

Electronic Supplementary Information

Synthesis of Carboxylic Acids via Hydrocarboxylation of Alcohols with CO₂ and H₂

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Experimental

Chemicals

All chemicals were used as received from suppliers and without further purification. Iridium(III) acetate (>97%, Ir \geq 48.0%) was purchased from Shanghai Haohong Biomedical Technology Co., Ltd. Cyclohexanol (99%+) was provided by Adamas Reagent, Ltd. Iridium (IV) iodide (IrI₄, 99.95% (metals basis), Ir 27.0%), iridium (III) chloride (IrCl₃, anhydrous, 99.99% (metals basis)), iridium(IV) oxide dihydrate (IrO₂ · 2H₂O, 99.99% (metals basis)), iron iodide (FeI₂, anhydrous, 97% (metals basis)), rhodium (III) iodide (RhI₃, 99.9%, (metals basis), Rh 20.8% min), ruthenium (III) iodide (RuI₃, anhydrous, Ru 20.5% min), dihydrogen hexabromoosmate (IV) hydrate (H₂O₈Br₆ · xH₂O, 99.9%, (metals basis)), carbonylchlorobis(triphenylphosphine)iridium (Ir(CO)(PPh₃)₂Cl), iridium powder (Ir, -325 mesh, 99.9%, (metals basis)), lithium fluoride (LiF, 99.99%), sodium iodide (NaI, 99.5%), methanesulfonic acid (CH₃SO₃H, 98%+) were obtained from Alfa Aesar China Co, Ltd. Lithium iodide (LiI, 99.99%), octane (99%), lithium triflate (98%), n-propanol (\geq 99.8%), sec-butanol (\geq 99.8%), tert-butanol (>99.8%), 1,4-butanediol (\geq 99.5%), 1,3-butanediol (99%), 1-pentanol (99%), 1-hexylalcohol (>99.5%), 1-heptanol (99%), 2-cyclohexylethanol (>98%), glycerol (>99%), n-butanol (\geq 99.9%), 3-phenylpropanol (99%) and succinic acid (99.5%) were bought from Aladdin. Dicobaltoctacarbonyl (Co₂(CO)₈, stabilized with 1-5% hexane), palladium (II) acetate (Pd(OAc)₂, 98%), lithium chloride (LiCl, 98%), iodocyclohexane (stabilized with copper chip, 98%), cyclopentanol (>99%), methyl iodide (CH₃I, >99.5%) and cyclohexyl acetate (99%) were bought from TCI Shanghai Co., Ltd. Lithium acetate (99%), iodine (I₂, 99.8%), iodoform (99%), 1-methyl-2-pyrrolidinone (NMP, 99%), cyclohexene (99%), trifluoroacetic acid (CF₃COOH, 99%), formic acid (HCOOH, 98%) and phenethyl alcohol (99%) were obtained from J&K Scientific Ltd. Potassium iodide (KI, 99.0%), sulfuric acid (H₂SO₄, 95%-98%), propionic acid (CH₃CH₂COOH, \geq 99.5%) were obtained from Sinopharm Chemical Reagent Co., Ltd. Acetic acid (AcOH, 99.8%) was provided by Acros Organics. 1,2-cyclohexanediol was purchased from Ark Pharm. Cyclohexane (\geq 99.7%) and ethanol (>99.7%) were bought from kangkede Tianjin Co., Ltd. Dimethyl sulfoxide (DMSO, A.R.) was provided by Beijing Chemical works. Isopropanol (\geq 99.7%) was offered by Xi Long scientific Technology Co. Ltd. CO₂ (99.99%), H₂ (99.99%) and CO (99.99%) were provided by Beijing Analytical Instrument Company. Deuterium gas (D₂, 99.999%) was offered by Zhengzhou Xingdao Chemical Technology Co. Ltd. Carbon dioxide-¹³C (¹³CO₂, 99% ¹³C) was obtained from Beijing Gaisi Chemical Gases Center. Lithium bromide (LiBr, 99%), deuterated dimethyl sulfoxide-d₆ (99.8 atom % D, with 0.03%(V/V) TMS), D₂O (99.9 atom % D) and H₂¹⁸O (97 atom % ¹⁸O) were purchased from Beijing InnoChem Science & Technology Co., Ltd.

Catalytic reaction

The reaction was conducted in a 16 mL Teflon-lined stainless steel batch reactor with 18 mm inner diameter, and the reactor was equipped with a magnetic stirrer. In a typical experiment, the desired amount of Iridium acetate as catalyst, LiI as promoter, cyclohexanol as substrate and AcOH as solvent were sequentially added into the reactor. The reactor was sealed and purged twice with 1 MPa of CO₂, then CO₂ and H₂ of desired pressure at room temperature were charged sequentially into the reactor. The reactor was heated to and kept at a specified temperature during the reaction, and the stirrer rotated at 800 rpm. When the reaction was finished the reactor was put into an ice-water bath to cool down. After cooling completely, the residual gas in the reactor was released slowly and collected in a gas bag. The products and intermediates of the reaction were identified by GC-MS (SHIMADZU GCMS-QP2010) using Rtx-WAX column (length = 30 m, diameter = 0.32 mm, film = 0.25 μ m) as well as comparing the retention time with the respective standard in the LC or GC traces. The gaseous samples were analyzed and quantified by a gas chromatograph (Agilent 7890B) equipped with a packed column (carbon

molecular sieve TDX-01, 3 mm in diameter and 1 m in length) and a TCD detector using argon as carrier gas. The amount of carboxylic acid in the reaction solution was determined by a liquid chromatograph (LC-10AT, SHIMADZU) equipped with a BP-800 H+ carbohydrate column (S/N 23757, Benson polymeric) and a refractive index detector (RID). The column temperature was maintained at 323.15 K. The column was eluted with 5 mmol/L H₂SO₄ solution at a flow rate of 0.4 mL/min or 0.8 mL/min according to the product analyzed. Before the LC analysis, the liquid mixture after the reaction was diluted with 10 mL 1/1 AcOH/H₂O, followed by addition of 10 μL DMSO or succinic acid as internal standard. An aliquot of this sample was filtered through syringe filters with hydrophilic PTFE membrane, and the filtrate was immediately injected into the chromatograph. The liquid intermediates in the reaction solution were quantified by a gas chromatograph (GC, Agilent 7890B) equipped with a flame ionization detector (FID) and an HP-INNOWAX capillary column (length = 30 m, diameter = 0.25 mm, film = 0.25 μm). Before this analysis, the liquid solution was diluted with 5 mL acetone, followed by addition of 15 μL octane as internal standard. Liquid ¹³C NMR spectra were recorded on Bruker Avance III 400 HD NMR spectrometer. NMR chemical shifts δ are given in parts per million (ppm) relative to tetramethylsilane. Infrared Radiation (IR) spectroscopy was recorded on Bruker Tensor-27 FT-IR Spectrometer. High-resolution electrospray ionization mass spectrometry (HR-ESI-MS) was recorded on Bruker FT-ICR-MS (Solarix 9.4T).

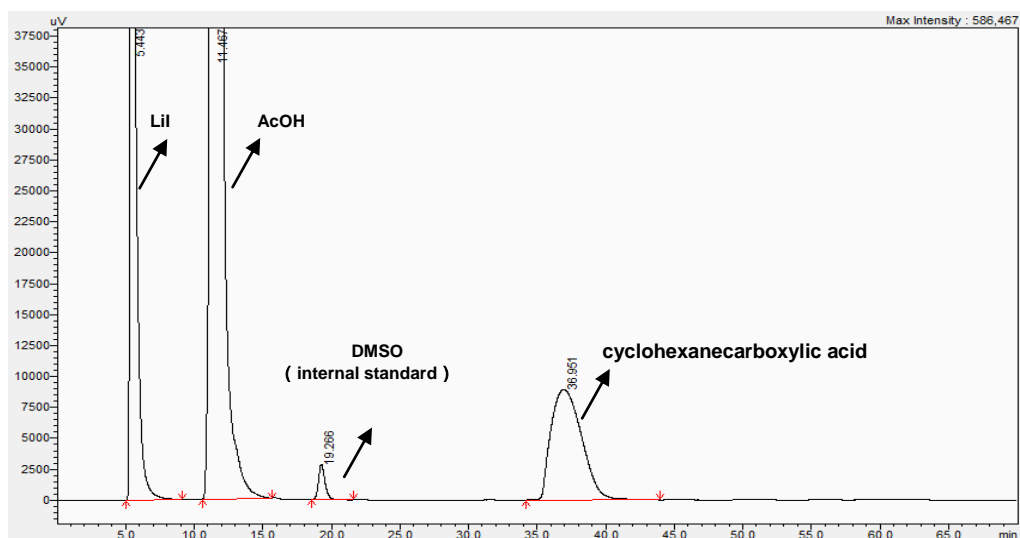
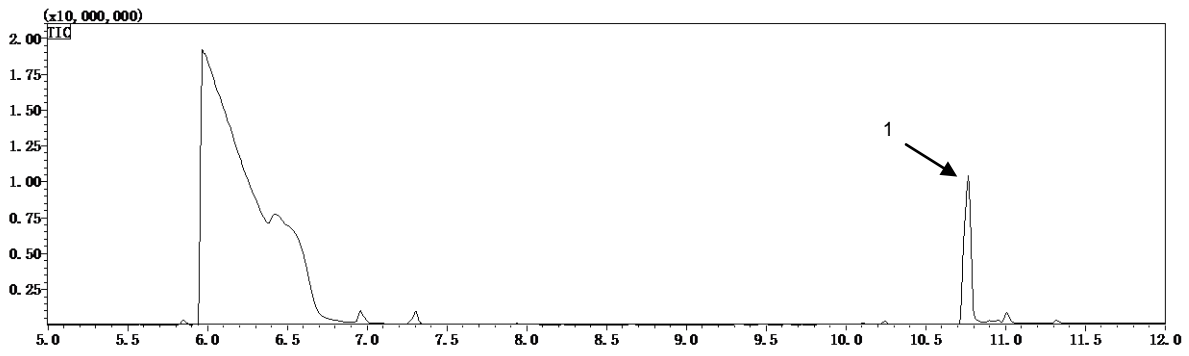


Fig. S1 The LC graph of the reaction liquid. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 6 MPa (68 mmol) CO_2 and 1 MPa H_2 (at room temperature), 16 h, 170 $^\circ\text{C}$.



Peak 1

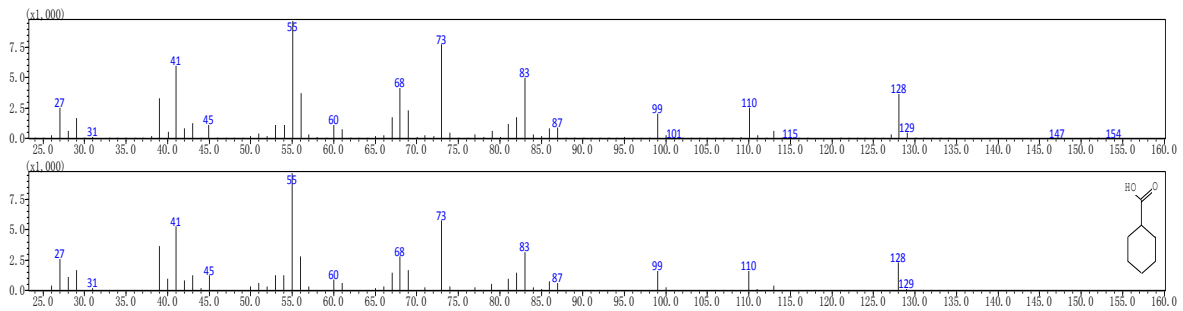


Fig. S2 The GC-MS graph of the liquid sample using cyclohexanol as substrate.

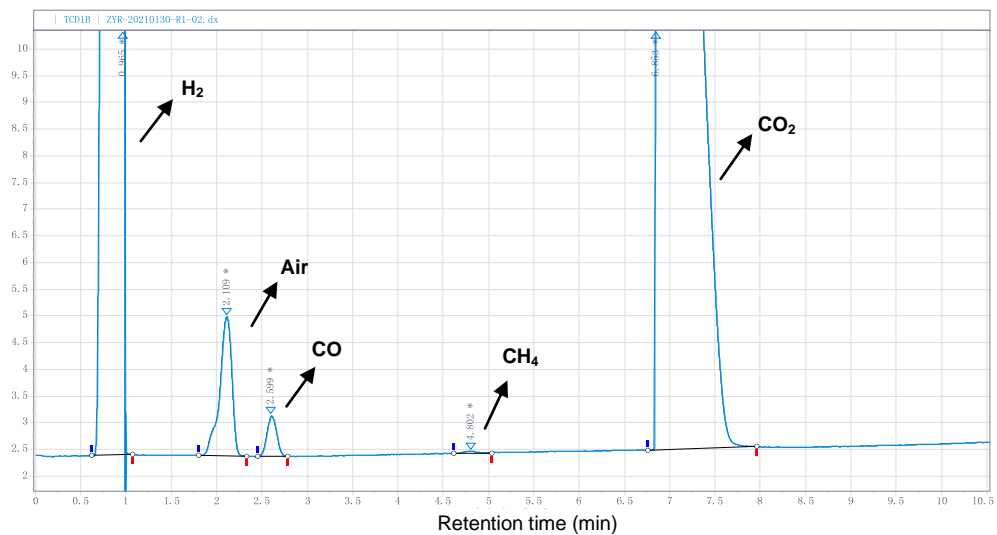
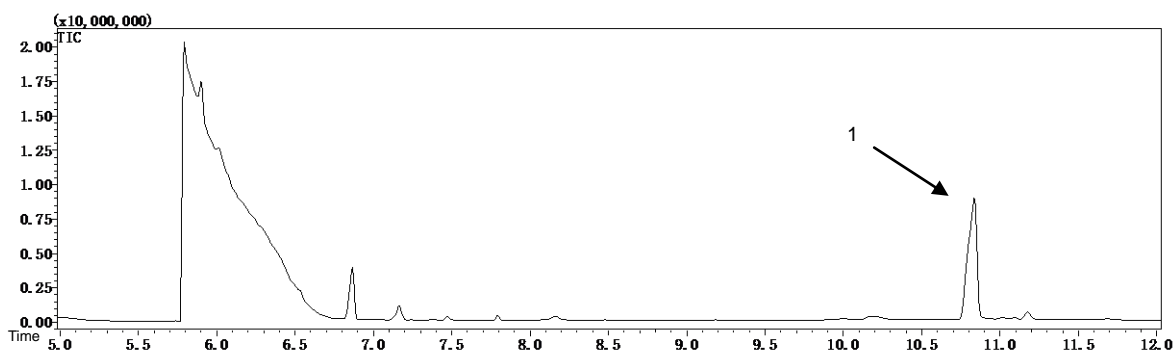


Fig. S3 The GC graph of gaseous sample after the reaction. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 6 MPa (68 mmol) CO_2 and 1 MPa H_2 (at room temperature), 1 h, 170 $^\circ\text{C}$.



Peak 1

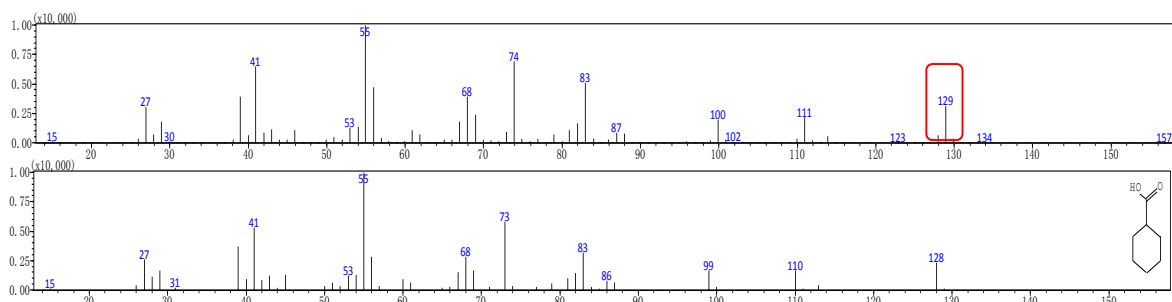


Fig. S4 The GC-MS graph of the liquid sample after the ^{13}C CO_2 labelling test. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 1.5 MPa ^{13}C CO_2 and 1 MPa H_2 (at room temperature), 16 h, 170 $^\circ\text{C}$.

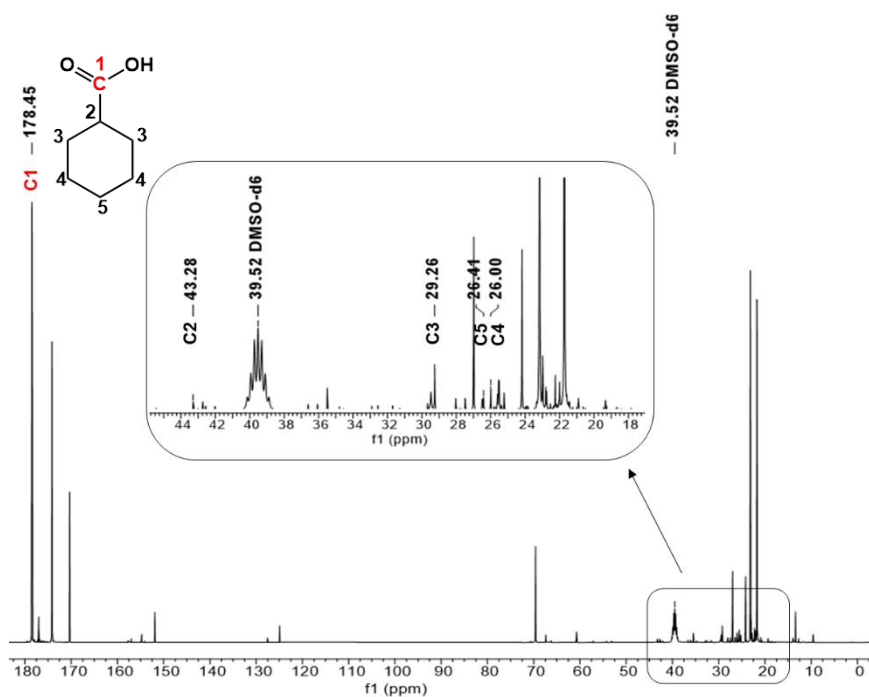
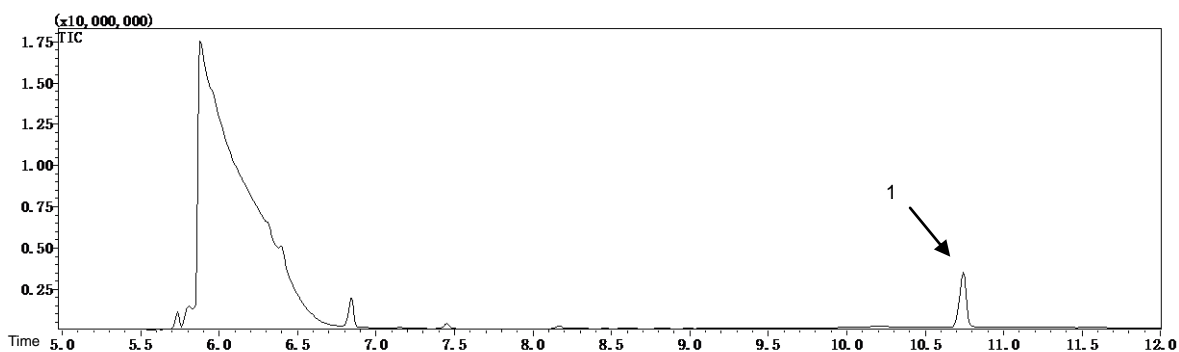


Fig. S5 The ^{13}C NMR spectra of the ^{13}C CO_2 labelling experiment. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 1.5 MPa ^{13}C CO_2 and 1 MPa H_2 (at room temperature), 16 h, 170 $^\circ\text{C}$. The peaks of C2, C3, C5, and C4 (δ 43.28 ppm, 29.26 ppm, 26.41 ppm, 26.00 ppm) belong to alkyl carbons of cyclohexanecarboxylic acid. The peak of C1 is attributed to the carbon of the carboxyl groups of the cyclohexanecarboxylic acid, which is remarkably larger than those of the alkyl carbons of the product. It indicated that CO_2 took part in forming the carboxyl group of the product.



Peak 1

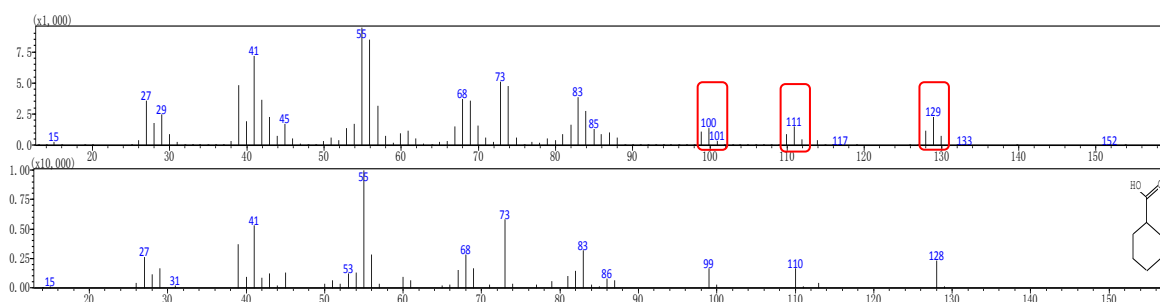
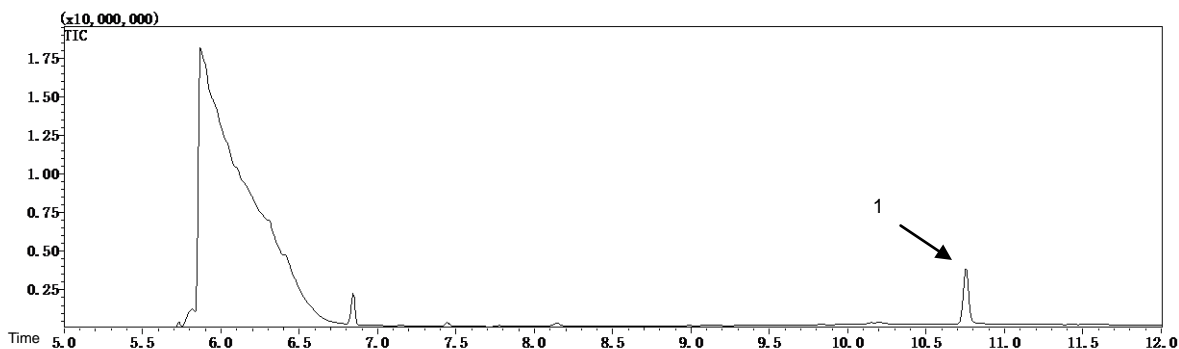


Fig. S6 The GC-MS graph of the liquid sample after the D₂O labelling test. Reaction conditions: 45 μ mol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 0.2 mL D₂O, 2.25 mmol cyclohexanol, 6 MPa (68 mmol) CO₂ and 1 MPa H₂ (at room temperature), 16 h, 170 °C.



Peak 1

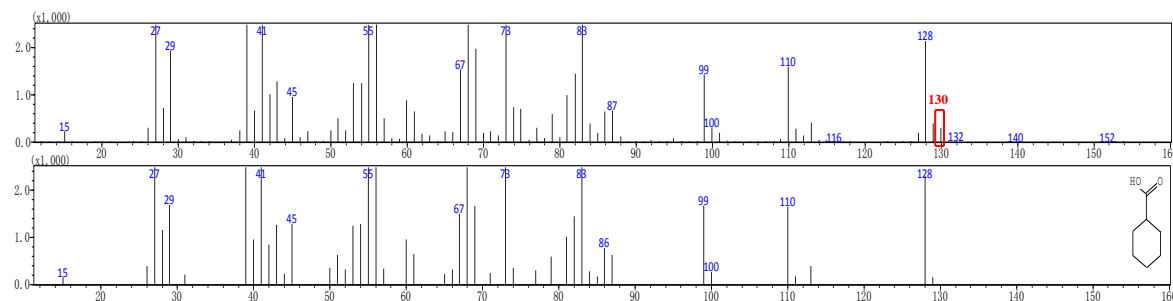
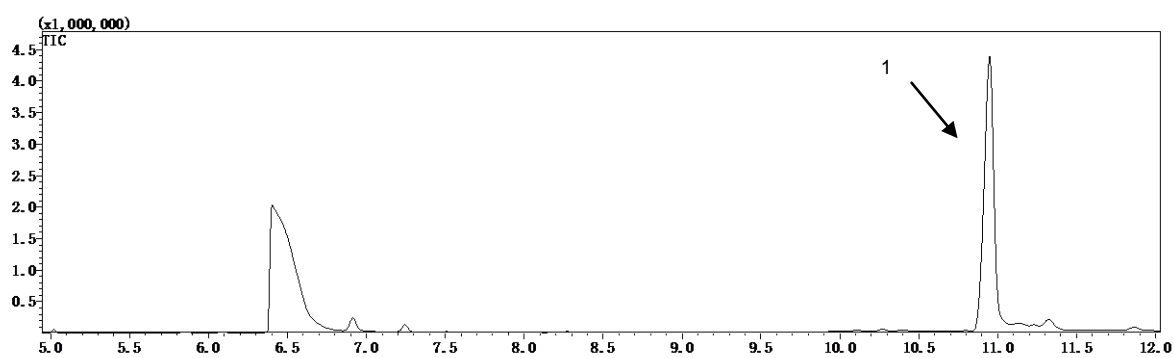


Fig. S7 The GC-MS graph of the liquid sample after the H₂¹⁸O labelling test. Reaction conditions: 45 μ mol iridium(III) acetate (based on Ir), 2 mmol LiI and 0.5 mL AcOH, 0.2 mL H₂¹⁸O, 2.25 mmol cyclohexanol, 6 MPa (68 mmol) CO₂ and 1 MPa H₂ (at room temperature), 16 h, 170 °C.



Peak 1

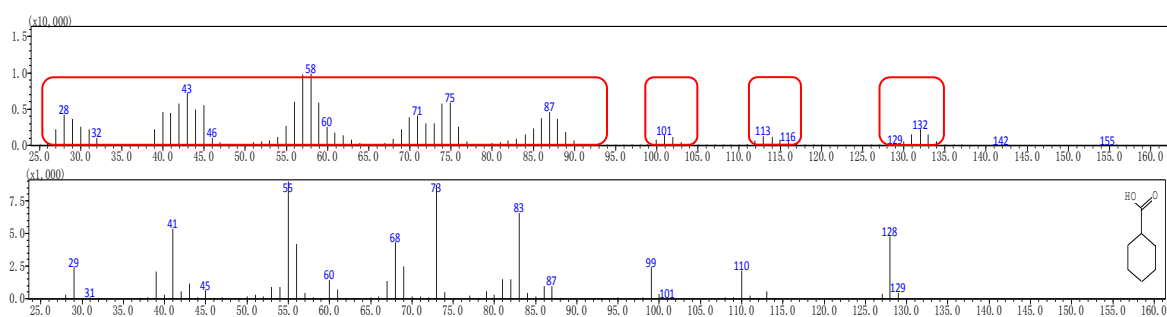


Fig. S8 The GC-MS graph of the liquid sample after the D₂ labelling test. Reaction conditions: 45 μ mol iridium(III) acetate (based on Ir), 2 mmol LiI, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 6 MPa (68 mmol) CO₂ and 1 MPa D₂ (at room temperature), 16 h, 170 °C.

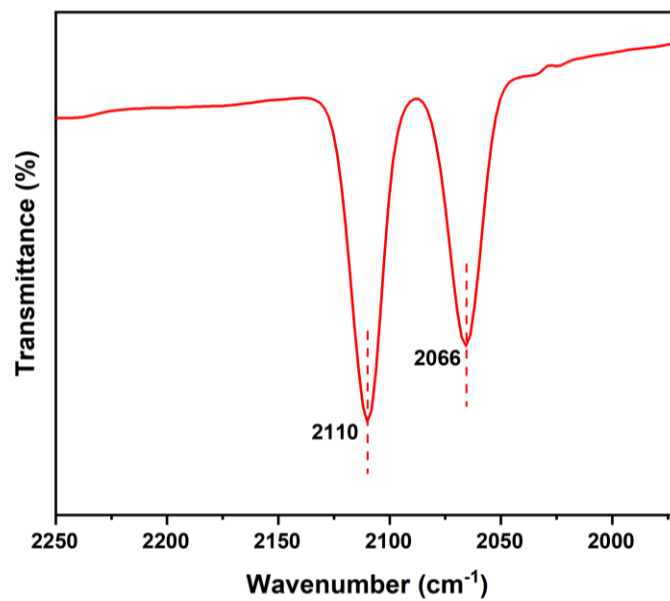


Fig. S9 FTIR spectra of reaction liquid. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI and 0.5 mL AcOH, 2.25 mmol cyclohexanol, 6.0 MPa (68 mmol) CO_2 and 1 MPa H_2 (at room temperature), 16 h, 170 $^\circ\text{C}$. (The peaks at $\nu = 2110 \text{ cm}^{-1}$ and $\nu = 2066 \text{ cm}^{-1}$ are attributed to $\nu(\text{CO})$ of $\text{cis-}[\text{Ir}(\text{CO})_2\text{I}_4]^-$ species)¹.

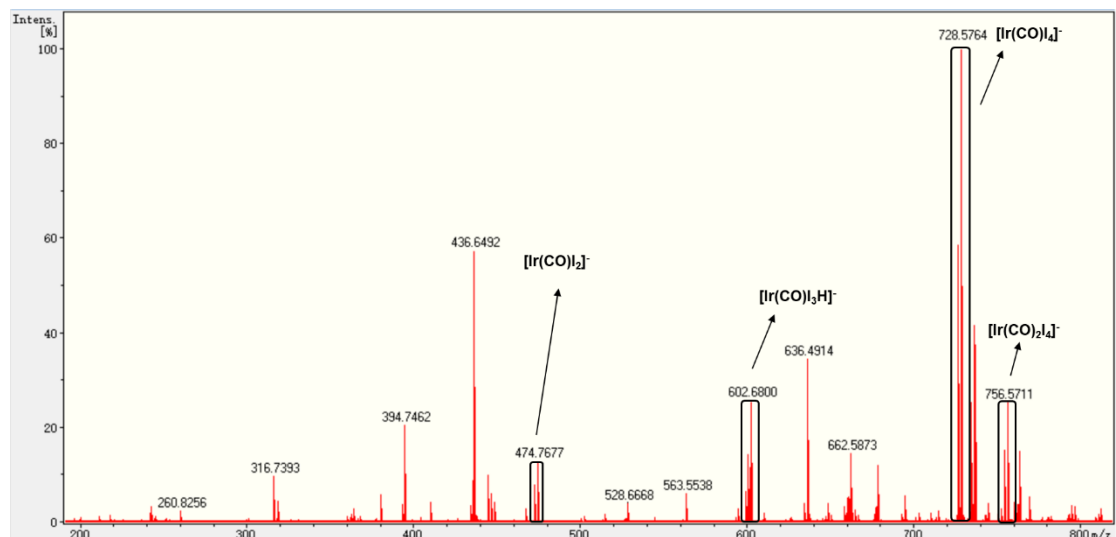
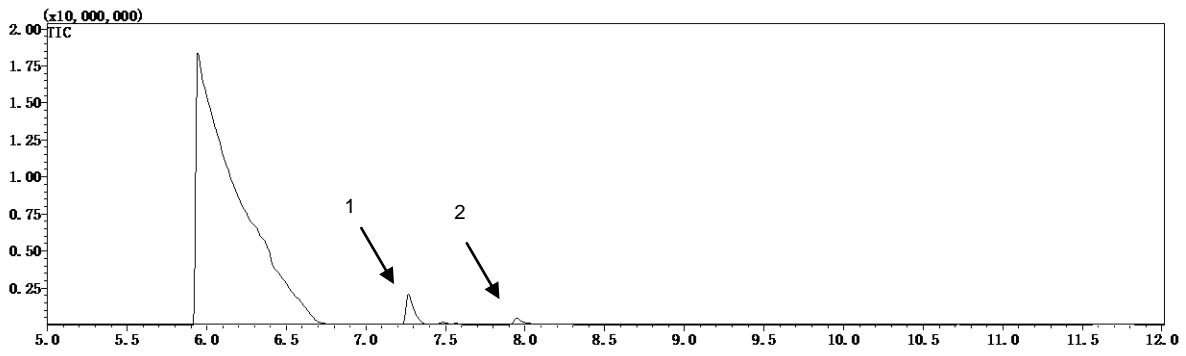
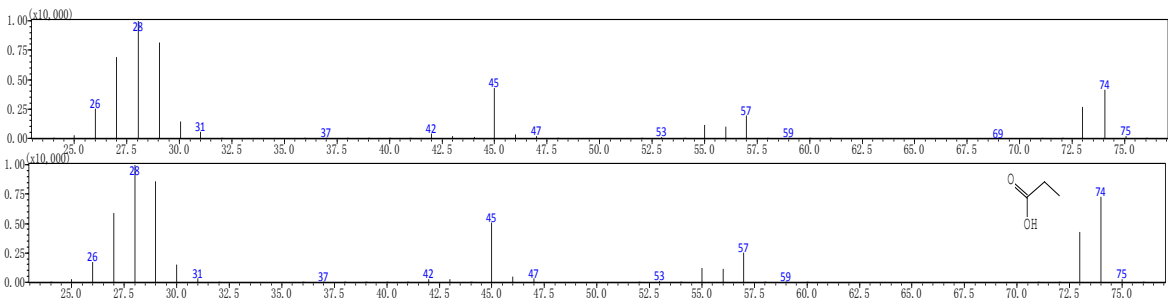


Fig. S10 The HR-ESI(-)-MS result of the reaction liquid. Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI and 0.5 mL AcOH, 2.25 mmol cyclohexanol, 6.0 MPa (68 mmol) CO_2 and 1 MPa H_2 (at room temperature), 16 h, 170 $^\circ\text{C}$. The spectra of detected Ir species are in good agreement with their calculated isotope distribution spectra.



Peak 1



Peak 2

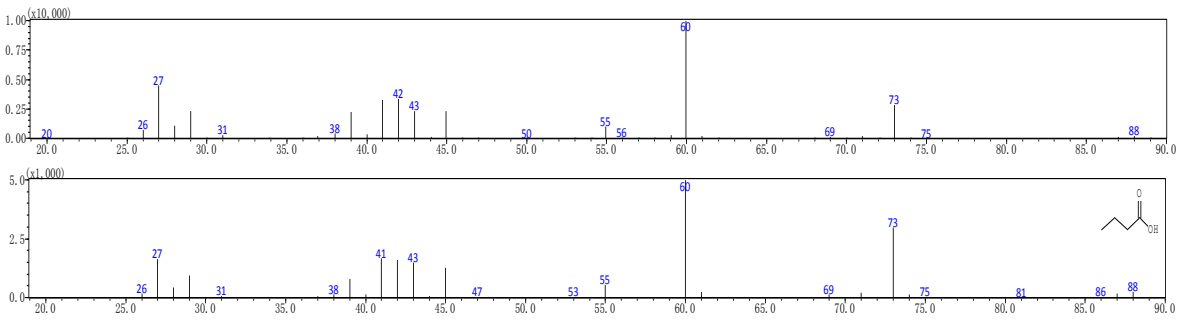
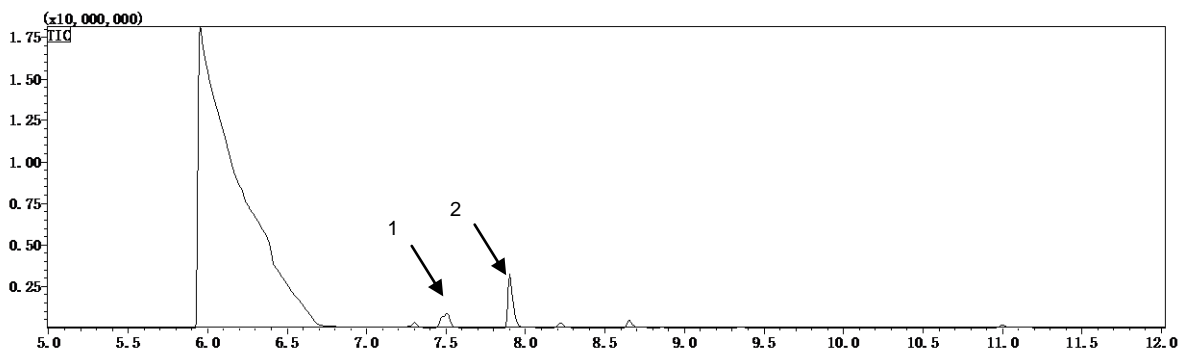
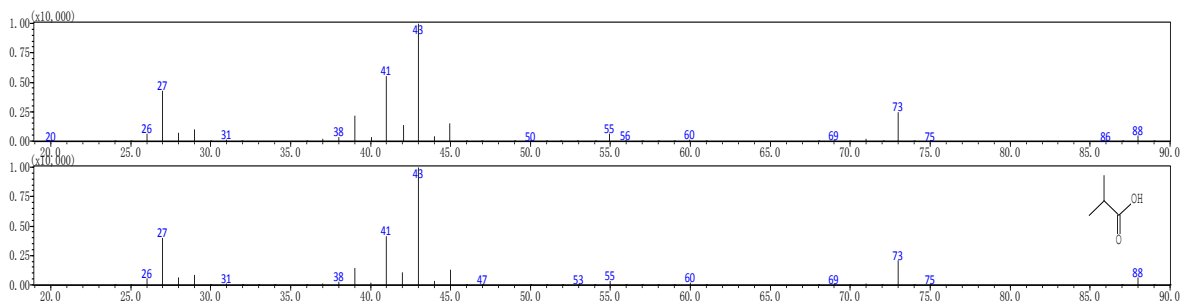


Fig. S11 The GC-MS graph of the liquid sample using ethanol as substrate.



Peak 1



Peak 2

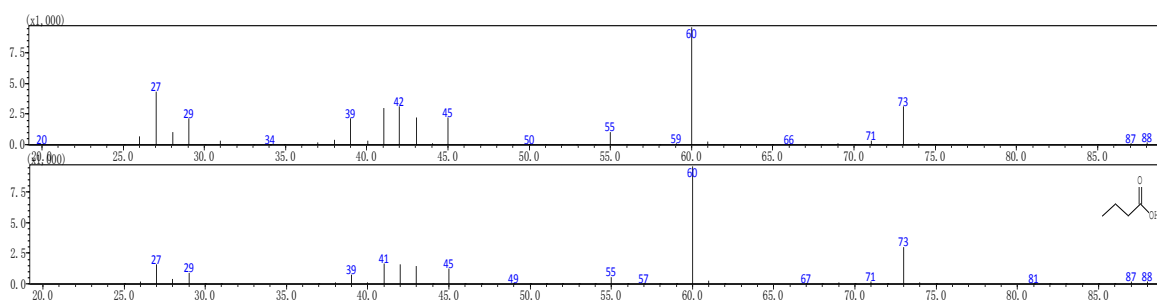
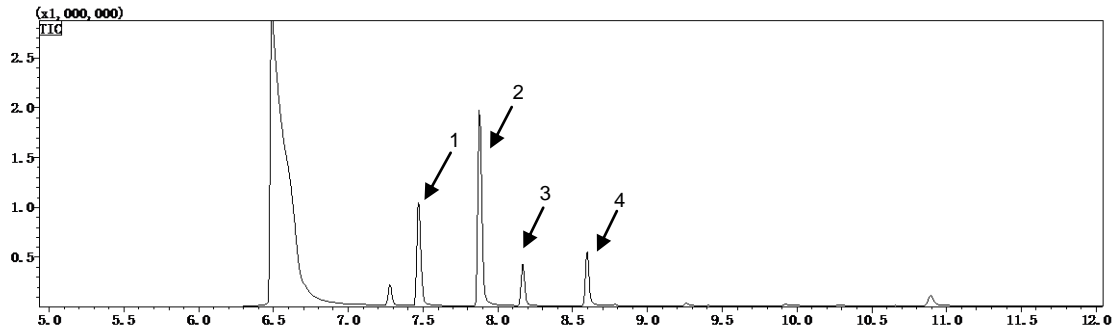
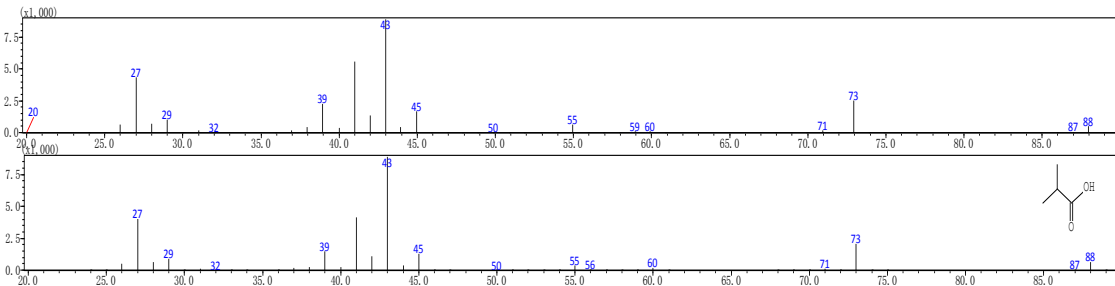


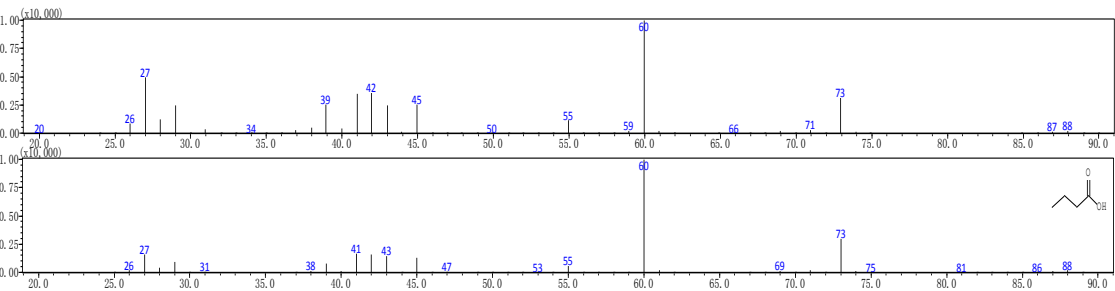
Fig. S12 The GC-MS graph of the liquid sample using 1-propanol as substrate.



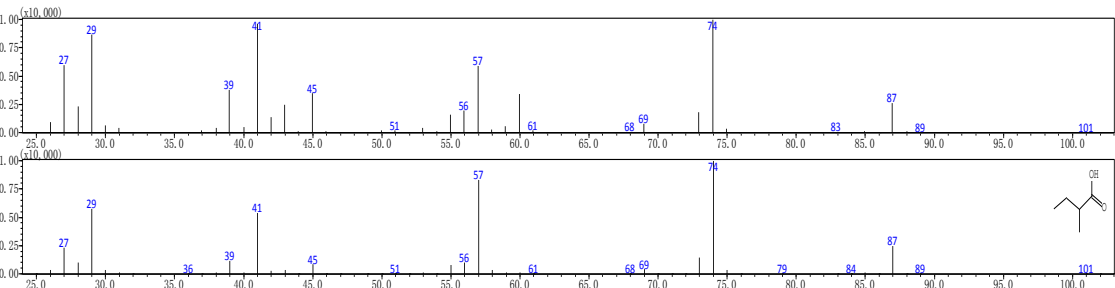
Peak 1



Peak 2



Peak 3



Peak 4

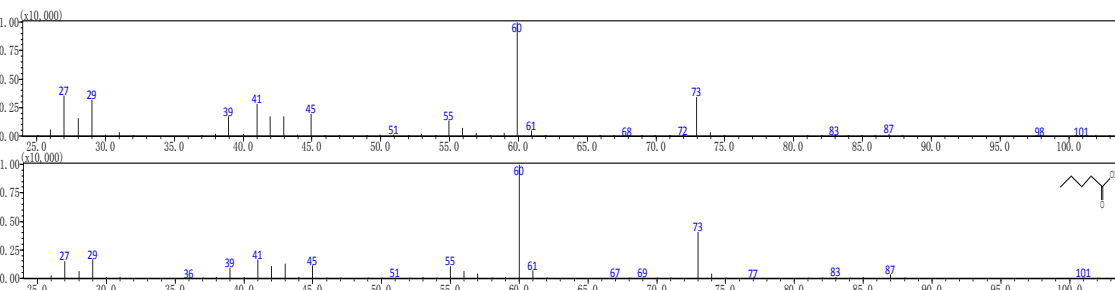
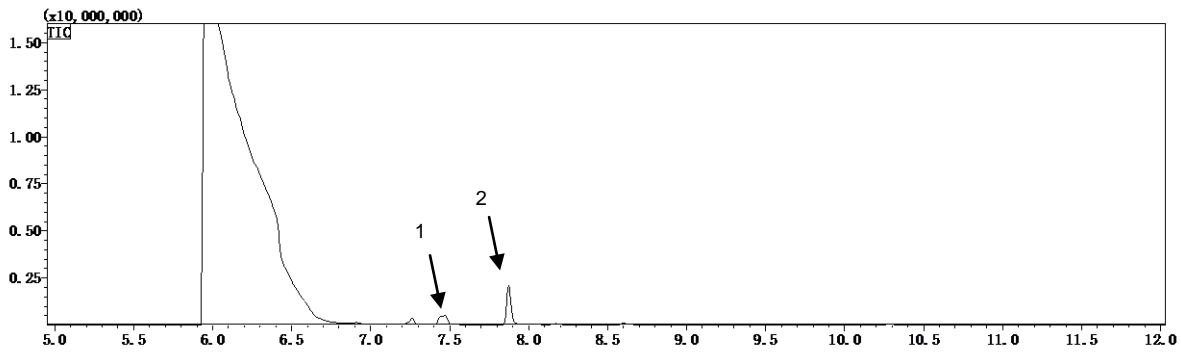
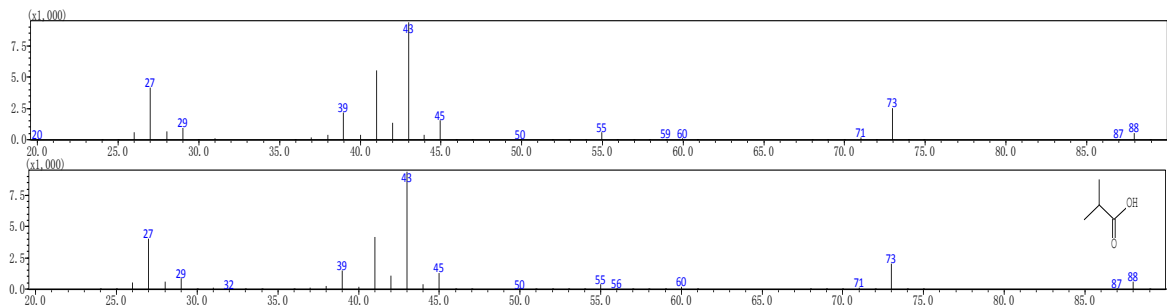


Fig. S13 The GC-MS graph of the liquid sample using isopropanol as substrate.



Peak 1



Peak 2

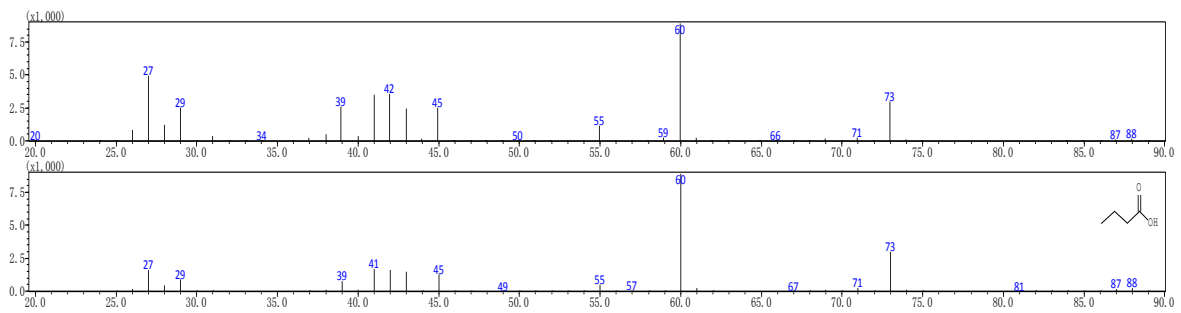
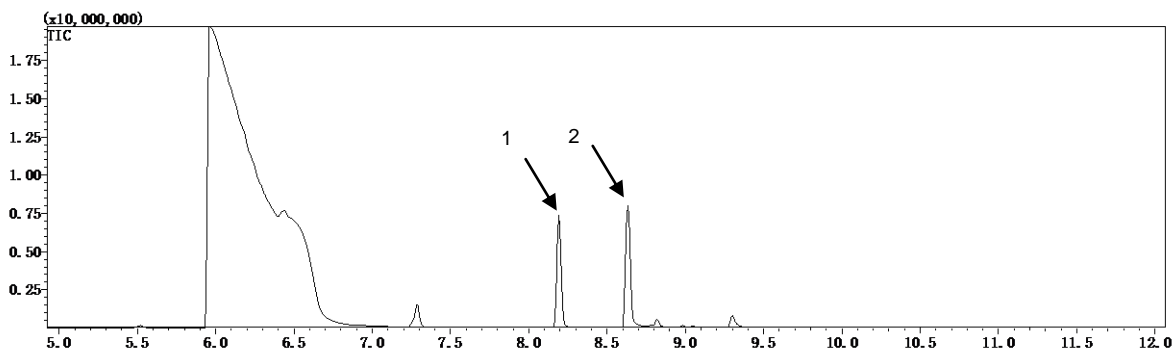
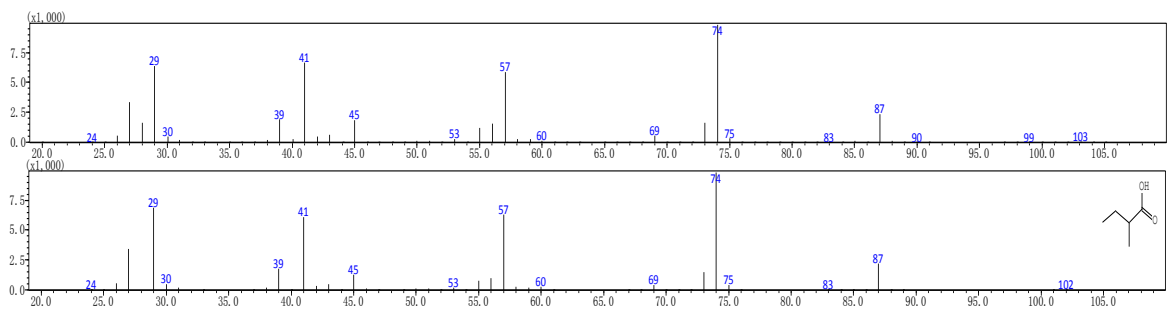


Fig. S14 The GC-MS graph of the liquid sample using glycerol as substrate.



Peak 1



Peak 2

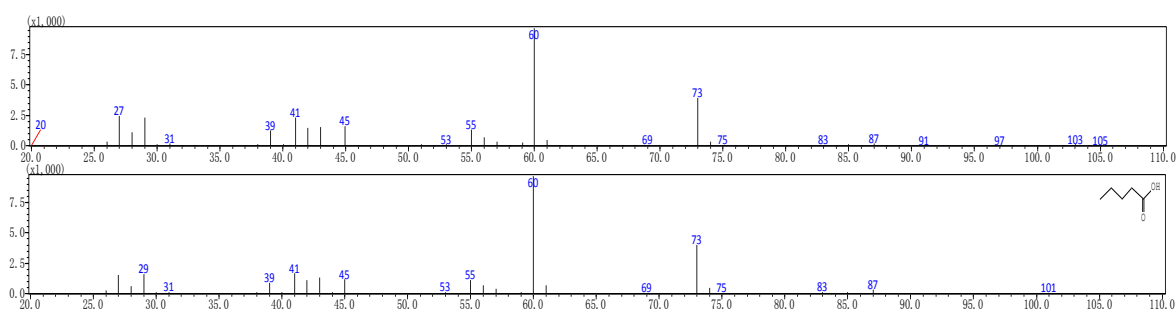
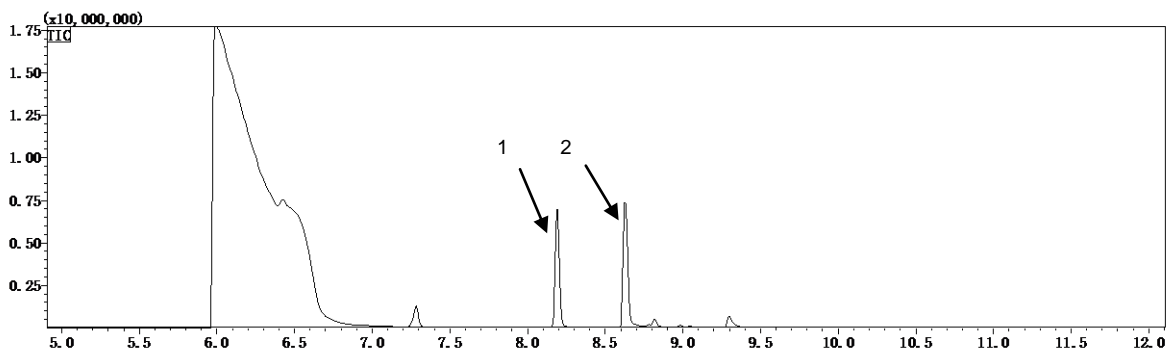
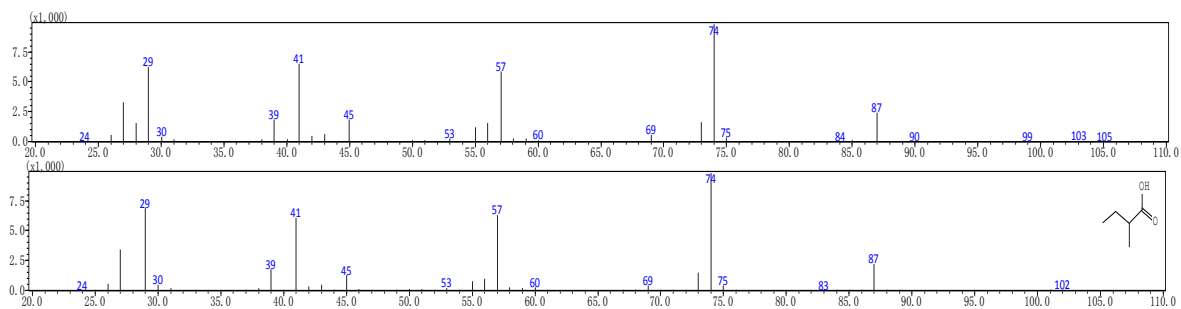


Fig. S15 The GC-MS graph of the liquid sample using 1-butanol as substrate.



Peak 1



Peak 2

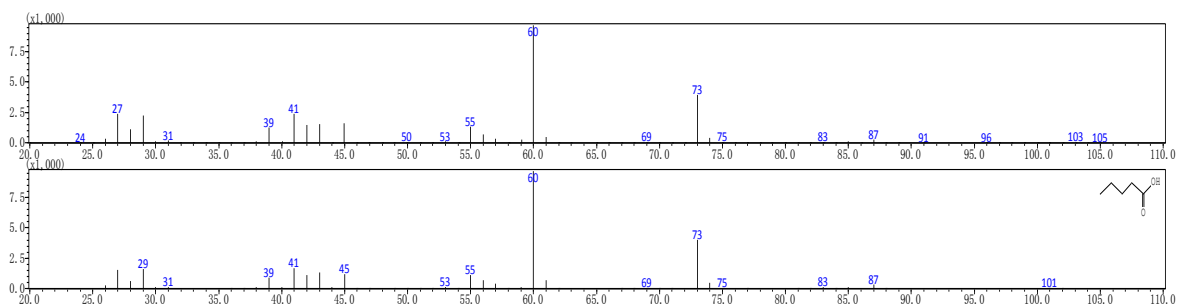
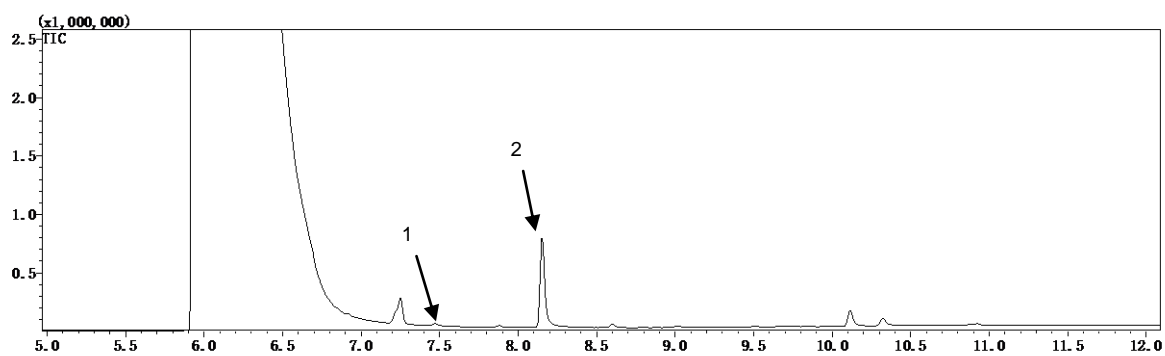
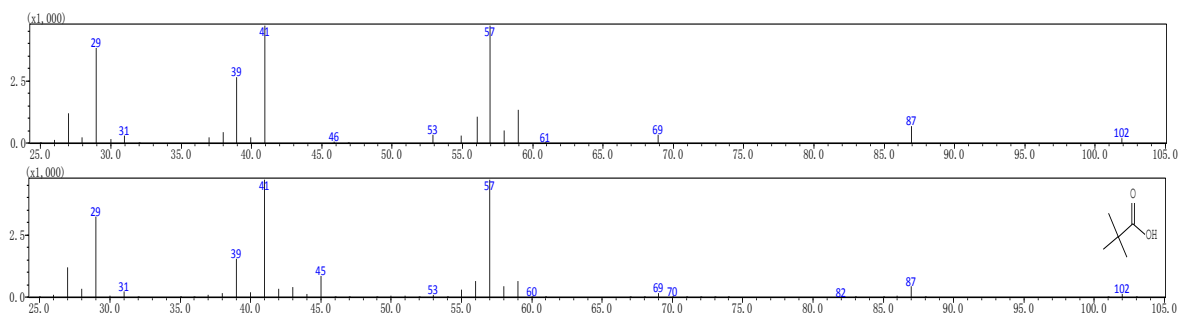


Fig. S16 The GC-MS graph of the liquid sample using sec-butanol as substrate.



Peak 1



Peak 2

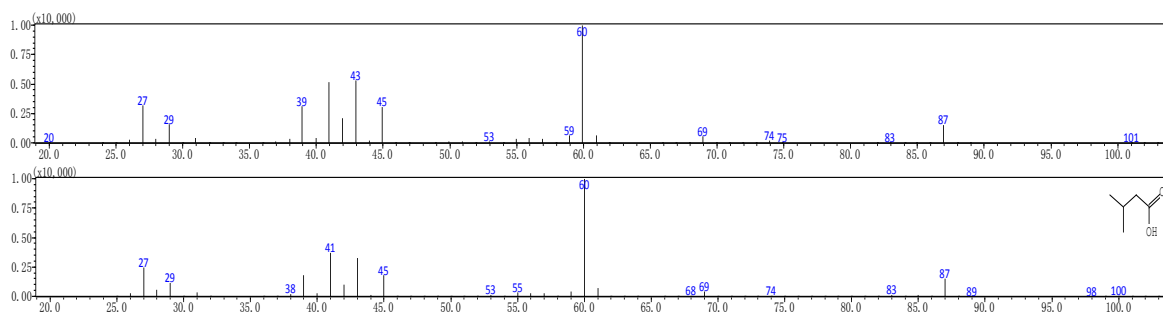
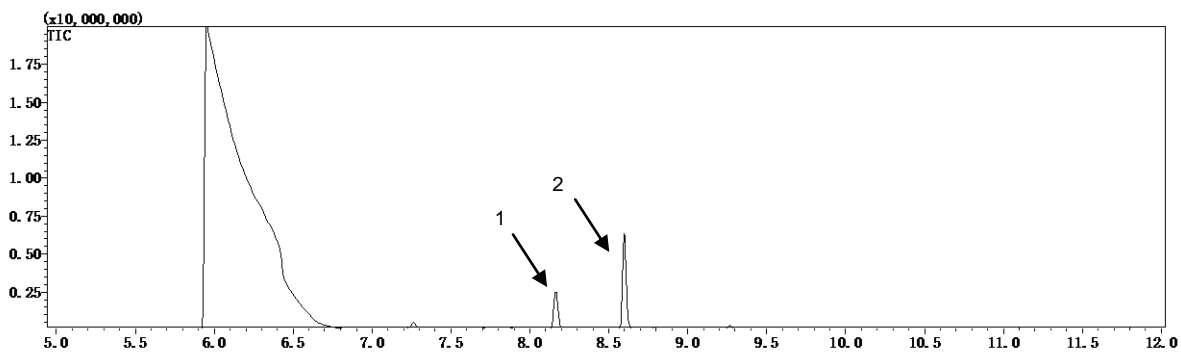
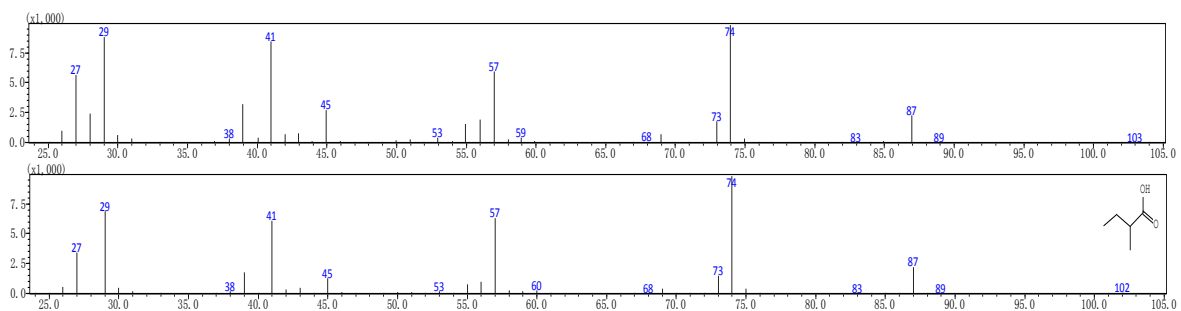


Fig. S17 The GC-MS graph of the liquid sample using tert-butanol as substrate.



Peak 1



Peak 2

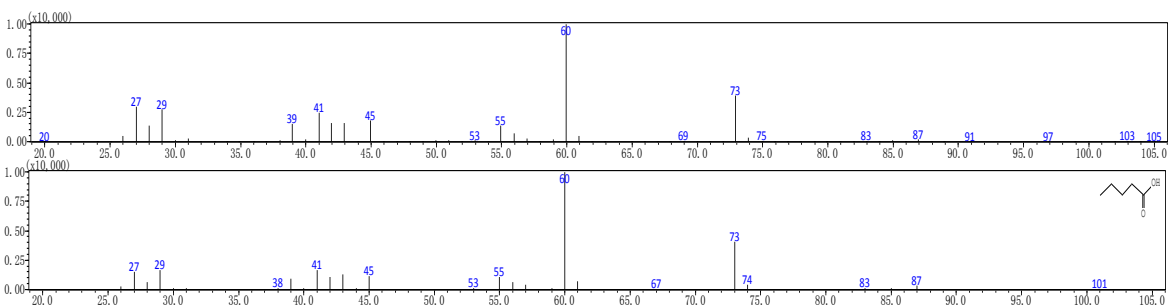
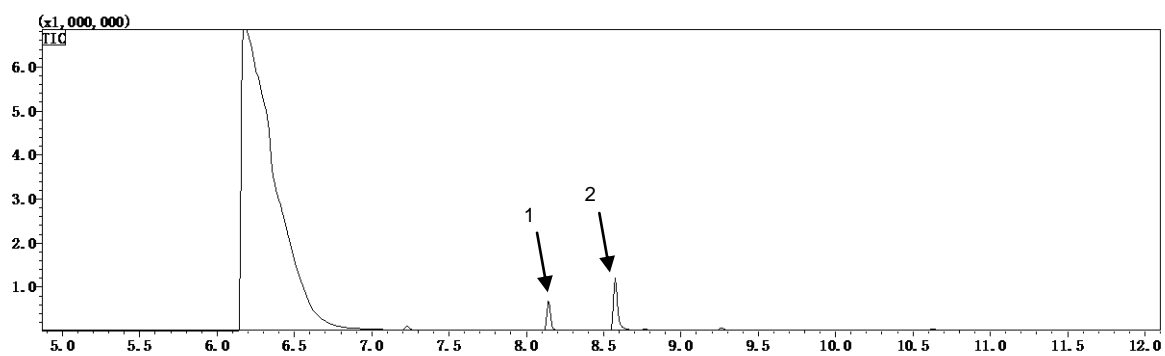
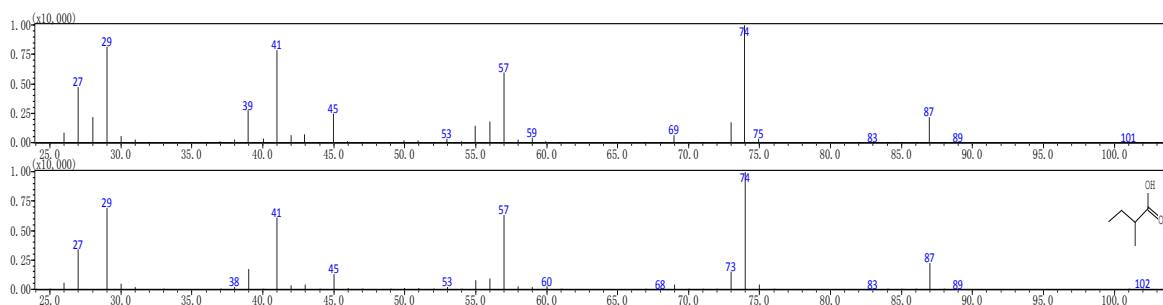


Fig. S18 The GC-MS graph of the liquid sample using 1,4-butanediol as substrate.



Peak 1



Peak 2

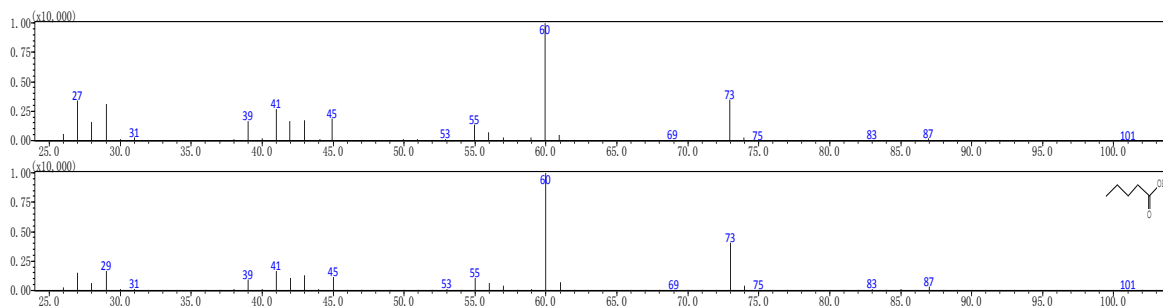
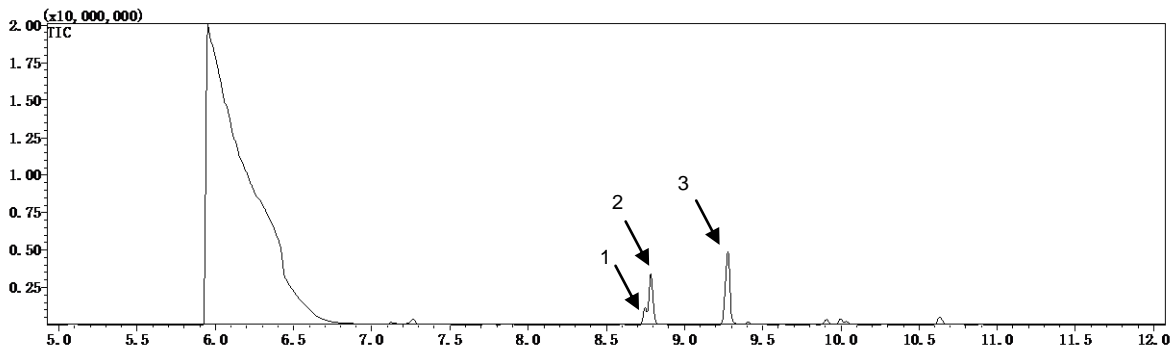
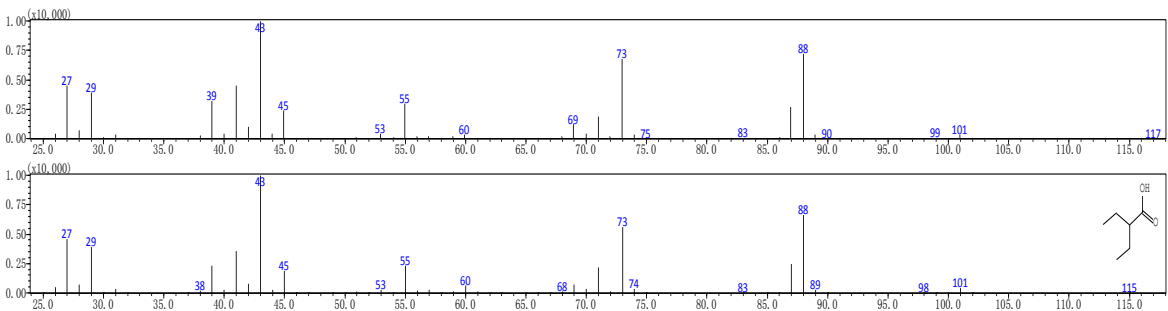


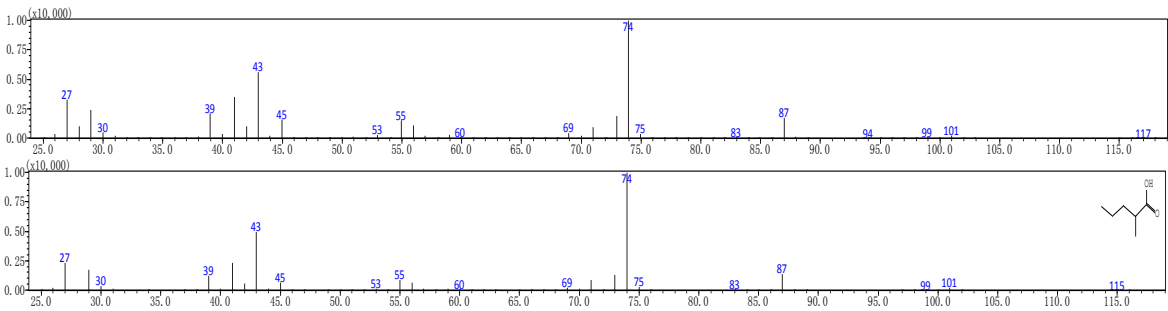
Fig. S19 The GC-MS graph of the liquid sample using 1,3-butanediol as substrate.



Peak 1



Peak 2



Peak 3

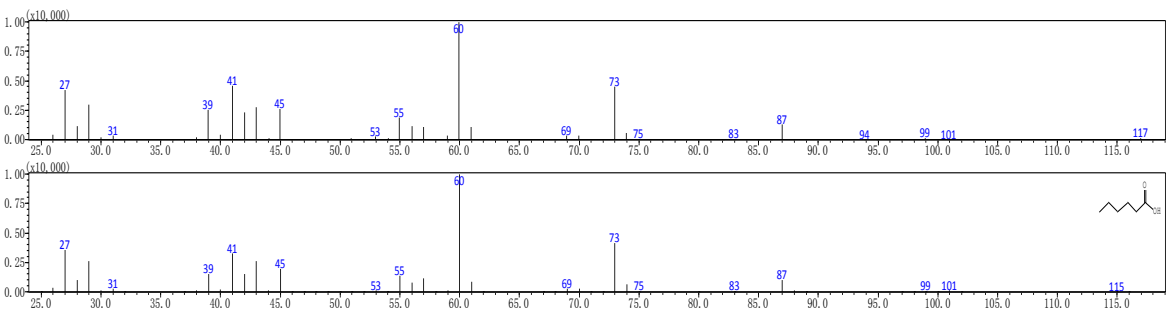
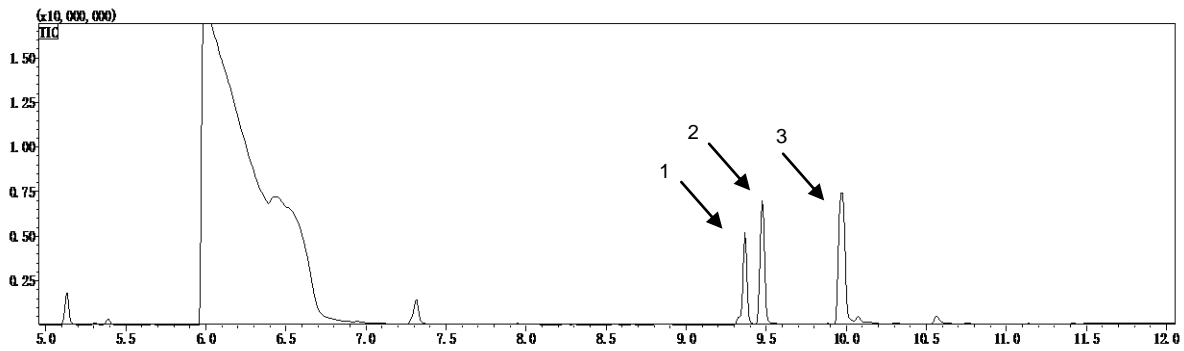
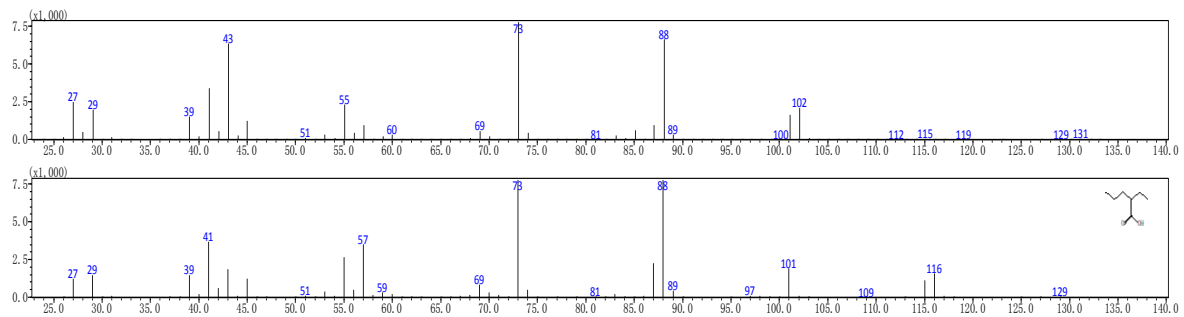


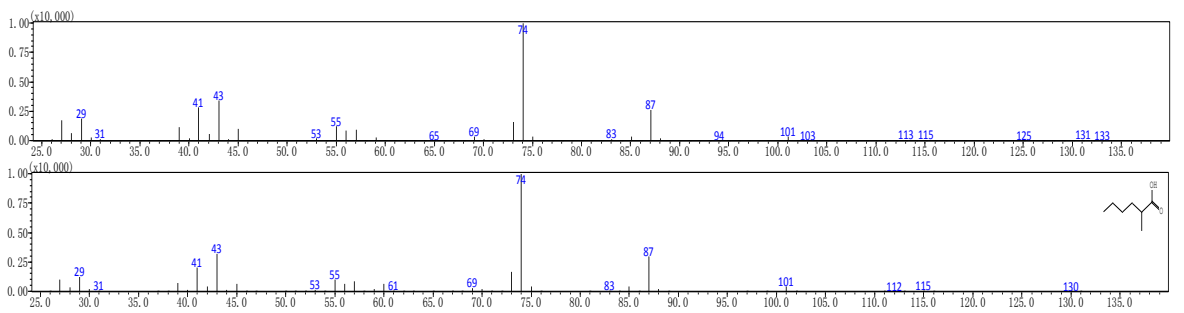
Fig. S20 The GC-MS graph of the liquid sample using 1-pentanol as substrate.



Peak 1



Peak 2



Peak 3

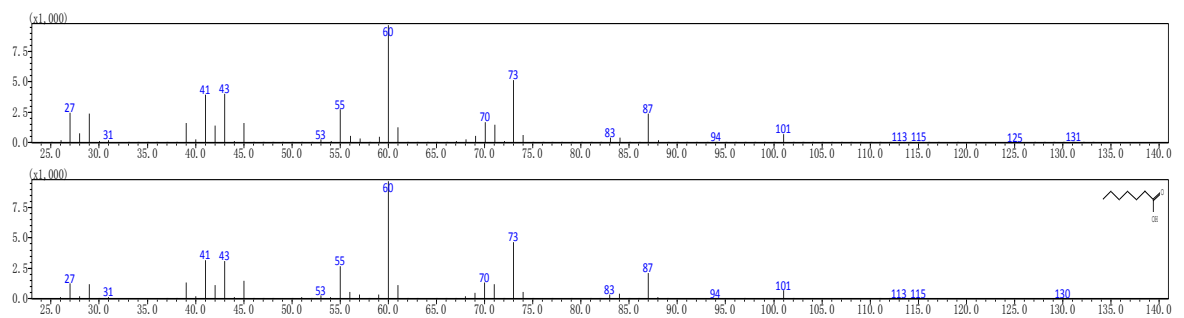
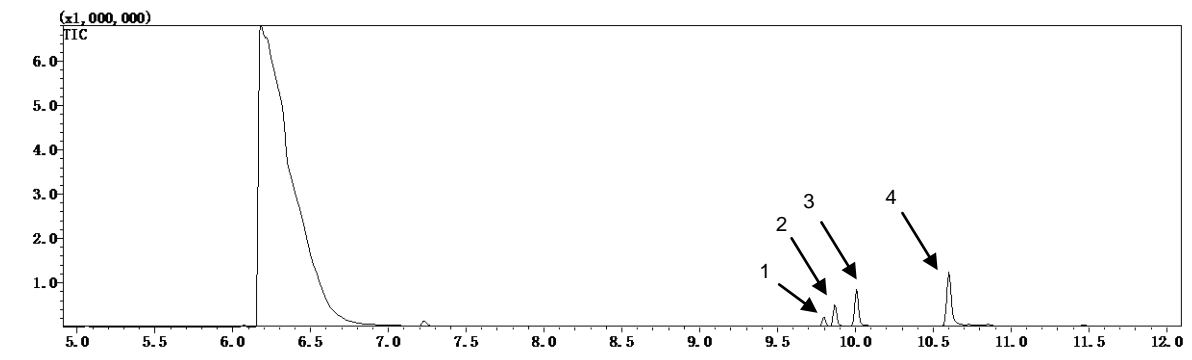
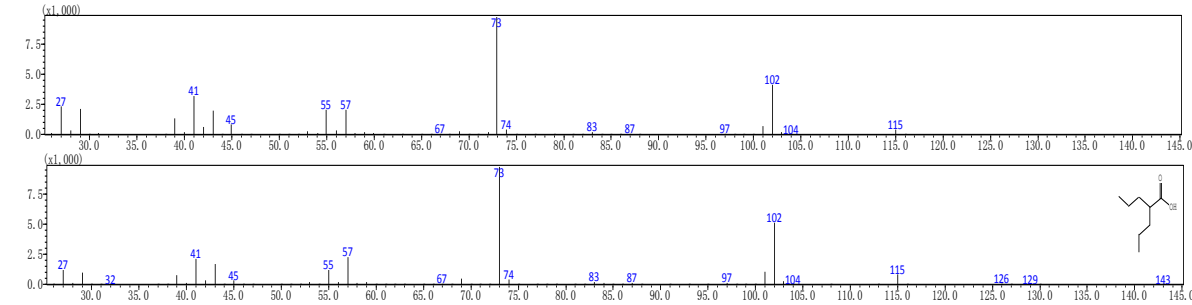


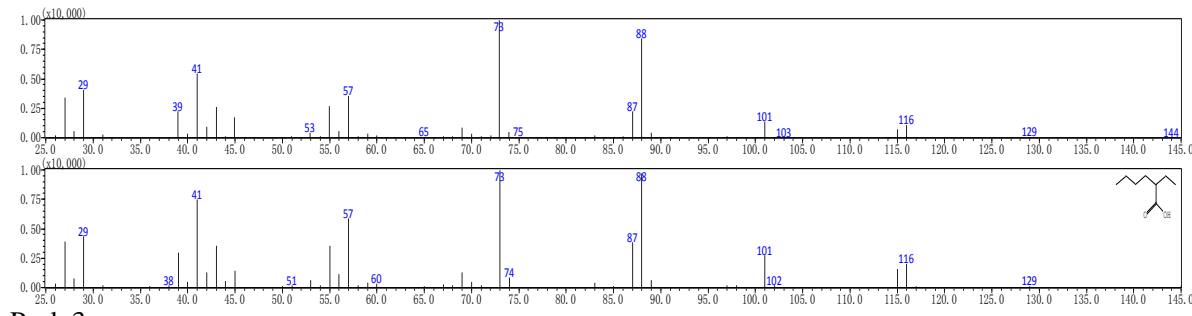
Fig. S21 The GC-MS graph of the liquid sample using 1-hexylalcohol as substrate.



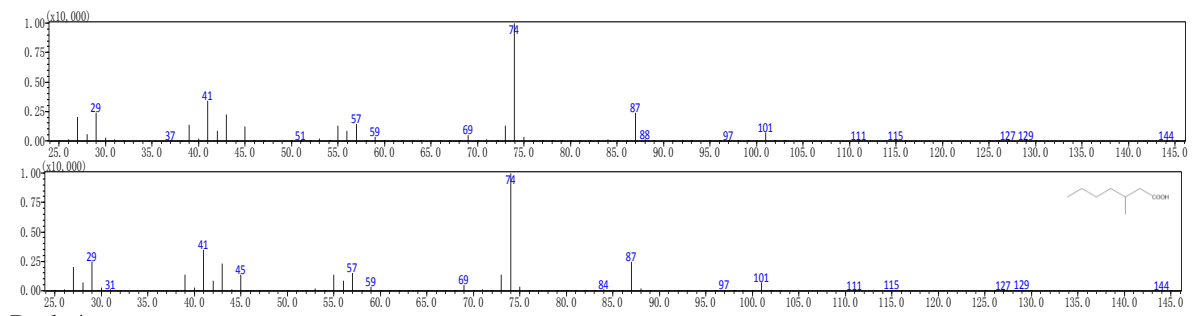
Peak 1



Peak 2



Peak 3



Peak 4

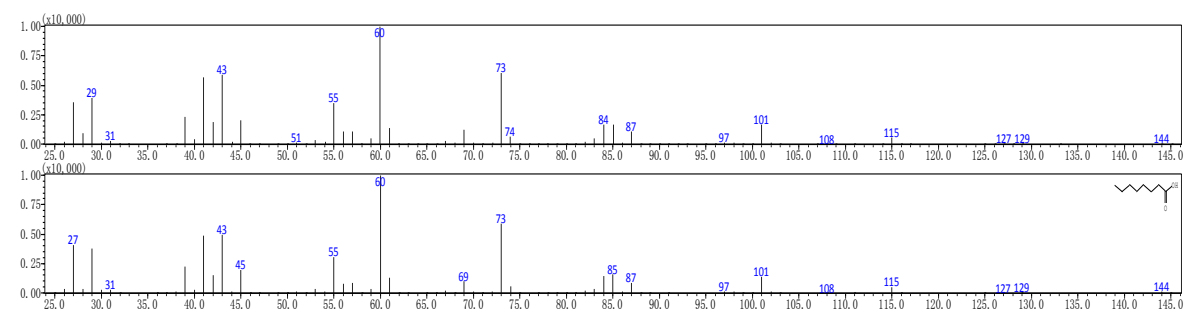
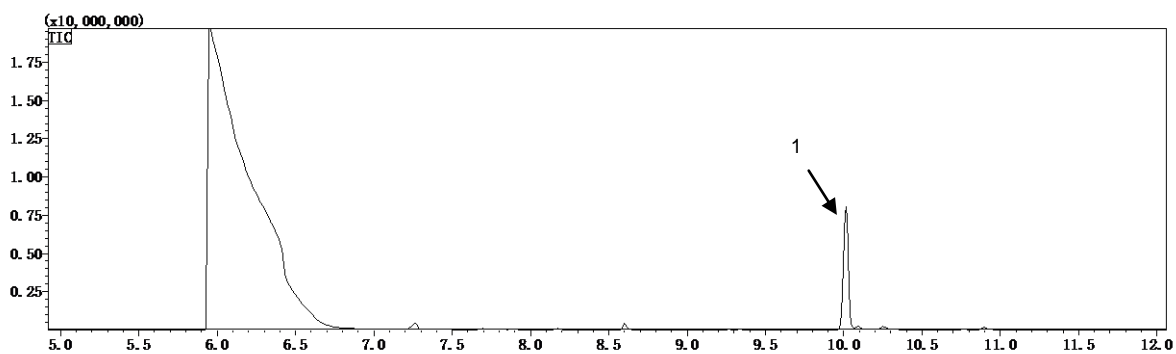


Fig. S22 The GC-MS graph of the liquid sample using 1-heptanol as substrate.



Peak 1

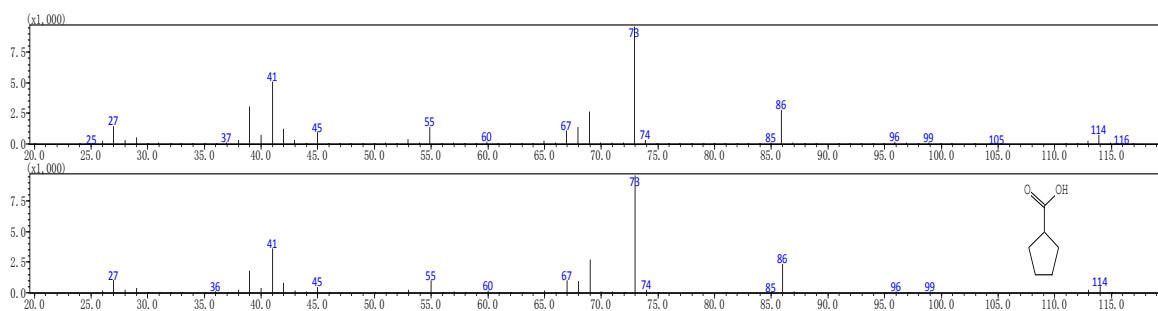
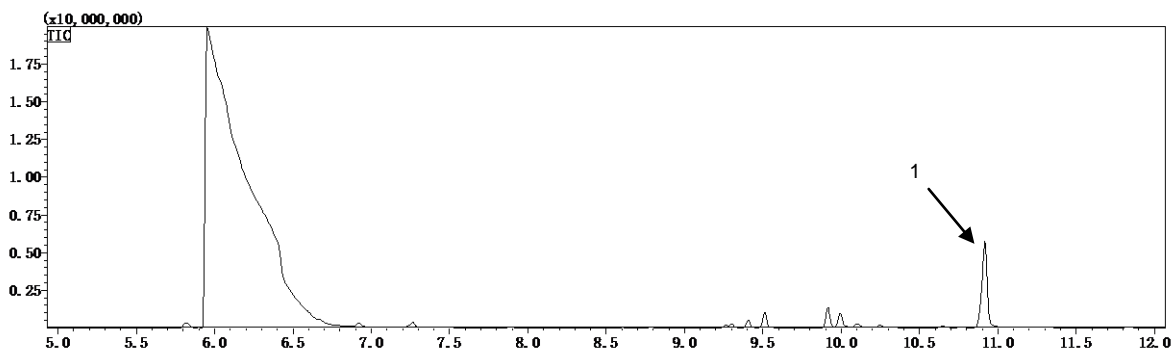


Fig. S23 The GC-MS graph of the liquid sample using cyclopentanol as substrate.



Peak 1

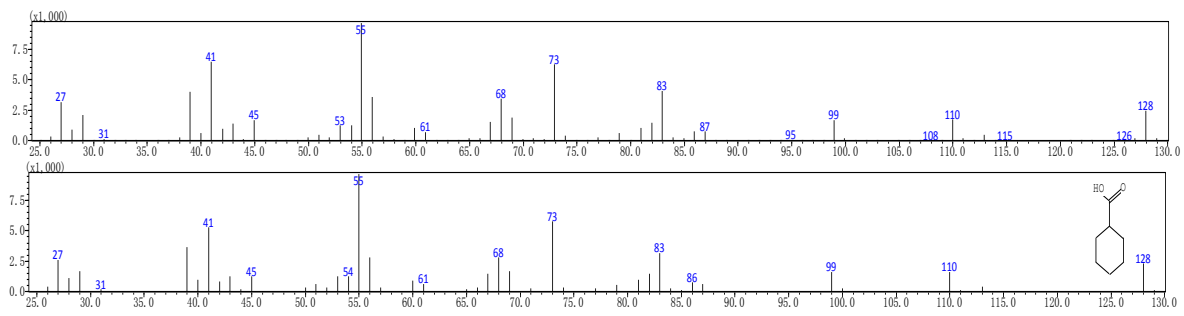
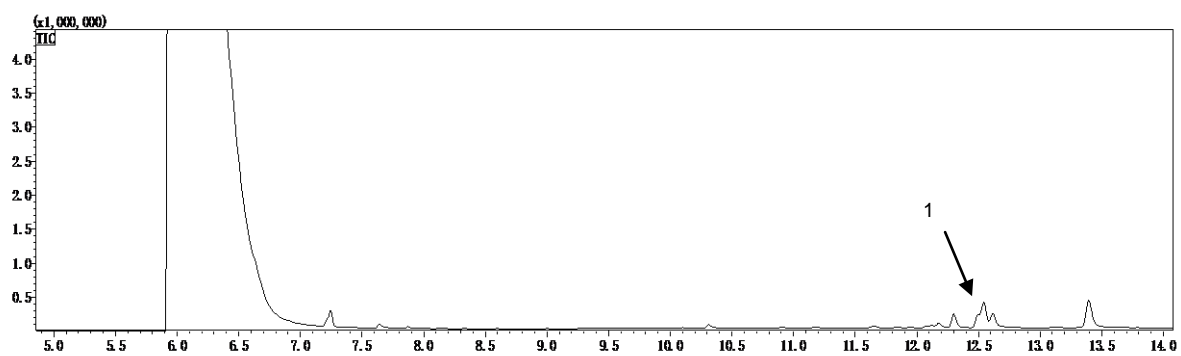


Fig. S24 The GC-MS graph of the liquid sample using 1,2-cyclohexanediol as substrate.



Peak 1

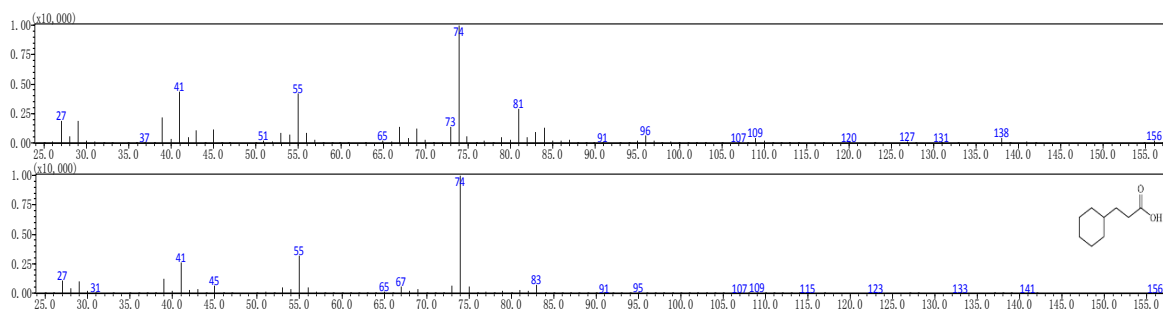


Fig. S25 The GC-MS graph of the liquid sample using 2-cyclohexylethanol as substrate.

Tables

Table S1 The price of different alcohol substrates and corresponding products.

Entry	Substrates	Products
1	cyclohexanol, ¥1.60/L (Aladdin)	cyclohexanecarboxylic acid, ¥514.00/Kg (Aladdin)
2	ethanol, ¥27.96/L (Aladdin)	propanoic acid, ¥99.20/L (Aladdin)
3	1-propanol, ¥56.90/L (Aladdin)	butyric acid, ¥456.61 /L (Aldrich) iso-butyric acid, ¥1337.46 /L (Aldrich)
4	isopropanol, ¥39.96/L (Aladdin)	
5	glycerol, ¥63.50/L (Aladdin)	
6	1-butanol, ¥31.96/L (Aladdin)	valeric acid, ¥204.4/L (Aladdin) 2-methylbutanoic acid, ¥674.00/L (Aladdin)
7	sec-butanol, ¥100.50/L (Aladdin)	
8	tert-butanol, ¥86.40/L (Aladdin)	
9	1,4-butanediol, ¥109.95/Kg (Aladdin)	
10	1,3-butanediol, ¥137.90/Kg (Aladdin)	
11	1-pentanol, ¥142.00/Kg (Aladdin)	hexanoic acid, ¥1103.29/Kg (Aldrich)
		2-methylpentanoic acid, ¥1570.00/Kg (Aladdin)
		2-ethylbutyric acid, ¥784.00/L (Aladdin)
12	1-hexanol, ¥139.80/Kg (Aladdin)	heptanoic acid, ¥336.84/Kg (Aldrich)
		2-methylhexanoic acid, ¥12990.00/L (Aladdin)
		2-ethylpentanoic acid, ¥6336000.00/Kg (Matrix)
13	1-heptanol, ¥308.00/L (Aladdin)	octanoic acid, ¥295.09/L (Aldrich)
		2-methylheptanoic acid, ¥11900.00/Kg (Aladdin)
		2-ethylhexanoic acid, ¥110.09/L (Aladdin)
		2-propylvaleric acid, ¥1604.00/L (Aladdin)
14	cyclopentanol, ¥699.90/L (Aladdin)	cyclopentanecarboxylic acid, ¥7940.00/Kg (Aladdin)

The above price information was obtained from <https://www.inno-chem.com.cn/> in March, 2021.

Table S2 Reaction results of cyclohexanol, CO₂ and H₂ with other metal complexes as catalyst

Entry	Catalyst	Promoter	Solvent	Yield ^b
1	RuI ₃	LiI	AcOH	0
2	RhI ₃	LiI	AcOH	1.3
3	Palladium (II) acetate	LiI	AcOH	1.4
4	FeI ₂	LiI	AcOH	<1
5	Co ₂ (CO) ₈	LiI	AcOH	<1
6	H ₂ OsBr ₆ · xH ₂ O	LiI	AcOH	0

Other conditions were the same as those in Table 1.

Table S3 Effect of reaction parameters on the hydrocarboxylation of cyclohexanol with CO₂ and H₂.

Entry	Iridium(III) acetate [μmol]	LiI [mmol]	CO ₂ /H ₂ [MPa]	Yield [%]
1	45	2	6/1	65.2
2	25	2	6/1	55.8
3	65	2	6/1	64.0
4	45	1	6/1	53.5
5	45	3	6/1	52.8
6	45	4	6/1	33.5
7	45	2	3/0.5	15.7
8	45	2	6.5/0.5	60.2
9	45	2	5/2	57.6
10	45	2	4/3	37.4
11	45	2	3/4	19.8
12	45	2	2/5	8.5
13	45	2	1/6	5.1
14	45	2	0/1	0
15	45	2	6/0	2.4


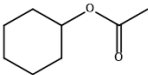

Reaction conditions: iridium(III) acetate (based on Ir) was used as catalyst precursor, LiI was used as promoter, 0.5 mL AcOH, 2.25 mmol cyclohexanol, 170 °C, 16 h.

Table S4 Catalytic results with CO as reactant gas.

Entry	CO [MPa]	H ₂ [MPa]	Yield [%]
1	0.5	0	84.6
2	1	0	79.2
3	2	0	55.7
4	3	0	49.1

Reaction conditions: 45 μ mol iridium(III) acetate (based on Ir), 2 mmol LiI and 0.5 mL AcOH, 2.25 mmol cyclohexanol, 16 h, 170 °C.

Table S5 Catalytic results of the reactions between CO and the derivatives from cyclohexanol.^a


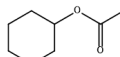

Entry	Substrate	Catalyst	Yield [%]
1		Iridium(III) acetate + LiI	37.6
2 ^b		Iridium(III) acetate + LiI	83.5
3 ^c		Iridium(III) acetate	0
4 ^{b,c}		Iridium(III) acetate	0
5		Iridium(III) acetate + LiI	59.3
6 ^b		Iridium(III) acetate + LiI	82.0
7 ^c		Iridium(III) acetate	0
8 ^{b,c}		Iridium(III) acetate	0
9		Iridium(III) acetate + LiI	13.3
10 ^b		Iridium(III) acetate + LiI	61.4
11		Iridium(III) acetate	39.3
12 ^b		Iridium(III) acetate	89.6

^a Reaction conditions: 45 μmol iridium(III) acetate (based on Ir), 2 mmol LiI (if used), 0.5 mL AcOH, 0.5 mmol substrate, 1 MPa CO (at room temperature), 170 $^{\circ}\text{C}$, 10 h.

^b 100 μL water was added before the reaction.

^c Gray/black fine powder was observed after the reaction, suggesting that the catalyst was unstable.

Table S6 Catalytic results with different intermediates as substrate to react with CO₂ and H₂.

Entry	Substrate	Yield [%]
1		56.1
2		59.7
3		0.5

Reaction conditions: 45 μ mol iridium(III) acetate (based on Ir), 2 mmol LiI and 0.5 mL AcOH, 2.25 mmol substrate, 6.0 MPa (68 mmol) CO₂ and 1 MPa H₂ (at room temperature), 170 °C, 16 h.

Supplementary References

1. A. Haynes, P. M. Maitlis and G. E. Morris, *J. Am. Chem. Soc.*, 2004, **126**, 2847-2861.