Beekwilder, Yeast 2015, 32, 159-171.

5: E. Jongedijk, K. Cankar, M. Buchhaupt, J. Schrader, H. Bouwmeester, J. Beekwilder, Appl Microbiol Biot 2016, 100, 2927-2938; A. E. Mars, J. P. Gorissen, I. van den Beld, G. Eggink, Appl Microbiol Biot 2001, 56, 101-107.

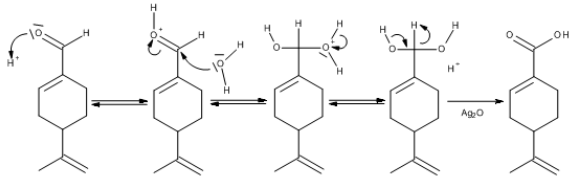
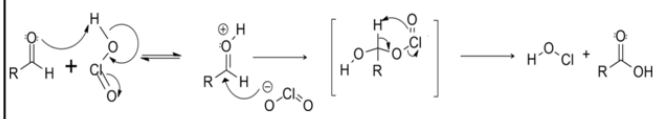
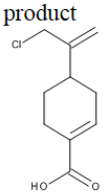
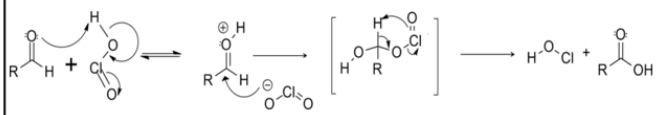
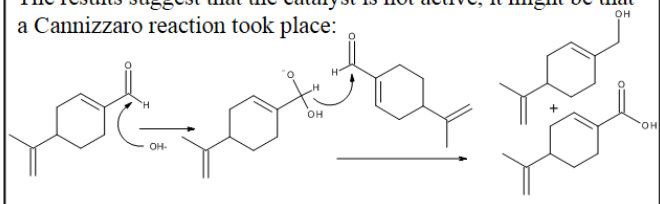
Method of oxidation	References	Reaction details	Result
1. Oxidation with Ag2O. Product: PA	Wang et al. (1993) Tetrahedron Vol 49:3 pp 619-638 Hortmann and Ong (1970) J Org Chem Vol 35:12 pp 4290-4292 Kádas et al. (1998) Org Prep Proc Int Vol 30:1 pp 79-85	- Ag2O catalyst made in-situ by AgNO3 + NaOH in water - 55°C, NaOH, filtered + washed with hot water, acidified with HCl (PA precipitates) 	√ 66% yield
2. Pinnick oxidation acetonitrile / water. Product: PA	Dalcanale (1986) J Org Chem Vol 51 pp 567-569	 - Oxidation with HClO2 (formed under acidic conditions from NaClO2) - H2O2 added as HOCl scavenger	+/- yields the chlorinated acid as a by-product 
3. Pinnick oxidation tert-butyl alcohol / 2-methyl-2-butene / water. Product: PA	Bal et al. (1981) Tetrahedron Vol 37 pp 2019-2096 Kitahara et al. (1988) Tetrahedron Vol 44:15 pp 4713-4720 Dong et al. (2013) J Asian Nat Prod Res Vol 15:8 pp 880-884	 - Oxidation with HClO2 (formed under acidic conditions from NaClO2)	+/- low yield ~7%
4. Oxidation on Au/TiO2. Product: PA or MP directly	Marsden et al. (2007) Green Chem Vol 10 pp 168-170 Biella et al. (2003) J Mol Catal A: Chem Vol 197 pp 207-212	To PA: NaOH, water, Au/TiO_2, 5 bar O_2, 80°C The results suggest that the catalyst is not active, it might be that a Cannizzaro reaction took place:  To MP directly: NaOMe (base), MeOH, Au/TiO_2, 5 bar O_2, 80°C	+/- maximum yield ~20%; without catalyst also yield ~20% +/- perillyl aldehyde in end-product (incomplete conversion)

Table S3 Different oxidations of (-)-perillaldehyde to PA, or directly to MPA, that were tested. These included Pinnick oxidations (method of oxidation numbers 2 and 3) and oxidations catalyzed by gold/titanium oxide (number 4) and silver oxide (number 1). Highest efficiency was achieved using oxidation with silver oxide. Literature references, reaction details and the obtained result of all oxidation methods are indicated in the table.

Table S4 Reaction conditions tested for dehydrogenation reactions of limonene to p-cymene

Catalyst	Temperature	Yield of p-cymene (mol%)
5% Pd/C	100 °C	0
5% Pd/C	150 °C	80
5% Pd/Al_2O_3	150 °C	56
5% Pd/Al_2O_3	125 °C	69
5% Pd/Al_2O_3	100 °C	75
5% Pd/Al_2O_3	75 °C	0
5% Pd/Al_2O_3	50 °C	0

Reaction time was 17-21 hours.
Limonene : acetone : Pd molar equivalents were 1 : 19 : 0.007.
Catalysts were dry and reduced. Reactions were performed under nitrogen.

Table S5 Selectivity of dehydrogenation limonene to p-cymene at different reaction times

Catalyst	**Temperature**	**Time**	**Yield of p-cymene (mole%)**	**Ratio p-cymene : diacetone alcohol : mesityl oxide**
5% Pd/Al_2O_3	125 °C	1 h	82**	1 : 0.14 : 0.00
5% Pd/Al_2O_3	125 °C	3.5 h	82	1 : 0.13 : 0.00
5% Pd/Al_2O_3	125 °C	20 h	80	1 : 0.15 : 0.18
5% Pd/Al_2O_3	125 °C	27 h	77	1 : 0.19 : 0.21

**optimal conditions, optimized for limonene.

2. Materials and Methods

2.1 Chemicals

(*R*)-(+)-limonene (97%, Sigma Aldrich), perillyl alcohol (96%, Sigma Aldrich), (*S*)-(-)-perillaldehyde (Sigma Aldrich), (*S*)-(-)-perillyl acetate (Wako), (*S*)-(-)-perillic acid (95%, Sigma Aldrich), *cis*-nerolidol (98%, Fluka), pentane (≥99.0%, CHROMASOLV® for HPLC, Sigma Aldrich), cumic acid (4-isopropylbenzoid acid, ≥98%, Sigma Aldrich), magnesium sulphate (dried, 1-2 mol hydration water, Alfa Aesar), ethyl acetate (pure, Acros Organics), hydrochloric acid (37%, reag. Ph. Eur., VWR), *p*-toluenesulfonic acid monohydrate (*p*-TSA, 98.5%, ACS reagent, Sigma Aldrich), methanol (for analysis, Merck), petroleum ether (PE, ACS reagent, boiling range 40-60°C, Acros Organics), trimethyl sulfonium hydroxide solution (TMSH, ~0.25 M in methanol, Sigma Aldrich), sicapent (Merck), silica gel 60 (0.040-0.063 mm, 230-400 mesh, Alfa Aesar), acetone (≥99.8%, Actu-All Chemicals), palladium 5% on alumina powder (reduced, Escat 1241, Strem Chemicals), palladium 5% on activated carbon (reduced, dry powder, Strem Chemicals), platinum on carbon (extent of labelling 10wt% loading, matrix activated carbon support, Aldrich), ruthenium 5% on carbon (Strem Chemicals), chloroform (HPLC grade, stabilized with ethanol, min. 99.9%, Actu-All Chemicals), sodium chloride (VWR Chemicals), celite 545 (Sigma Aldrich), nitric acid (65%, G.R. for analysis, Merck), sodium nitrite (puriss, p.a. ACS >99.0%, Fluka), silylation reagent (BSTFA + TMCS, 99:1, Supelco), DMSO-D_6 (99.5% D, containing 0.03 % v/v trimethylsilane (TMS), Aldrich)

2.2 Plant growth, multiplication and measurements

Salvia dorisiana plants were obtained from a local nursery. Standard growth conditions were 12 h day / 12 h night, 20°C / 18°C in the greenhouse.

2.3 Leaf extraction

Fresh leaves ≤ 3 cm were snap frozen in liquid nitrogen and ground with pestle and mortar. 139.8 mg of powder was extracted with 6 mL pentane containing 4.66 µg/mL *cis*-nerolidol as internal standard for analysis by GC-MS.

2.4 Essential oil distillation

Hydrodistillation was performed on lab-scale according to Stahl (Stahl, 1962). Hundred grams of fresh *Salvia dorisiana* leaves ≤ 3 cm were cut. The leaves were cooked in 1 L demi water in a 2 L round bottom flask for 1 h without organic solvent, and afterwards the pure essential oil layer was removed from the 4°C cooling bulb with a long Pasteur pipette. The essential oil was dried over a $MgSO_4$ column, and the oil yield in w/w% of fresh weight (FW) of the leaves determined, average yield from one distillation 0.13 g (0.13 w/w%).

Steam distillation was performed for larger-scale oil harvesting, in a home-made kettle and cooling system [http://indekoperenketel.nl/]. Tap water (30 L) was heated to 100°C and the steam lead through 16.34 kg of *Salvia dorisiana* prunings during 1 h. Steam with extracted volatiles was then cooled-down gradually to 10-15°C. The water layer of the condensate was continuously removed by a separation funnel during distillation. The water layer was extracted one time with diethyl ether, and this was combined with the oil layer. The solvent was evaporated and the essential oil was dried over $MgSO_4$, yield 10.7 g (0.065 w/w%).

2.5 Quantification of monoterpenes

The oil was diluted to 53.2 µg/mL in pentane for analysis by GC-MS. A standard series of limonene, methylperillate, perillyl alcohol, perillyl aldehyde and perillyl acetate was prepared ranging from 0.1- 50 µg/mL in pentane. Oil and leaf compounds were quantified using a linear and 2^{nd} order polynomal fitted equation from the standard series.

2.6 GC-MS analysis

GC-MS analysis of essential oil was performed on a 7890A gas chromatograph (Agilent) equipped with a mass selective detector (Model 5975C, Agilent) with settings as reported previously (Jongedijk et al., 2015).

GC-MS analysis of syntheses products was performed on an Interscience TraceGC Ultra GC with AS3000 II autosampler, connected to an Interscience TraceDSQ II XL quadrupole mass selective detector with settings as reported previously (van der Klis et al., 2012; van der Klis et al., 2017).

2.7 LC-MS analysis

LC-MS was performed on an Accela HPLC tower connected to a LTQ/Orbitrap hybrid mass spectrometer (Thermo Fisher Scientific), conditions and settings as described previously (van der Hooft et al., 2012).

2.8 NMR analysis

NMR spectra were recorded on a Bruker Avance III spectrometer operating at 400.17 MHz (^{1}H) and 100.62 MHz (^{13}C). Proton NMR chemical shifts are quoted in parts per million (ppm) referenced to the appropriate solvent peak. Carbon NMR was fully decoupled by broad band decoupling.

2.9 FT-IR

Fourier transform infrared (FT-IR) spectra were obtained on a Varian Scimitar 1000 FT-IR spectrometer equipped with a Pike MIRacle ATR Diamond/ZnSe single reflection plate and a DTSG-detector. The measurement resolution was set at 4 cm-1, and the spectra were collected in the range 4000-650 cm-1 with 64 co-added scans.

2.10 Synthesis of methylperillate

Perillyl aldehyde (50 g) was oxidized to perillic acid using silver oxide, prepared in-situ from silver nitrate and sodium hydroxide as described previously (Wang et al., 1993). After oxidation, the combined filtrate and washings were acidified with dilute hydrochloric acid until pH ~ 1.5 and filtered. Pure perillic acid was obtained, 33.65 g (yield 61%). The product was characterized by ^{1}H-NMR and ^{13}C-NMR. The product was characterized by GC-MS after derivatisation with TMSH. ^{1}H-NMR (400.17 MHz, $CDCl_3$): δ 1.41 (2H, m, *J*=4.0Hz, H-5,),1.68 (3H, s, H-10), 1.82 and 1.84 (2H, d, *J*=8.0Hz, H-6), 2,08 (2H, m, *J*=8.0Hz, H-3), 2.28-2.42 (1H, m, *J*=16.0Hz, H-4), 4.56 and 4.70 (2H, s, H-9), 7.07 (1H, s, H-2), 11.05 (1H, s, H-11); ^{13}C-NMR (100.62 MHz, $CDCl_3$): δ 20.69 (C-10), 24.15 (C-6), 26.95 (C-5), 31.26 (C-3), 39.94 (C-4), 109.28 (C-9), 129.48 (C-1), 141.87 (C-2), 148.61 (C-8), 172.82 (C-7).

Perillic acid was esterified with excess methanol, using toluenesulfonic acid as catalyst (Dayal et al., 1981). Perillic acid (3.00 mmol, 0.50 g) was dissolved in methanol (0.32 mol, 13 mL) and *p*-toluenesulfonic acid (0.15 mmol, 0.029 g), stirred (350 rpm) and heated to reflux (65 °C) for 22 h under N_2. The solution was cooled to room temperature and diluted with 12 mL chloroform, washed twice with saturated sodium bicarbonate (15 mL) and once with brine (15 mL). The organic layer (bottom) was diluted with chloroform to 20 mL, dried with magnesium sulphate and filtered. The solvent was removed using a rotary evaporator at 40 ˚C. The slightly-yellow oil was identified by GC-MS. A by-product was detected, that was identified as 8-methoxy-methylperillate by NMR and GC-MS. The product mixture was separated on column (2.3 cm diameter, 10 g silica, eluent PE:EtOAc 90:10). Fractions were evaporated and analysed with ^{1}H-NMR, ^{13}C-NMR and GC-MS. Methylperillate yield: 0.259 g (47 mole%). The procedure was scaled up at least 10 times with similar results. ^{1}H-NMR (400.17 MHz, $CDCl_3$): δ 1.43-1.48 (1H, m, *J*=4.0Hz, H-5), 1.75 (3H, s, H-10), 1.82-1.84 (2H, m, *J*=4.0Hz, H-5), 2,08 (2H, m, *J*=4.0Hz, H-6), 2.13-2.18 (2H, m, *J*=8.0Hz, H-3), 2.25-2.40 (1H, m, *J*=4.0Hz, H-4), 3.72 (3H, s, H-11), 4.66 and 4.70 (2H, s, H-9), 6.93 (1H, m, *J*=4.0Hz,

H-2); ^{13}C-NMR (100.62 MHz, $CDCl_3$): δ 20.53 (C-10), 24.44 (C-6), 26.92 (C-5), 30.93 (C-3), 39.93 (C-4), 51.30 (C-11), 109.05 (C-9), 129.78 (C-2), 138.90 (C-1), 148.53 (C-8), 167.55 (C-7). During methylation 8-methoxy-methylperillate (MMPA) was formed as a by-product. Longer reaction times yielded more MMPA (Fig. 1, Fig. A3). A reaction time of 21h ensured complete conversion of perillic acid to MPA with minimal MMPA formation. MMPA and other minor by-products could readily be separated from MPA by column chromatography or Kugelrohr distillation (Fig. A4). According to our knowledge the compound MMPA has not been reported before, characterization data of MPA and MMPA are added in Fig. A4.

2.11 Dehydrogenation to methyl cumate

Dehydrogenation conditions were initially optimized for limonene (Table 2). Methylperillate was dehydrogenated to methyl cumate using a supported palladium catalyst (Grau et al., 1999). Purified methylperillate (96% pure), 2.66 mmol, 0.479 g, 0.5 mL, was dissolved in acetone (0.300 mol, 22 mL) in a stirred (830 rpm) 75 mL reactor (MRS5000, Parr instrument company, Illinois, USA) with 5% Pd/Al_2O_3 catalyst (0.2038 g, ~0.096 mmol Pd), flushed 3 times with N_2 and then heated to 125 °C for 1 h under N_2. Subsequently, the reactor was let to cool down to room temperature. Then the solution was filtered over a Celite pad and washed with acetone. The solvent was removed using a rotary evaporator at 40 ˚C. The product was analysed with ^{1}H-NMR, ^{13}C-NMR and GC-MS. Some minor by-products related to acetone were observed, among these were diacetone alcohol, that can be formed by aldol addition of two molecules of acetone, and mesityl oxide, the dehydration product of diacetone alcohol. Yield: 0.721 g, 45% pure (total yield methylcumate from methylperillate 69 mole%). ^{1}H-NMR (400.17 MHz, $CDCl_3$) δ 1.25 (6H, s, H-9 and H-10), 2.92-2.98 (1H, m, *J*=8.0Hz, H-8), 3.89 (3H, 2, H-11), 7.27-7.29 (2H, m, *J*= 8.0Hz, H-3 and H-5), 7.94-7.96 (2H, m, *J*=8.0Hz, H-2 and H-6); ^{13}C-NMR (100.62 MHz, $CDCl_3$) δ 23.63-23.64 (C-9 and C-10), 30.83 (C-8), 34.19 (C-7), 51.85(C-

11), 126.40 (C-3 and C-5), 127.74 (C-1), 129.67 (C-2 and C-6), 154.24 (C-4), 167.09 (C-7). NMR characterization matches that reported in literature (Zhu et al., 2013).

2.12 Oxidation of cumic acid to terephthalic acid

A 50 mL round bottom flask was equipped with a magnetic stirring bar and a Liebig condenser. The round bottom flask was placed on a stirring plate with an aluminium heating mantle. The flask was charged with water (20 mL), followed by 65% nitric acid (14.4 g) and sodium nitrite (10 mg) to initiate the reaction. The mixture was stirred and gently heated to ~40 ˚C until the mixture became yellow. Next, cumic acid (5.0 g) was added to the stirred nitric acid solution, to give a white suspension. The suspension was heated to reflux, and became clear after ~30 min at reflux. After 24 h reflux, the reaction mixture had turned into a white suspension again. The mixture was allowed to cool down to room temperature, and the white solid was collected from the suspension by filtration (type 3 glass filter). The filter cake was washed with demineralized water, and dried under vacuum to constant weight (40 ˚C, ~50 mbar, in the presence of Sicapent). The product was obtained as a white powder. Yield: 4.5 g (89 mole%). The product was analysed with GC-MS after silylation, and with ^{1}H-NMR and ^{13}C-NMR. ^{1}H-NMR (400.17 MHz, DMSO-D_6) δ 13.32 (2H, s, H-7 and H-8), 8.03 (4H, s, H-2, H-3, H-5 and H-6); ^{13}C-NMR (100.62 MHz, DMSO-D_6) δ 129.43 (C-2, C-3, C-5, C-6), 134.44 (C-1, C-4), 166.64 (C-7, C-8).