Electronic Supplementary Material (ESI) for Green Chemistry.

Supplementary Information

Catalytic approach via retro-aldol condensation of glucose to furanic compounds

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Experimental Section

Materials

D-Glucose, D-Fructose, Sucrose, Microcrystalline cellulose (MCC) powder, Acetic acid, Glyceraldehyde, Acetylacetone (acac), 2-Methylfuran, Furfural, 5-Hydroxymethylfurfural, 98% H_2SO_4 were purchased from Sigma-Aldrich. D-Xylose, Mannose and Acetophenone were obtained from Merck. Glycolaldehyde (GA) was purchased from Fluorochem. H_2MoO_4 was obtained from BDH Chemicals Ltd (Analytical reagent). NaCl, KCl, NaBr and Na_2SO_4 were obtained from Fisher chemical. Ethanol, Methanol, Hexane, and Ethyl acetate were purchased from Honeywell. The Scots Pine (Pinus Sylvestris) wood stems were originated from Asikkala, Southern Finland. The stems were ground into fine powder using bench grinder. The Birch (Betula pendula and B. pubescens) wood powder was bought from Tuoterengas, a wood manufacturing company in Asikkala, Southern Finland and the birch powder was produced as a side product in Mölkky-game processing. The powder was stored in dry place protected from light. Deuterium oxide (D_2O), Methanol-d4 (MeOD) and Chloroform-d was supplied by Eurisotop. All chemicals and solvents were obtained from commercial suppliers and used as received.

General reaction procedure

Experiments were conducted in a stainless-steel autoclave (25 mL, Anhui Kemi Machinery Technology Co. Ltd.), equipped with mechanical stirring and heating jacket, where the heating was controlled by a temperature controller. A thermocouple thermometer inserting into the reactor chamber monitored the temperature. For a typical run, 300 mg glucose, 6.5 mL of H_2O and 6.5 mL of acetylacetone were added. For catalytic reaction, certain amount of H_2MoO_4 was added. The reactor was sealed and flushed with N_2 for five times before 2.5 MPa N_2 was finally purged for reaction. The stirring rate was 600 r/min and the reaction time was recorded when reaching the target temperature. After reaction, the reactor was cooled down with ice bath and the reaction mixture was collected for further analysis. Parallel experiments were conducted and the average value were presented (error within ± 3%).

The NMR (Nuclear magnetic resonance) study of GA and acac was conducted in a pre-heated oil bath for 1 min in D_2O. For a typical run, 90 mg GA, 2 mL D_2O, 2 mL acac, 30 mg H_2MoO_4 (for catalytic reaction) were used.

Product analysis

^{1}H, ^{13}C, 2D HSQC and HMBC NMR spectra of separated product were recorded on a Bruker Avance Ⅲ 400-MHz spectrometer. The calibration and analysis of spectra was conducted by using MestReNova. High-resolution electrospray-ionization mass spectra (HRESI-MS) were recorded with a Bruker microTOF mass spectrometer in a positive ion mode using sodium formate as a calibrant.

The reaction mixture was purified by silica-gel column chromatography (eluent: ethyl acetate/ hexane = 1/20) to give 2-methyl-3-acetylfuran (MAF). MAF was analyzed qualitatively by gas chromatography mass spectrometer (GC-MS, Agilent 5973-6890N) and quantitatively by Agilent 7890B GC system equipped with a FID detector. HP-5 MS Ultra Inert column (30 m × 250 μm × 0.25 μm) was employed and He as a carrier gas at a flow rate of 0.9 mL/min. For GC-MS analysis, the initial oven temperature 60 °C was held for 0.5 min and then increased to 90 °C at a rate of 10 °C /min followed by the temperature ramp of 20 °C/min to 300 °C, and held for 6 min. The detector temperature was 300 °C. For GC analysis, the initial oven temperature 60 °C was held for 0.5 min and then increased to 100 °C at a rate of 10 °C /min followed by the temperature ramp of 15 °C/min to 200 °C (held for 2 min), and then to 300 °C (20 °C/min, held for 2 min). The isolated MAF was used as authentic chemical for quantification and acetophenone was employed as internal standard (calibration curve: y = 6.4676x - 0.0365, R^2 = 0.9992).

The erythrose C4 fragment derived product 1- (5- (1,2-dihydroxyethyl) -2-methylfuran-3-yl) ethan-1-one (DMAF) in catalytic reactions was separated by silica-gel column chromatography (eluent: ethanol/ hexane = 1/10) from the reaction mixture. For a typical reaction, after the evaporation of water and acac, the amount of DMAF was determined by ^{1}H NMR in MeOD using 2-Methylfuran as internal standard.

The yield of MAF and DMAF was calculated based on the mol of sugar units in the substrate as follows:

(a) For glucose, $MAF\ (DMAF)\ Yield = \dfrac{mol\ of\ MAF\ (DMAF)}{mass\ of\ glucose/180} \times 100\%$

$$Carbon\ Yield\ of\ MAF = \frac{mol\ of\ MAF}{mol\ of\ glucose} \times \frac{2}{6} \times 100\%$$

$$Carbon\ Yield\ of\ DMAF = \frac{mol\ of\ DMAF}{mol\ of\ glucose} \times \frac{4}{6} \times 100\%$$

(b) For cellulose, $MAF\ Yield = \dfrac{mol\ of\ MAF}{mass\ of\ cellulose/162} \times 100\%$

(c) For real wood biomass, $MAF\ Yield = \dfrac{mol\ of\ MAF}{mol\ of\ glucose\ in\ wood\ +\ mol\ of\ xylose\ in\ wood} \times 100\%$

The yield of MAF obtained from wood material was evaluated based on the content of representative C6 glucose and C5 xylose measured by HPLC. The determination of their content in wood materials

followed an acid hydrolysis method described by Sluiter et al. (2004).[1] The below Table shows the mol of sugar units in 300 mg of pine and birch wood.

Entry	glucose (mg)	xylose (mg)	Total mol of sugar units (mol)
Pine	124	58	1.08
Birch	106	73	1.08

Monosaccharides (glucose, mannose, xylose) were quantitative analysed by HPLC (1200 Infinite series, Agilent) equipped with a refractive index detector (G1362A RID) and an Phenomenex column (Rezex™ ROA-Organic Acid H+ (8%), 300 × 7.8 mm). The eluent was dilute H_2SO_4 (5 mM) flowing at a rate of 0.5 mL min^{-1} while the column temperature maintained at 40 °C. The RI detector was maintained at 35 °C. Samples were filtered (0.2 μm) before injection. Data were elaborated according to calibration curves with standard glucose, mannose, and xylose (glucose: y = 103160x + 59.751, R^2 = 0.9999; mannose: y = 98456x - 501.55, R^2 = 0.9998; xylose: y = 830993x – 4554, R^2 = 0.9998).

$$Conversion\ of\ glucose = 100 - \frac{mol\ of\ glucose\ after\ reaction}{mol\ of\ glucose} \times 100\%$$

$$Yield\ of\ mannose = \frac{mol\ of\ mannose}{mol\ of\ glucose} \times 100\%$$

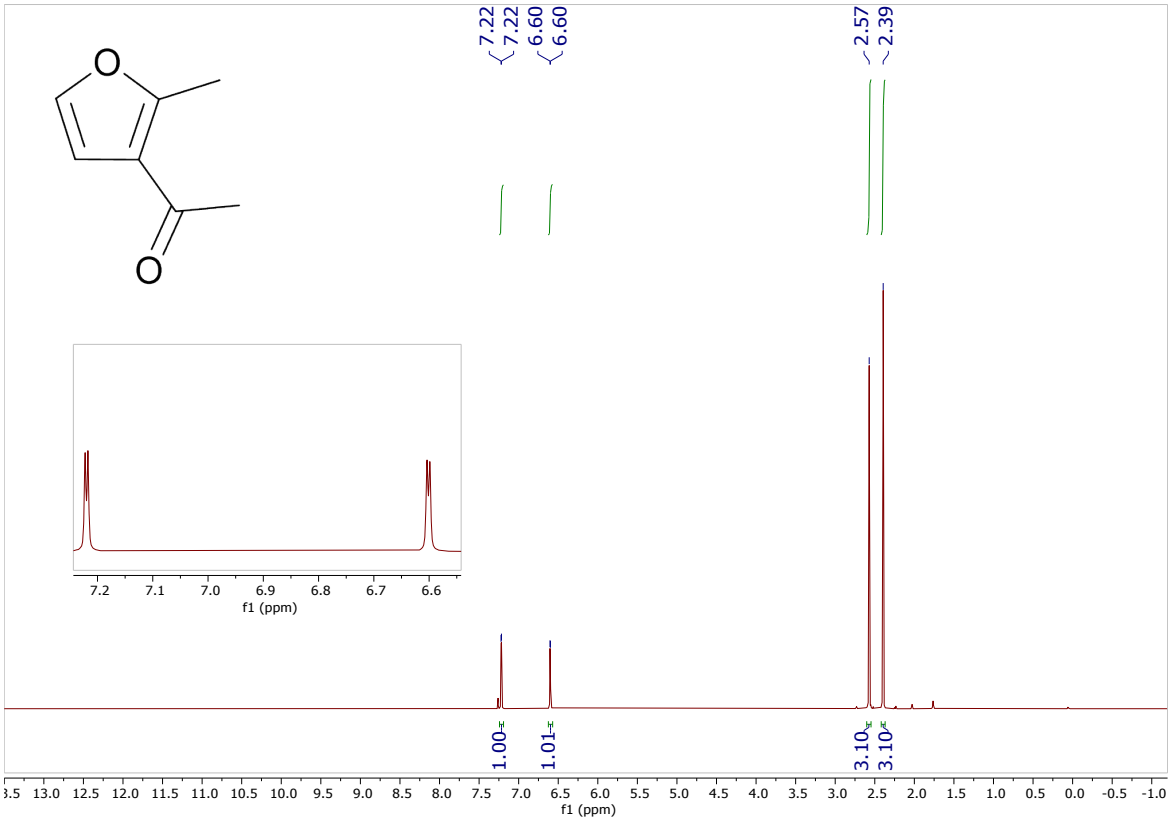


Fig. S1 ^{1}H NMR spectrum of 2-methyl-3-acetylfuran (400 MHz, chloroform-d) δ: 7.22 (d, J = 2.0 Hz, 1H), 6.60 (d, J = 1.9 Hz, 1H), 2.57 (s, 3H), 2.39 (s, 3H).

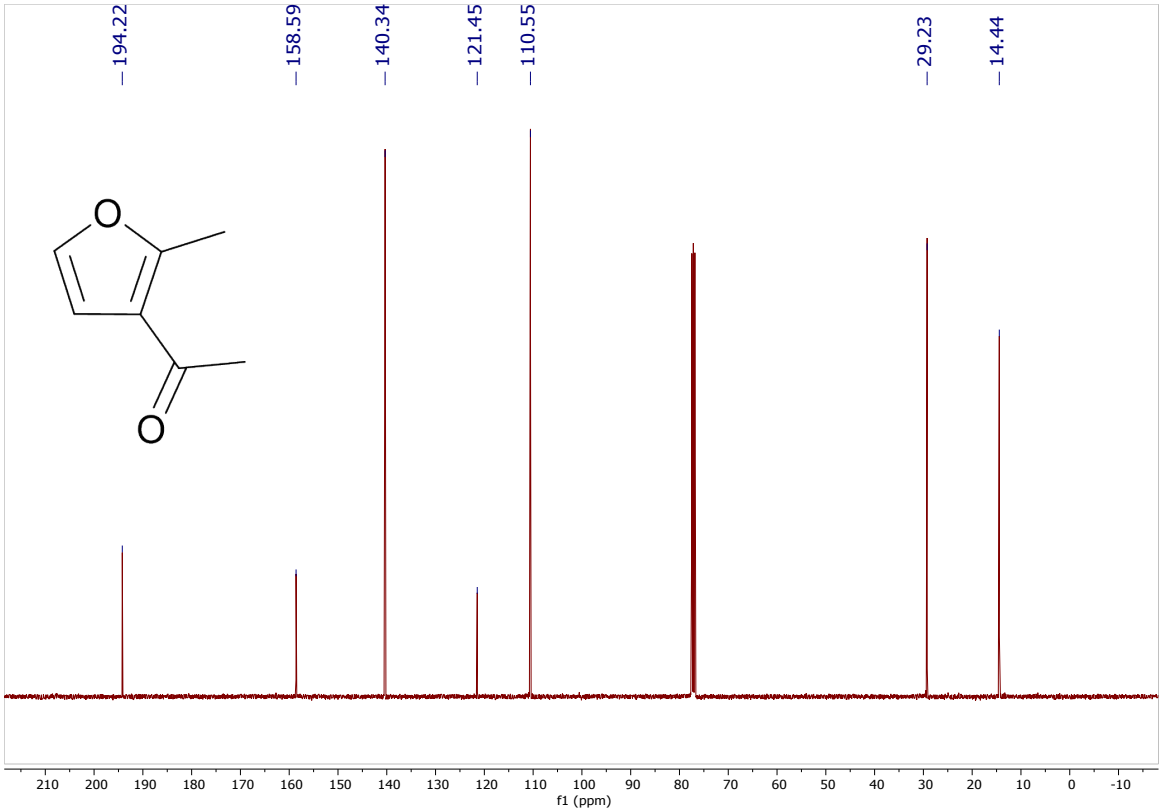
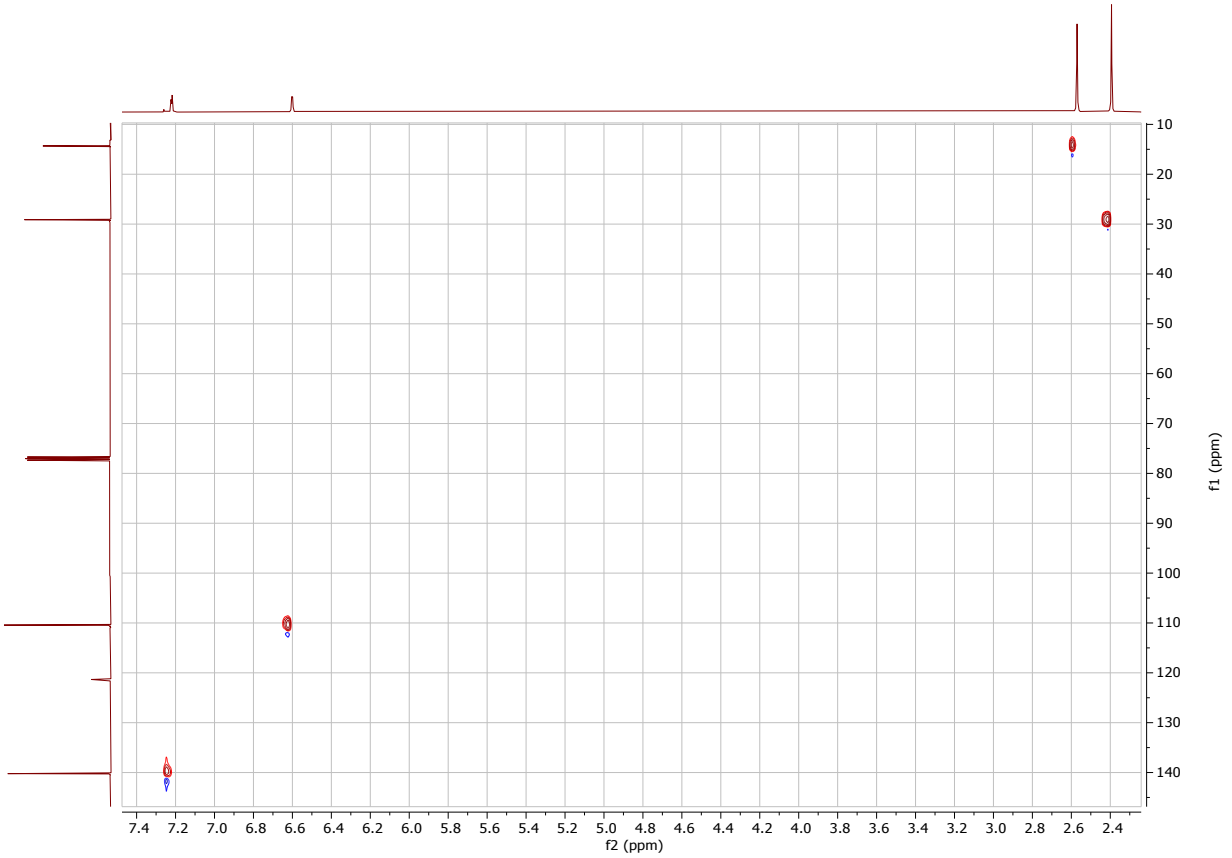


Fig. S2 ^{13}C NMR spectrum of 2-methyl-3-acetylfuran (100 MHz, Chloroform-d) δ: 194.22, 158.59, 140.34, 121.45, 110.55, 29.23, 14.44.



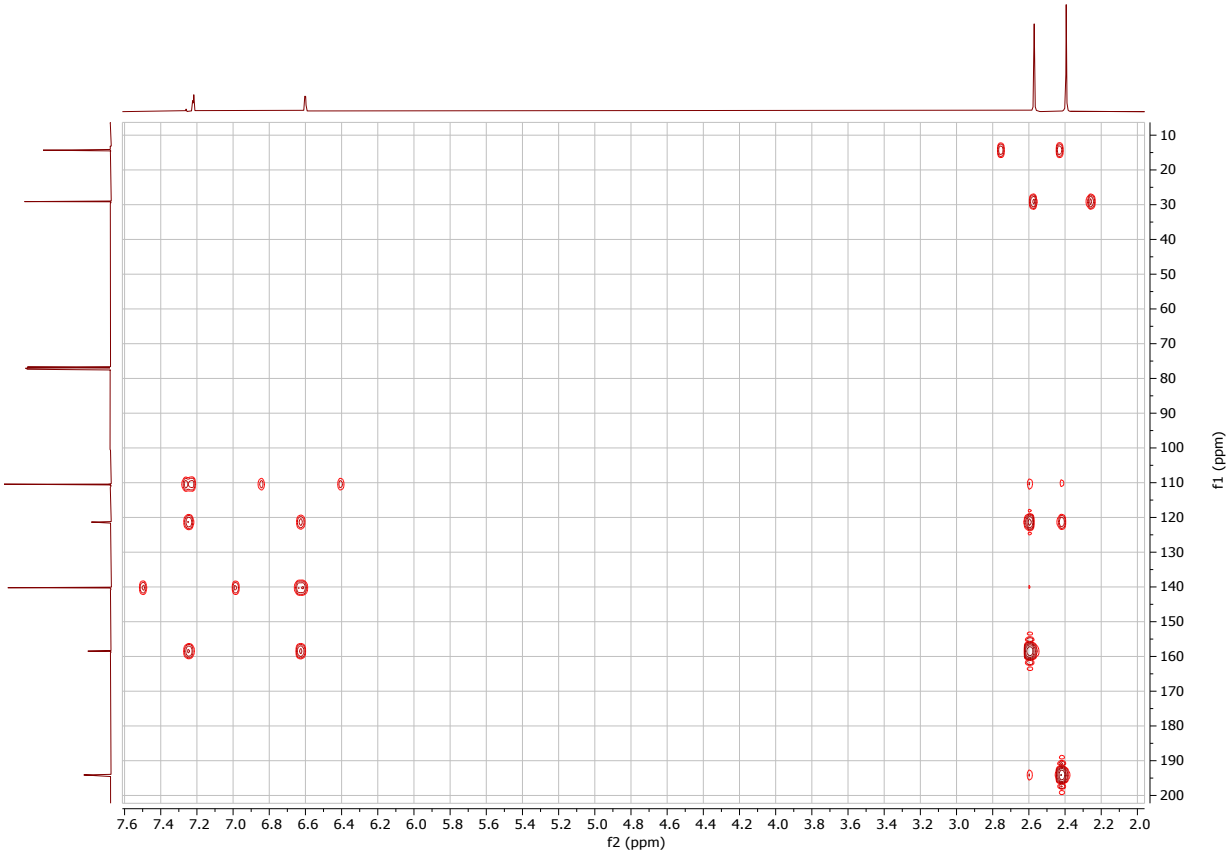


Fig. S3 2D HSQC and HMBC spectra of 2-methyl-3-acetylfuran (chloroform-d).

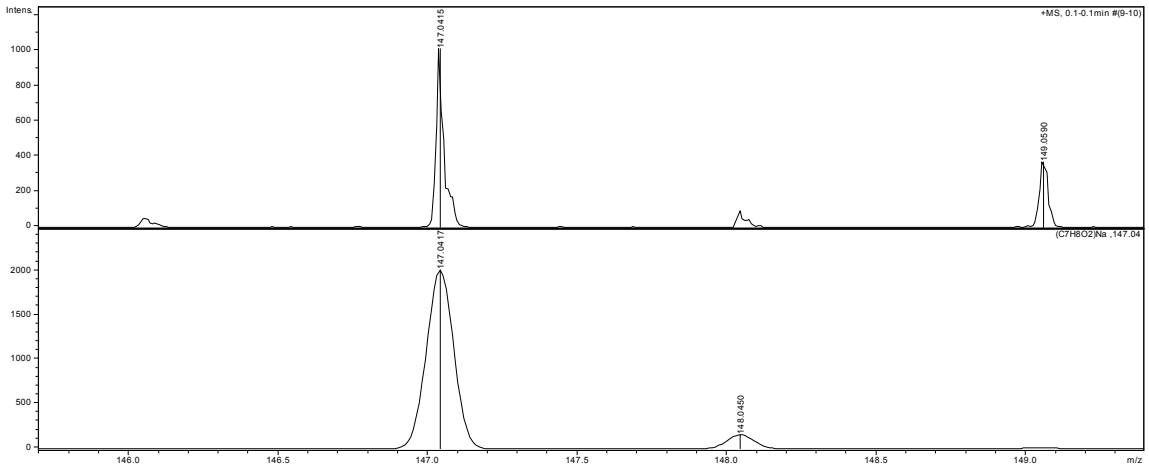


Fig. S4 Experimental (above) and calculated (below) isotopic patterns of 2-methyl-3-acetylfuran. $[C_7H_8O_2+Na]^+$ calculated m/z 147.0417, found 147.0415 m/z, error 1.172 ppm.

Table S1 The effect of temperature on the yield of MAF

Entry	Temperature (°C)	MAF Yield (%)
1	160	23
2	180	33
3	200	39
4	220	46
5	240	49
6	260	45

Reaction conditions: 300 mg of glucose, H_2O/acac = 1/1 (6.5 mL/6.5 mL), 30 min, 2.5 MPa N_2, 600 r/min.

Table S2 Test of starting material on the formation of MAF

Entry	Solvent system	Starting material	MAF Yield (%)
1	H_2O/acac = 1/1	Glyceraldehyde	4
2	H_2O/acac = 1/1	Acetic acid	-
3	H_2O/acac = 1/1	Furfural	-
4	H_2O/acac = 1/1	2-Methylfuran	-
5	H_2O/acac = 1/1	5-Hydroxymethylfurfural	-

Reaction conditions: 300 mg of starting material, 6.5 mL of H_2O, 6.5 mL of acac, 220 °C, 30 min, 2.5 MPa N_2, 600 r/min.

Table S3 The pH value of aqueous phase at different reaction temperature

Entry	Temperature (°C)	pH value
1	room temperature	3.1
2	160	3.0
3	180	2.7
4	200	2.7
5	220	2.7
6	240	2.7
7	260	2.8

Reaction conditions: 300 mg of glucose, H_2O/acac = 1/1 (6.5 mL/6.5 mL), 30 min, 2.5 MPa N_2, 600 r/min.

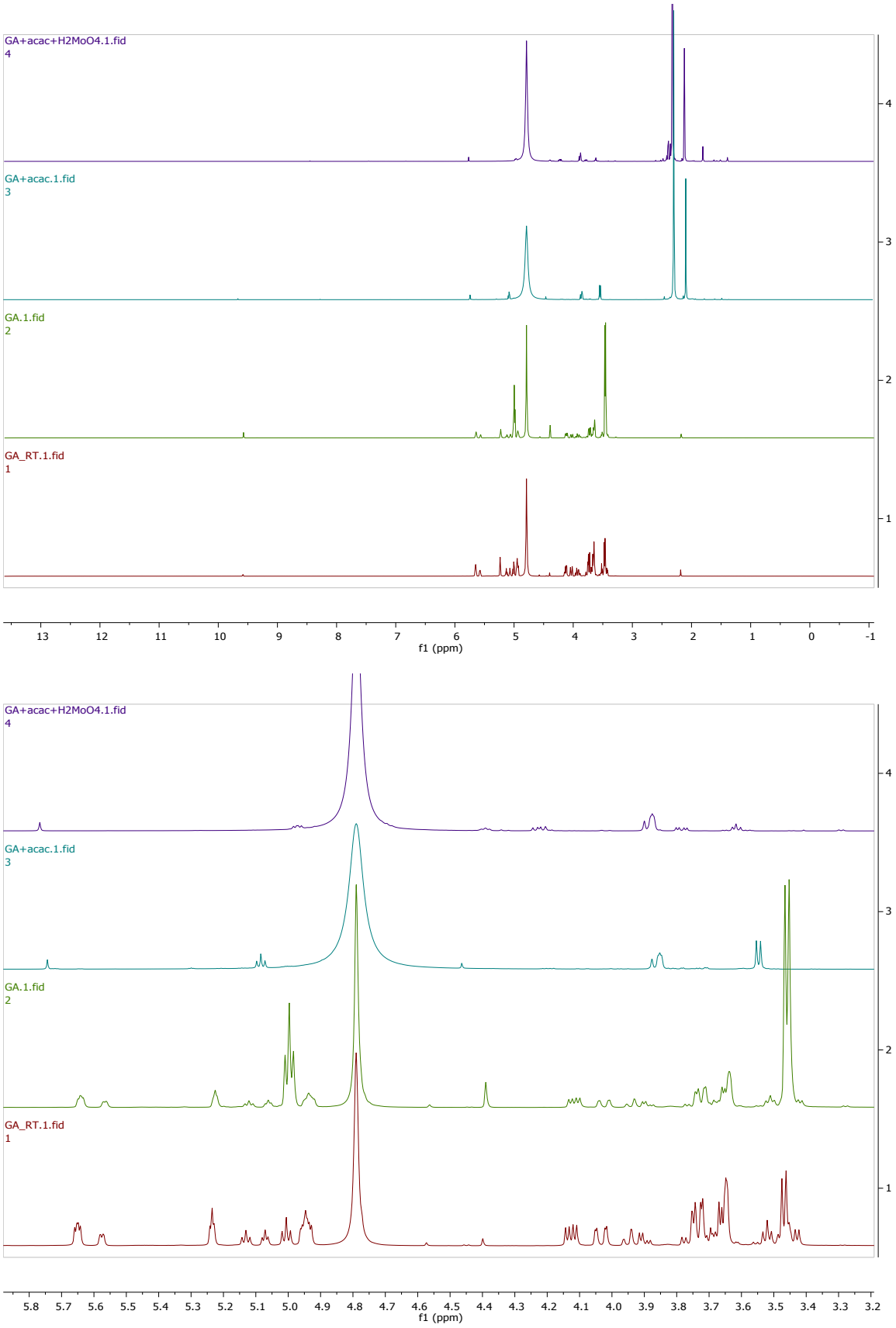


Fig. S5 ^{1}H NMR spectrum of reaction between GA and acac: (1) GA dissolved in D_2O at room temperature; (2) GA dissolved in D_2O at 100 ^{o}C for 1 min; (3) GA and acac in D_2O at 100 ^{o}C for 1 min; (4) GA and acac in D_2O with H_2MoO_4 at 100 ^{o}C for 1 min.

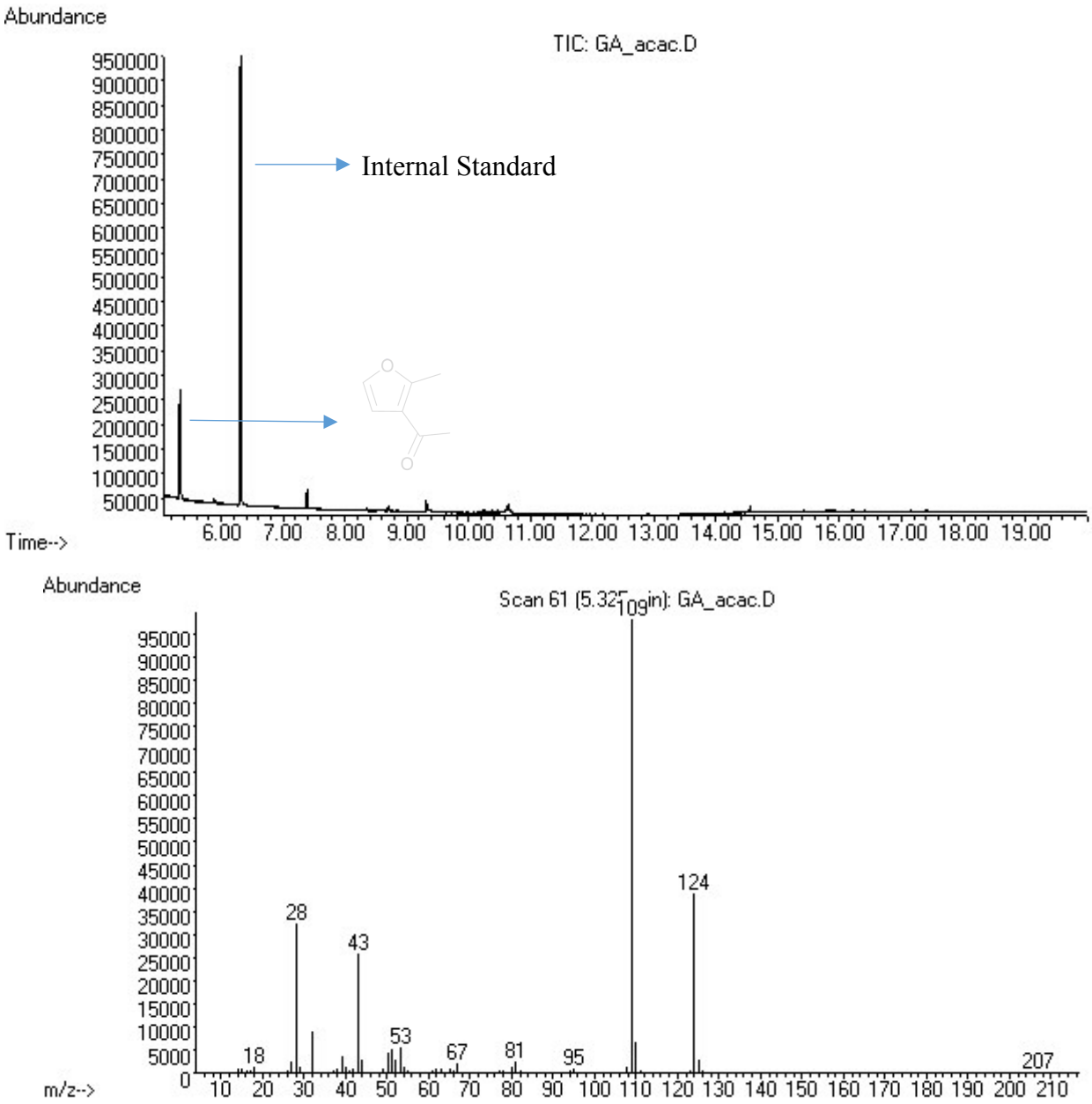


Fig. S6 Observation of MAF from reaction between GA and acac in H_2O at 100 ^oC for 1 min, a GC-MS spectra and MS data.

GA could be generated from the RAC of glucose and erythrose, followed by the aldol reaction with acac to give MAF. No GA was directly detected by HPLC or ESI-MS in any experiments, but huge amount of black stuff was formed in pure H_2O system. This suggested that GA is an unstable short-lived intermediate under the applied conditions, which would be further converted to humins by many side reactions if not stabilized. The above results implied that the reaction between GA and acac was highly favourable under the applied system and strongly supported the proposed reaction pathway. The rapid in situ capture of GA by acac promoted the reaction equilibrium to RAC direction, limited the polymerization and eventually favoured the formation of high yield MAF. In addition, the effect of H_2O was evaluated. When replaced H_2O by ethanol (Table 1, entry 5), the yield of MAF decreased dramatically to 16%. Similar yield (18%) was obtained by using pure acac as reaction medium (Table 1, entry 4). The absence of H_2O showed also negative effect on step 2, as the yield of MAF decreased from 83 % to 66 % when GA reacted with pure acac (Table 1, entry 6 vs. 11). From this perspective, the presence of H_2O is critical for the formation of MAF. The variation of H_2O and acac ratio displayed no significant influence on the yield of MAF until the amount of acac decreased to 1 mL, humins were formed and only 7 % MAF was obtained (Table S4, entry 5). As H_2O and acac are naturally immiscible, acac acted alternatively as an extraction solvent to extract GA from aqueous phase, by which the further side-reactions could be limited. This two-phase system allowed an energy efficient downstream product separation. In short, the synergistic effect of H_2O and acac is responsible for the high yield of MAF.

Table S4 The yield of MAF at different reaction parameters

Entry	Solvent system (v/v)	MAF Yield (%)
1	acac	18
2	H_2O/acac = 1/12	24
3	H_2O/acac = 3/10	46
4	H_2O/acac = 10/3	47
5	H_2O/acac = 12/1	7

Reaction conditions: 300 mg of glucose, total solvent volume 13 mL, 220 °C, 30 min, 2.5 MPa N_2, 600 r/min.

Table S5 The catalyst loading on the yield of MAF

Entry	Catalyst Loading (wt%)	MAF Yield (%)
1	10	45
2	20	47
3	33	59
4	40	59
5	90	59

Reaction conditions: 300 mg of glucose, 100 °C, H_2O/acac = 1/1 (6.5 mL/6.5 mL), 30 min, 2.5 MPa N_2, 600 r/min.

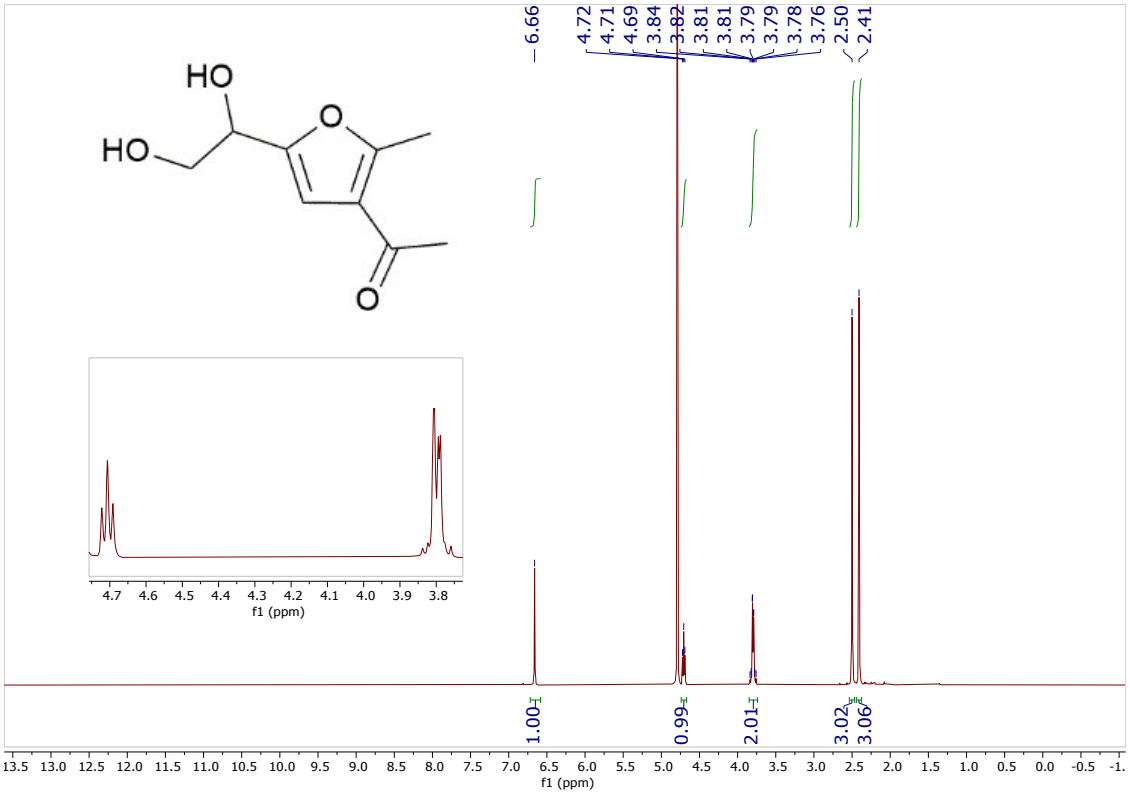


Fig. S7 ^{1}H NMR spectrum of C4 fragment-derived product DMAF: 1-(5-(1,2-dihydroxyethyl)-2-methylfuran-3-yl) ethan-1-one (400 MHz, D_2O) δ: 6.66 (s, 1H), 4.71 (t, J = 6.1 Hz, 1H), 3.85-3.75 (m, 2H), 2.50 (s, 3H), 2.41 (s, 3H).

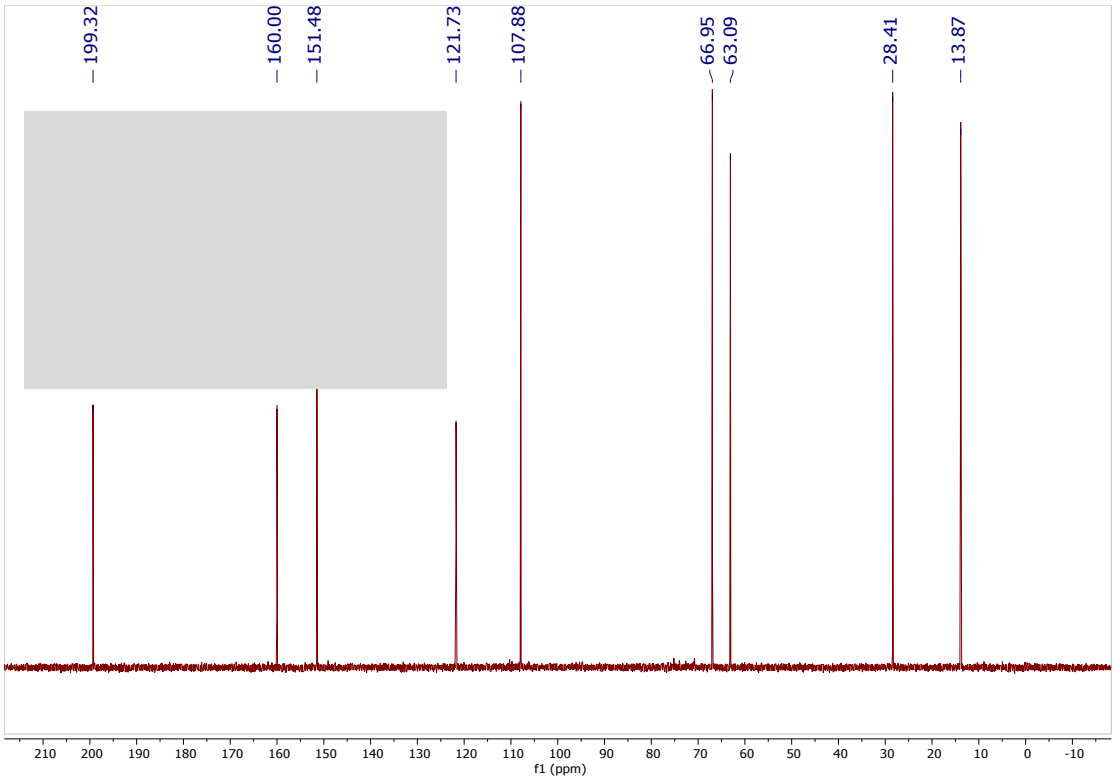


Fig. S8 ^{13}C NMR spectrum of C4 fragment-derived product DMAF: 1-(5-(1,2-dihydroxyethyl)-2-methylfuran-3-yl)ethan-1-one (100 MHz, D_2O) δ: 199.32, 160.01, 151.48, 121.73, 107.88, 66.95, 63.09, 28.41, 13.87.

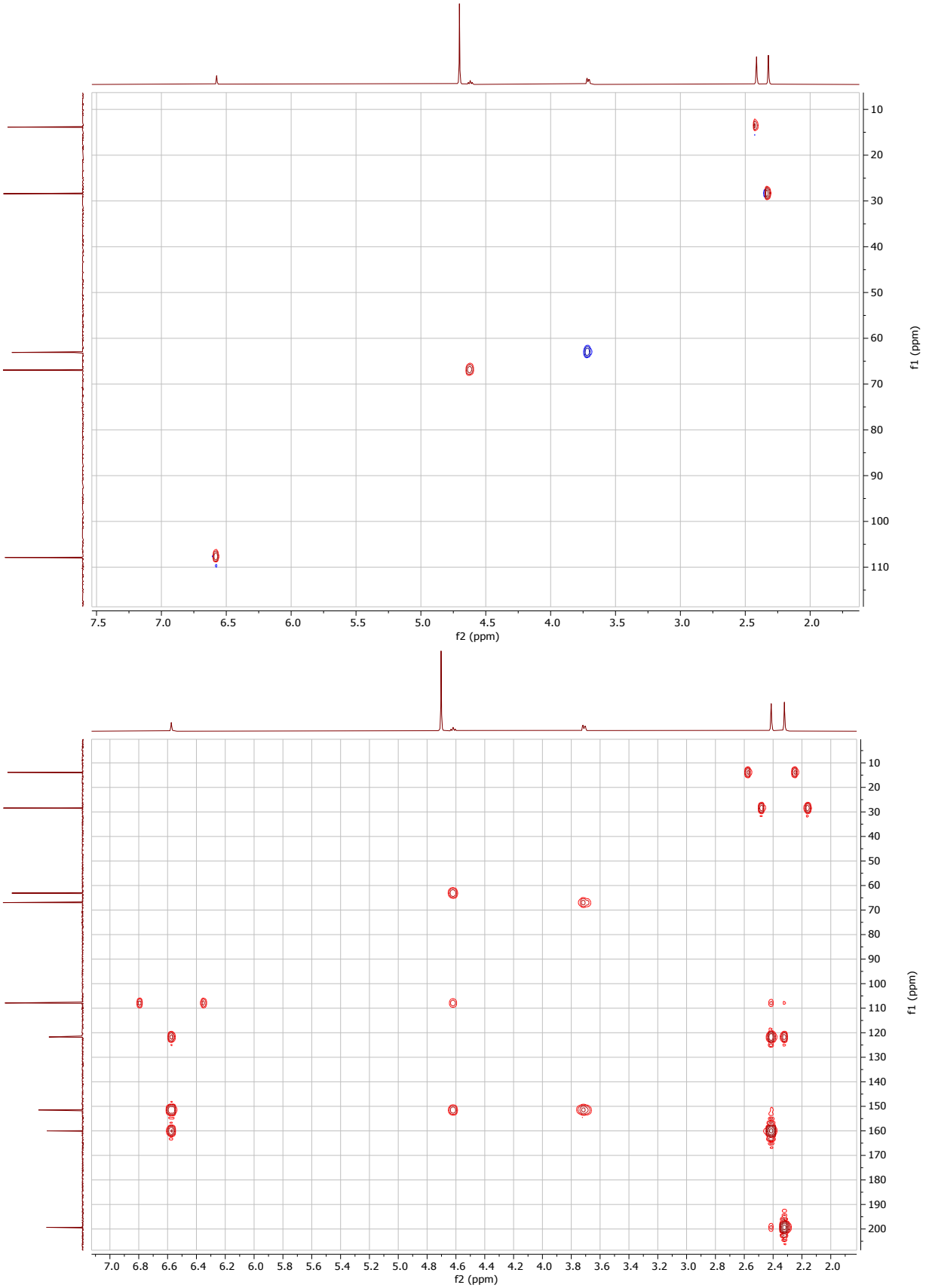


Fig. S9 2D HSQC and HMBC spectra of C4 fragment-derived product DMAF: 1-(5-(1,2-dihydroxyethyl)-2-methylfuran-3-yl)ethan-1-one (D_2O).

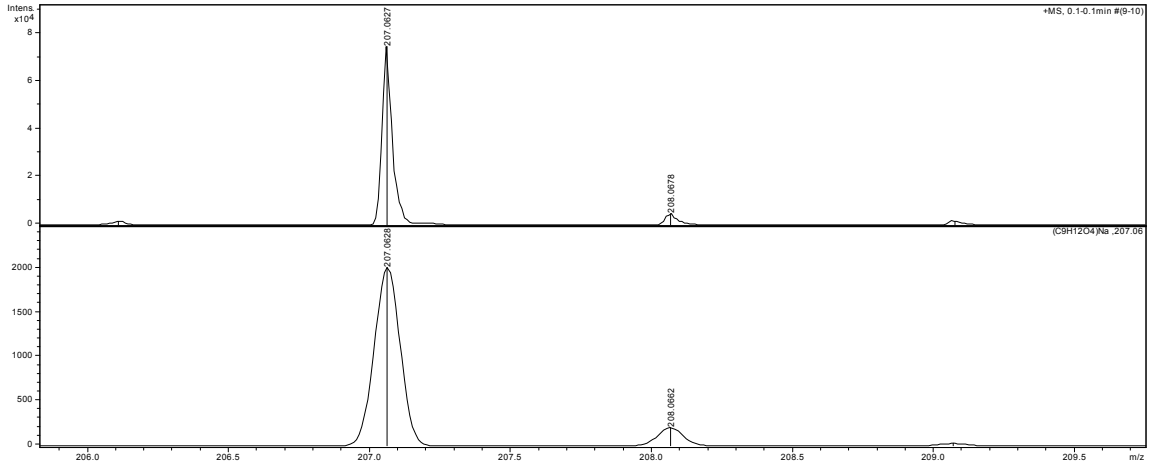


Fig. S10 Experimental (above) and calculated (below) isotopic patterns of C4 fragment-derived product DMAF: 1-(5-(1,2-dihydroxyethyl)-2-methylfuran-3-yl) ethan-1-one. $[C_9H_{12}O_4+Na]^+$ calculated m/z 207.0628, found 207.0627 m/z, error 0.163 ppm.

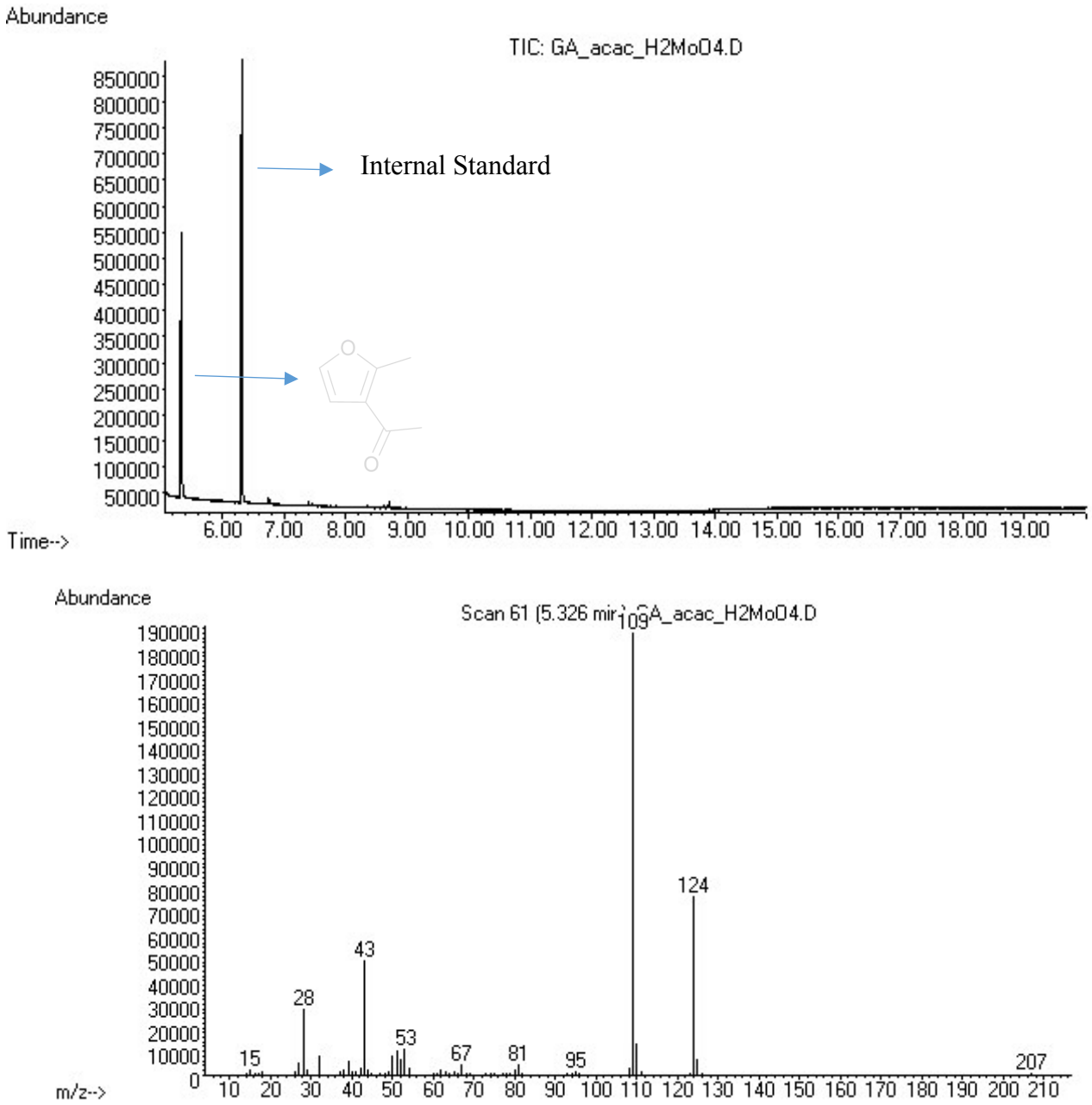


Fig. S11 Observation of MAF from reaction between GA and acac in H_2O with H_2MoO_4 at 100 °C for 1min, a GC-MS spectra and MS data.

Table S6 Glucose concentration on the yield of MAF

Entry	Glucose concentration (g L^{-1})	Reaction time (min)	MAF Yield (%)
1	100	30	54
2	100	120	58
3	150	30	49
4	150	120	52
5	150	180	50
6	200	120	44

Reaction conditions: 100 °C, 33 wt% of H_2MoO_4, H_2O/acac = 1/1 (6.5 mL/6.5 mL), 2.5 MPa N_2, 600 r/min.

Conversion of natural carbohydrates

The present H_2O/acac system is promising as it enabled the straightforward conversion of microcrystalline cellulose (MCC) and lignocellulosic wood material with the aid of NaCl, where NaCl facilitated the formation of monosaccharides and fulfilled the transformation of natural carbohydrates into MAF. KCl worked as good as NaCl, followed by NaBr. Na_2SO_4 gave the lowest yield. The result is in accord with the literature reports. NaCl displayed significant role to promote the conversion of cellulose, by which Cl^- can interact strongly with the end -OH group of a single glucose unit, resulting in the cleavage of both inter- and intramolecular hydrogen bonds in cellulose.[2] The yield of MAF from MCC increased with the temperature, reaching 33% at 240 °C (Table S7). We were able to apply this H_2O-NaCl/acac system to raw pine and birch wood. The advantage was that both hemicellulose and cellulose in wood could be converted, offering around 33% of MAF (Table S8, entry 8-9). The addition of H_2MoO_4 catalyst increased the yield of MAF from MCC to 45% (Table S8, entries 6 and 7) and from pine to 59% (Table S8, entries 9 and 10). The hydrolysis of cellulose to glucose is the limited step for MAF formation at mild temperature.

Table S7 The effect of temperature on the yield of MAF from MCC without catalyst

Entry	Temperature (°C)	MAF Yield[a] (%)
1	160	3.3
2	180	8.1
3	200	24
4	220	27
5	240	33

Reaction conditions: 300 mg of MCC, H_2O/acac = 1/1 (6.5 mL/6.5 mL), saturated concentration for NaCl, 60 min, 2.5 MPa N_2, 600 r/min; [a] MAF yield = mol of MAF/(mass of cellulose/162) × 100%.

Table S8 The conversion of natural carbohydrates

Entry	Starting material	Additives and catalyst	T (°C)	Time (min)	MAF Yield (%)
1	MCC	-	200	60	5
2	Sucrose	H_2MoO_4	100	30	23
3	MCC	Na_2SO_4	200	60	5
4	MCC	NaBr	200	60	16
5	MCC	KCl	200	60	22
6	MCC	NaCl	200	60	24
7	MCC	NaCl_H_2MoO_4	200	60	45
8	Birch[a]	NaCl	220	30	33
9	Pine[a]	NaCl	220	30	38
10	Pine[a]	NaCl_H_2MoO_4	220	30	59

Reaction conditions: 300 mg of starting material, H_2O/acac = 1/1 (6.5 mL/6.5 mL), 200 °C, 2.5 MPa N_2, 600 r/min, saturated concentration for salt additives, 100 mg H_2MoO_4. [a] MAF yield = mol of MAF/(mol of glucose in wood + mol of xylose in wood) × 100%.

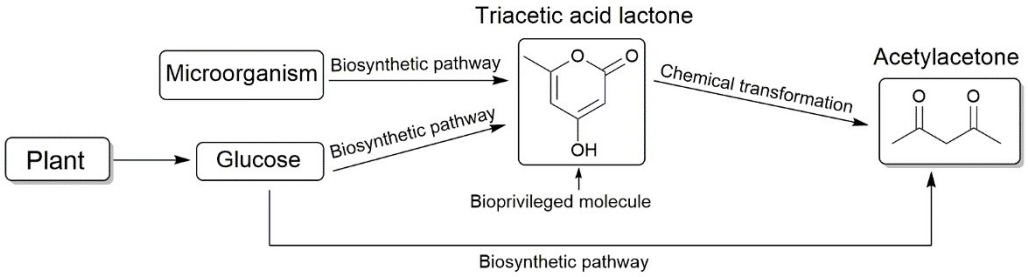


Fig. S12 Sustainable synthesis of acetylacetone from natural sources.

References:

1. A. Sluiter, B. Hames, R. Ruiz, C. Scarlata, J. Sluiter, D. Templeton, and D. Crocker, Determination of Structural Carbohydrates and Lignin in Biomass. National Renewable Energy Laboratory (NREL) Analytical Procedures, 2004.
2. (a) J. Li, Z. Jiang, L. Hu and C. Hu, *ChemSusChem*, 2014, **7**, 2482-2488; (b) Z. Jiang, J. Yi, J. Li, T. He and C. Hu, *ChemSusChem*, 2015, **8**, 1901-1907.