

Title: Method for the synthesis of 5-alkoxymethylfurfural ethers and their use.

The present invention relates to a method for the preparation of derivatives of 5-hydroxymethylfurfural (HMF), in particular ether derivatives of HMF, more in particular to 5-alkoxymethylfurfural ethers and to their application as a fuel or fuel additive.

The conversion of sugars or sugar (hexoses) containing biomass into more economically useful compounds is of increasing interest. Current fuel activities are mainly directed towards ethanol from sugar/glucose. Typically, sucrose and glucose are fermented into ethanol. One glucose molecule is converted into two molecules of ethanol and two molecules of CO₂. This conversion has drawbacks especially in view of atom economy, the low energy density of ethanol (7.7 kWh/kg or 6.1 kWh/L) and its relative low boiling point (78,4 degrees Celsius).

Another application area involves the conversion of sugars such as fructose into HMF in the presence of an acid catalyst has been reported (for example in EP0230250 to Suedzucker or EP0561928 to CEA)). In this case HMF is obtained as a highly potential starting material for obtaining bio-based monomer such as furandicarboxylic acid which can *inter alia* be used as an alternative to terephthalic acid as a monomer for polyethylene terephthalate type polyesters (Moreau et. al. in Topics in Catalysis Vol 27, Nos. 1-4, 2004, 11 - 30 and references cited therein). When under these conditions sucrose or glucose was used as a feed, no conversion to HMF is observed (Moreau et. al. in Topics in Catalysis Vol 27, Nos. 1-4, 2004, p13, col 2. line 2-3), which is a distinct disadvantage given the low price and abundant availability of sucrose and glucose. Only in the presence of DMSO, DMF and DMA (low HMF yields from glucose: Ishida et. al. Bull. Chem. Soc. Jpn 74 2001, 1145) or in a sub- and supercritical mixture of acetone and water (fructose, glucose, sucrose and inulin conversion to HMF in 77%, 48%, 56% and 78% yields respectively: Vogel et. al. Green Chemistry 5, 2003, 280) reasonable HMF yields from starting materials other than fructose were obtained.

In the current market situation, fructose as feed is undesirable given the high price thereof, compared to glucose and/or

sucrose. Therefore, so far, no process for the synthesis of HMF has been developed on an industrial scale.

The synthesis chemistry and applications of HMF are reviewed extensively in Lewkowski, ARKIVOC 2001, (i) 17-54; in Gandini, Prog. Polym. Sci. 22, 1997, 1203; in Lichtenthaler, C.R. Chimie, 7, 2004, 65 and Acc. Chem. Res. 35, 2002, 728; and Moreau, Topics in Catalysis, 27, 2004, 11.

Concluding, the current methods for the synthesis of HMF mostly start from fructose and typically do not give high yield, partly attributable to the instability of HMF under the acidic reaction conditions. In most acid-catalysed water-based reactions, the further reaction to levulinic acid and humins has been reported, making this a less attractive alternative.

The present inventors have set out to overcome these disadvantages.

Surprisingly, the inventors have found that the conversion of hexose-containing starting material, in particular fructose and/or glucose -containing starting material and more particular glucose-containing material that may be derived from biomass in the presence of a catalytic or sub-stoichiometric amount of acid in the presence of an alcohol with or without the presence of one or more additional diluents leads to the formation of the corresponding HMF-ether in good yield and selectivity.

Thus, the invention pertains to a method for the manufacture of 5-alkoxymethylfurfural ethers by reacting a fructose and/or glucose-containing starting material with an alcohol in the presence of a catalytic or sub-stoichiometric amount of acid catalyst.

It was found that this in situ formation and derivatisation of HMF prevents the occurrence of the onward and undesired reaction towards the above-mentioned levulinic acid and humins, thus leading to an efficient procedure for the conversion of fructose and/or glucose -containing material into HMF derivatives.

The energy density of 5-ethoxymethylfurfural (EMF), the ether resulting from reaction of HMF with (bio)ethanol, can be calculated. Taking into account stoichiometry and a calculated enthalpy of formation using increment tables of 502.32 kJ/mole, the reaction enthalpy can be calculated as 3854.76 kJ/mol, leading to an energy density of 7.0 kWh/kg or 8.7 kWh/L. This is as good as regular gasoline (12.7 kWh/kg, 8.8 kWh/L) and diesel ((11.7 kWh/kg, 9.7 kWh/L) and significantly higher than ethanol (7.7 kWh/kg, 6.1 kWh/L). This high energy density of EMF, the fact that these HMF derivatives

can now be obtained in high yields, in one step, from very cheap hexose or hexose-containing starting materials such as sucrose and glucose, and as these ethers are, in contrast to HMF, liquids at room temperature, make these very interesting fuels or fuel additives.

5 In certain embodiments, the alcohol is selected from the group consisting of primary (un)branched aliphatic alcohols. In certain preferred embodiments, the alcohol is selected from the group consisting of primary C1-C5 (un)branched aliphatic alcohols, preferably methanol, ethanol, 1-propanol, 2-hydroxymethyl-propanol,
10 1-butanol. More preferable are methanol and/or ethanol. The resulting (m)ethyl ether ((m)ethoxymethylfurfural, MMF or EMF) has a high energy content and may directly be used as a fuel additive as an alternative for MTBE or as a fuel. Mixtures of alcohols may also be employed. Ethanol is the most preferred alcohol in the method of the
15 present invention as the ethanol that is used can also be derived from biomass or glucose-containing material (bio-ethanol).

The acid catalyst in the method of the present invention can be selected from amongst (halogenated) organic acids, inorganic
20 acids, salts, Lewis acids, ion exchange resins and zeolites or combinations and/or mixtures thereof. In certain preferred embodiments, the acid catalyst is a heterogeneous catalyst. In certain embodiments, the acid catalyst is a homogenous catalyst. The acid may be a protonic, Brønsted or, alternatively, a Lewis acid. In
25 certain embodiment, the acid may be organic or inorganic. In certain embodiments, the organic acid can be selected from amongst oxalic acid, levulinic acid, maleic acid or para-toluenesulphonic acid. In certain embodiments, the inorganic acid can be selected from amongst phosphoric acid, sulphuric acid, hydrochloric acid, hydrobromic acid,
30 nitric acid, hydroiodic acid, optionally generated in situ. In certain embodiments, the inorganic acid is selected from the group of sulphuric acid, phosphoric acid, hydrochloric acid, nitric acid. In certain embodiments, the salt can be one of $(\text{NH}_4)_2\text{SO}_4/\text{SO}_3$, ammonium phosphate, triethylamine phosphate, pyridinium salts, pyridinium
35 phosphate, pyridinium hydrochloride/hydrobromide/perbromate, DMAP, aluminium salts, Th and Zr ions, zirconium phosphate, Cr-, Al-, Ti-, Ca-, In-ions, ZrOCl_2 , $\text{VO}(\text{SO}_4)_2$, TiO_2 , V-porphyrine, Zr-, Cr-, Ti-porphyrine. In certain embodiments, the Lewis acid can be one of ZnCl_2 , AlCl_3 , BF_3 . In certain embodiments, the ion exchange resins
40 can be one of Amberlite, Diaion, Levatit. In certain embodiments, it is preferred that the acid catalyst is a solid catalyst that may be

selected from the group consisting of acid resins, natural clay mineral, zeolites, supported acids such as silica impregnated with mineral acids, heat treated charcoal, metal oxides, metal sulfides, metal salts and mixed oxides and mixtures thereof. In certain

5 embodiments, mixtures or combinations of acid catalysts can be used.

The temperature at which the reaction is performed may vary, but in general it is preferred that the reaction is carried out at a temperature from 50 to 300 degrees Celsius, preferably from 125 to 250, more preferably from 175 to 225 degrees Celsius. In general,
10 temperatures higher than 300 are less preferred as the selectivity of the reaction as many by-products occur, *inter alia* caramelisation of the sugar. Performing the reaction below the lowest temperature is also less preferable because of the slow reaction speed.

The fructose and/or glucose-containing starting material can
15 be selected from a wide variety of feeds. In general any feed with a sufficient high fructose or glucose content can be used. It is preferred that the fructose and/or glucose -containing starting material is selected from the group of starch, amylose, galactose, cellulose, hemi-cellulose, glucose-containing disaccharides such as
20 sucrose, maltose, cellobiose, lactose, preferably glucose-containing disaccharides, more preferably sucrose or glucose.

The catalyst can be added to the reaction mixture in an amount varying from 0.01 to 40 mole % drawn on the fructose or glucose content of the fructose and/or glucose -containing starting material
25 preferably from 0.1 to 30 mole %, more preferably from 1 to 20 mole %.

In certain embodiments, one or more solvents or diluents may be added, in general to aid the dissolution of the glucose containing material or as a diluent. The solvent may be selected from the group
30 consisting of water, sulfoxides, preferably DMSO, ketones, preferably methyl ethylketone, methylisobutylketone and acetone or mixtures of two or more of the above solvents.

In certain embodiments, the ratio of alcohol/solvent is from 50 to 0.1, preferably from 20 to 1, more preferably from 10 to 2.

35 Higher amounts of alcohol may have the result that the reaction is too slow due to the limited solubility (hence availability of the starting material), whereas too much solvent in the system may lead to a too high dilution, which in both cases are less preferred results. One of the possible solvents is water.

40 In certain embodiments, the method can be performed in a continuous flow process. In such method, homogenous catalysts may be

used and the residence time of the reactants in the flow process is between 0.1 second and 10 hours, preferably from 1 second to 5 hours, more preferably from 1 minute to 1 hour.

In certain embodiments the continuous flow process is a fixed bed continuous flow process or a reactive (catalytic) distillation process with preferably a heterogeneous acid catalyst. To initiate or regenerate the heterogeneous acid catalyst or to improve performance, an inorganic or organic acid may be added to the feed of the fixed bed or reactive distillation continuous flow process. In a fixed bed process, the liquid hourly space velocity (LHSV) can be from 1 to 1000, preferably from 5 to 500, more preferably from 10 to 250 and most preferably from 25 to 100.

As explained above, the application of the products of the method of the present invention, i.e. the ethers, is in the use as a fuel or fuel additive and as precursor for the manufacture of 2,5-di(hydroxymethyl)furan, furan-2,5-dicarboxylic acid, 2-hydroxymethylfuran-5-carboxylic acid, 2,5-(dihydroxymethyl)tetrahydrofuran, which can be used as monomers in a polymerisation process, optionally after conversion of the diol to a diamine. See for a review Moreau, Topics in catalysis, 2004, 27, 11-30.

Figures:

Figure 1. Plot of a) conversion, b) selectivity to furan derivatives versus space velocity. 180C, heterogeneous catalysts, reaction medium water. Catalyst 1: □; Catalyst 2: ■ Catalyst 3: * Catalyst 4: ●.

Figure 2. Plot of a) conversion, b) selectivity to furan derivatives versus space velocity. 180C, heterogeneous catalysts, reaction medium 88.7% ethanol. Catalyst 1: □; Catalyst 2: ■ Catalyst 3: * Catalyst 4: ●.

Examples

Example 1:

In a continuous flow reactor, sucrose 10 mmol/l, dissolved in water/ethanol/10% H₂SO₄, was reacted at a temperature of 195 degrees Celsius with a residence time between 6 and 60 seconds and a flow rate of 10 ml/min, i.e. 3.33 ml/min/reactor. At 6 seconds, mainly conversion into fructose and glucose was observed, but at prolonged residence times, 2 main furan peaks were observed in the UV spectrum.

Mass spectrometry identified these products as HMF and EMF with a selectivity of >90 % at a conversion of 25%.

Example 2:

5 In a continuous flow reactor, glucose 10 mmol/l, dissolved in water/ethanol/10% H₂SO₄, was reacted at a temperature of 195 degrees Celsius with a residence time between 6 and 60 seconds and a flow rate of 10 ml/min, i.e. 3.33 ml/min/reactor. At 30 seconds, 2 main furan peaks were observed in the UV spectrum. Mass spectrometry
10 identified these products as HMF and EMF with a selectivity of >90 % at a conversion of 10%.

15 **Apparatus**

Continuous parallel flow reactor system consisting of four quartz reactors inserted in a silver heating block; temperature and flow regulators and three HPLC pumps. Two of the pumps deliver the liquid to the reactors and third one is employed to dilute the reaction
20 products prior to collection.

Analytical Method

The reaction products were quantified with the aid of HPLC-analysis with an internal standard (saccharine, Sigma Aldrich). A Merck-
25 Hitachi L7000 chromatograph, equipped UV and RI detectors, was used. Stationary phase were reverse phase C18 (Sunfire 3.5 µm, 4.6x100mm, Waters) and cation exchange (SupelcogelH, 4.6x300mm, SigmaAldrich) columns connected in series. A gradient elution at a constant flow 0.6 ml/min and temperature 60 °C was used according to the following
30 scheme.

Time (min)	0.2% TFA (aq)	Methanol	Acetonitrile
0	90.0	7.0	3.0
10	90.0	7.0	3.0
11	80.0	0.0	20.0
15	80.0	0.0	20.0
16	90.0	7.0	3.0
21	90.0	7.0	3.0

General Procedure

A 1.25 wt% solution of glucose (99.7 % Sigma Aldrich) in water or 88.7 % ethanol was flowed through a fixed bed (200 μ l) of a heterogeneous catalyst at 180 °C. Flow rates were chosen such to achieve a space velocity 0.25 or 0.5 min⁻¹, i.e. contact time 2 or 4 min. Liquid coming out of the reactors was diluted by a mixture of water and ethanol (50:50) to prevent tubing blockages.

Catalysts tested:

- 10 Catalyst 1 Zeolite beta SAR25 (CBV Zeolyst)
- Catalyst 2 Zeolite Y high SAR (CBV Zeolyst)
- Catalyst 5 Mordenite H SAR 90 (CBV Zeolyst)
- Catalyst 7 Zeolite Y SAR 5.17 (CBV Zeolyst)

- 15 Contact time and space velocity were calculated as follows:

$$Sv = Fr_{feed} / V_{cat}$$

Sv space velocity (min⁻¹)

Fr_{feed} flow rate feed (ml/min)/

- 20 V_{cat} catalyst volume (ml)

$$t_c = 1 / Sv$$

t_c contact time (min)

- 25 Conversion of substrate, selectivity and yield of furan derivatives were calculated according to the following formulae:

$$X = 100 * m_r \text{ substrate} / m_0 \text{ substrate}$$

X conversion (%)

m_r substrate amount of reacted substrate (mg)

- 30 m₀ substrate amount of substrate in feed (mg)

$$S_{compound} = 100 * n_r \text{ substrate} / n_0 \text{ substrate}$$

S_{compound} selectivity to compound (%)

n_r substrate moles of substrate reacted

- 35 n₀ substrate moles of substrate in feed

$$Yield = 100 * n_{product} / n_0 \text{ substrate}$$

Yield yield (%)

n_{product} moles of product formed

Catalysts tested:

Catalyst 1 Zeolite beta SAR25 (CBV Zeolyst)

Catalyst 2 Zeolite Y high SAR (CBV Zeolyst)

Catalyst 3 Mordenite H SAR 90 (CBV Zeolyst)

5 Catalyst 4 Zeolite Y SAR 5.17 (CBV Zeolyst)

Reactions in water.

Figure 1 a) and b) show that a conversion achieved for the catalysts tested was 76% (Zeolite beta). This catalyst gave 7% selectivity to
10 HMF and EMF.

Zeolite Y with high SAR presented 9% selectivity to furans at 20% conversion. Y zeolite with low SAR (catalyst 4) shows selectivity of 4% at very low conversion. Mordenite presented both reduced activity and selectivity to furan derivatives.

15 HMF was a main furan found in the reaction mixture.

Reactions in ethanol.

With the use of Zeolite beta about 4 % selectivity to HMF and EMF was achieved at 17% conversion at a low space velocity. For the other
20 catalysts tested, the conversion developed initially to more than 20% and the selectivity was in the range between 1 and 3 %.
The predominant furan derivative was the desired EMF.

DATA Fructose + Ethanol with solid acid catalyst 1 fructose conc 55.5 mmol/L; 90% EtOH

Res time	fructose conversion	Y (HMF)	Y (EMF)	S (HMF)	S (EMF)
/ s	%	%	%	%	%
10	42	2	9	5	21
30	76	3	24	4	32
60	93	1	35	1	38
120	98	1	37	1	38

DATA Glucose + Ethanol with solid acid catalyst 1 glucose conc 55.5 mmol/L; 90% EtOH

Res time	glucose conversion	Y (HMF)	Y (EMF)	S (HMF)	S (EMF)
/ s	%	%	%	%	%
60	73	2	23	3	32
180	92	1	23	1	25
300	97	1	24	1	25
600	98	1	22	1	22

DATA Sucrose + Ethanol with solid acid catalyst 1sucrose conc 27.8 mmol/L (55.5 mmol/L C₆H₁₂O₆); 90% EtOH

Res time	Glu + fru Conversion	Y (HMF)	Y (EMF)	S (HMF)	S (EMF)
/ s	%	%	%	%	%
60	86	4	22	5	26
180	96	3	26	3	27
300	98	3	28	3	29
600	99	2	27	2	27

engine test

In a small-scale model diesel engine, comparative testing is performed with normal commercial diesel as a fuel and the same commercial diesel to which samples of 1 wt.%, 2 wt.%, 3 wt.%, 5 wt%, and 10 wt.% HMF or EMF are added, respectively. The diesel samples with HMF are less homogenous on visual inspection (solid particles remain visible, flocculation) and above 5 wt.% HMF, a solid deposit is sometimes observed. EMF is added as a liquid and does not yield any mixing or flocculation problems. The engine is run stationary with a set volume (100 mL) of fuel until empty. HMF containing fuels run less regular, whereas EMF containing fuels run at a regular pace and for a longer period (up to 15%). On visual inspection of the engine, EMF provides less visual contamination.

Claims

1. Method for the manufacture of ethers of 5-hydroxymethylfurfural by reacting a fructose and/or glucose-containing starting material with an alcohol in the presence of a catalytic or sub-stoichiometric amount of a heterogeneous acid catalyst.
5
2. Method according to claim 1, wherein the alcohol is selected from the group consisting of primary (un)branched aliphatic alcohols, preferably C1-C5 primary (un)branched aliphatic alcohols, more preferably methanol, ethanol, 1-propanol, iso-
10 propanol, 1-butanol, most preferably methanol, ethanol, more particular preferable ethanol or mixtures thereof.
3. Method according to claim 1 or 2, wherein the acid catalyst is selected from the group consisting of solid (halogenated)
15 organic acids, inorganic acids, salts, Lewis acids, ion exchange resins, zeolites or mixtures and/or combinations thereof.
4. Method according to claim 1, wherein the acid is a solid
20 Brønsted acid.
5. Method according to claim 1, wherein the acid is a solid Lewis acid.
- 25 6. Method according to any one of the claims 1 to 5, wherein the reaction is performed at a temperature from 50 to 300 degrees Celsius, preferably from 125 to 250, more preferably from 175 to 225 degrees Celsius.
- 30 7. Method according to any one of the claims 1 to 6, wherein the fructose and/or glucose-containing starting material is selected from the group of starch, amylose, galactose, cellulose, hemi-cellulose, glucose-containing disaccharides such as sucrose, maltose, cellobiose, lactose, preferably
35 glucose-containing disaccharides, more preferably sucrose or glucose.

8. Method according to any one of the claims 1 to 7 wherein one or more solvents or diluents are present in addition to the alcohol.
- 5 9. Method according to claim 8, wherein the solvent or solvents are selected from the group consisting of water, sulfoxides, preferably DMSO, ketones, preferably methyl ethylketone, methylisobutylketone and/or acetone and mixtures thereof.
- 10 10. Method according to claim 9, wherein the ratio of alcohol/solvent is from 50 to 0.1, preferably from 20 to 1, more preferably from 10 to 2.
11. Method according to any one of the claims 1 to 10, wherein the
15 method is performed in a continuous flow process.
12. Method according to claim 11, wherein the residence time in the flow process is between 0.1 second and 10 hours, preferably from 1 second to 5 hours, more preferably from 1 minute to 1
20 hour.
13. Method according to claim 12, wherein the continuous flow process is a fixed bed continuous flow process.
- 25 14. Method according to claim 13, wherein the fixed bed comprises a heterogeneous acid catalyst.
15. Method according to claim 13, wherein the continuous flow process is a reactive distillation or a catalytic distillation
30 process.
16. Method according to claim 15, wherein in addition to a heterogeneous acid catalyst, an inorganic or organic acid catalyst is added to the feed of the fixed bed or catalytic
35 distillation continuous flow process.
17. Method according to claim 13-16, wherein the LHSV is from 1 to 1000, preferably from 5 to 500, more preferably from 10 to 250 and most preferably from 25 to 100.

18. Use of 5-alkoxymethylfurfural, preferably 5-methoxymethylfurfural or 5-ethoxy-methylfurfural as a fuel or as a fuel additive.