

Title: Crystalline microporous material mediated conversion of C₁₋₃ oxygenate compounds to C₄- oxygenate compounds.

Background:

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The selective and high yielding preparation of C₄ oxygenate compounds, e.g. C₄ sugars such as erythrose, threose and erythrulose, could prove valuable for their use in the chemical industry for the preparation of, for example: C₄ polyols; methyl vinyl glycolate or products obtainable therefrom; 2-hydroxy-4-methoxybutanoic acid or salts or esters thereof such as methyl 2-hydroxy-4-methoxybutanoate.

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Known methods for preparing C₄ oxygenate compounds include the aldol self-condensation of glycolaldehyde. It has been observed that aldol condensations are not selective for the preparation of C₄ oxygenate compounds; a mix of products is observed as the C₄ product continues to react to form oxygenate compounds with a greater number of carbon atoms. In order to control the reaction's selectivity for C₄ oxygenate compounds, the formation of C₄-oxygenate and silicate or borate complexes, or the use of C₄-oxygenate selective catalysts is required.

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An example of the use of a silicate complex for the selective formation of C₄ oxygenate compounds includes the aldol condensation of glycolaldehyde in the presence of aqueous sodium silicate; Science (2010) 327, pp 984-986. During the reaction a silicate-C₄-sugar complex is formed, consequently controlling the selectivity of the reaction. A further example includes the condensation of glycolaldehyde in the presence of a borate buffer. A high yield of C₄ oxygenate

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compounds (C₄ sugars) is obtained (86%); J. Am. Chem. Soc. (2011) 133, pp 9457-9468.

5 An example of a C₄-oxygenate selective catalyst includes the preparation of C₄ oxygenate compounds by the aldol condensation of glycolaldehyde in the presence of a homochiral dipeptide catalyst. The yield of C₄ oxygenate compound products was up to 63 %; PNAS (2006) 103, pp 12712-12717. Alternatively, a zinc-proline catalyst may be used. The total yield of the C₄-sugar products was approximately 51 %. 10 C₆-sugars were formed in a yield of approximately 30 %; Org. Biomol. Chem. (2005) 3, pp 1850-1855.

Alternative preparations of C₄ oxygenate compounds from glycolaldehyde include the proposed tetrose transient intermediate in the preparation of 2-hydroxy-4-methoxybutanoate (C₄) and methyl vinyl glycolate (C₄). The reaction proceeds in the presence of a zeotype catalyst. The zeotype material was Sn-BEA, a twelve-membered ring pore structure; 15 Green Chemistry (2012) 14, pp 702-706. 20

An alternative zeotype material, such as a ten-membered ring pore structured zeotype (e.g. Sn-MFI or Ti-MFI), may be used to isomerise C₂ oxygenate compounds. Such a zeotype 25 has been used for the isomerisation of glyoxal to glycolic acid. The yield of glycolic acid was approximately 90%; Green Chemistry (2014) 16, pp 1176-1186.

It is an object of the present invention to provide a process for the preparation of C₄ oxygenate compounds from a composition comprising C₁₋₃ oxygenate compounds, wherein the 30

process is selective for the production of C₄ oxygenate compounds and the product is obtained in high yields.

Summary

In one aspect of the present disclosure, there is provided a process for the preparation of one or more C₄ oxygenate compounds of the formula C₄H₈O₄ from a composition comprising C₁₋₃ oxygenate compounds, wherein the composition comprising C₁₋₃ oxygenate compounds comprises glycolaldehyde and wherein the C₄ oxygenates are selectively formed from glycolaldehyde in the presence of a solvent and a crystalline microporous material comprising a ring pore structure selected from one or more of the group consisting of an eight-membered ring pore structure and a ten-membered ring pore structure.

In another aspect of the present disclosure, there is provided a use of C₄ oxygenate compounds prepared according to the process disclosed herein for the preparation of one or more α -hydroxy methionine analogues.

Disclosure of the invention

It has now been discovered that glycolaldehyde may be selectively transformed into C₄ oxygenate compounds in the presence of a crystalline microporous material comprising a small- or medium-pore structure. The reaction proceeds in a high yield. Additionally, it is possible for the reaction to proceed in the presence of additional compounds to selectively form the desired C₄ oxygenate compounds.

The invention is further defined by a process for the preparation of C₄ oxygenate compounds from a composition comprising C₁₋₃ oxygenate compounds, wherein the process is carried out in the presence of a crystalline microporous material comprising a small- or medium-pore structure.

C₄ oxygenate compounds may be known as C₄ sugars or oxygenated compounds with a carbon chain length of four carbon atoms. The molecular formula of the C₄ oxygenate compounds may be C₄H₈O₄. C₄ oxygenate compounds may also be described as tetroses. The C₄ oxygenate compounds are selected from one or more of the group consisting of threose, erythrose and erythrulose.

In one embodiment of the invention compositions comprising C₁₋₃ oxygenate compounds comprise one or more oxygenate compounds selected from the group consisting of C₁ oxygenate compounds, C₂ oxygenate compounds and C₃ oxygenate compounds. C₁, C₂ and C₃ oxygenate compounds means compounds

that have a carbon chain length of one, two or three carbon atoms respectively. The molecular formulae of the C₁₋₃ oxygenate compounds are formulae selected from one or more of the group consisting of: CH₂O; C₂H₄O₂; C₂H₂O₂; C₃H₆O₂ and C₃H₄O₂. Preferably, the composition comprising C₁₋₃ oxygenate compounds is a composition comprising one or more compounds selected from the group consisting of formaldehyde, glyoxal, glycolaldehyde, pyruvaldehyde and acetol. In a second embodiment, preferably the composition comprising C₁₋₃ oxygenate compounds is a composition comprising one or more C₂ oxygenate compounds selected from the group consisting of glycolaldehyde (2-hydroxyacetaldehyde) and glyoxal. Glycolaldehyde is a compound with a carbon chain length of two carbon atoms, also known as a C₂ oxygenate compound or C₂ sugar.

The composition comprising C₁₋₃ oxygenate compounds may be in the form of a solution, wherein the solvent is selected from the group consisting of water, methanol and a water and methanol mixture. For example, the composition comprising C₁₋₃ oxygenate compounds may be an aqueous or methanolic solution of glycolaldehyde or an aqueous or methanolic solution of a composition comprising one or more compounds selected from the group consisting of formaldehyde, glyoxal, glycolaldehyde, pyruvaldehyde and acetol.

Compositions comprising C₁₋₃ oxygenate compounds are obtainable by pyrolysis of biomass or pyrolysis of one or more oxygenate compounds selected from the group consisting of C₅ oxygenate compounds, C₆ oxygenate compounds and sucrose. C₅ oxygenate compounds and C₆ oxygenate compounds means one or more compounds selected from the group consisting of

glucose, fructose, xylose and isomers thereof. Exemplary pyrolysis reactions are provided in US 7,094,932 B2 and PCT/EP2014/053587.

5 Crystalline microporous material includes zeolite materials and zeotype materials. Zeolite materials are crystalline alumino-silicates with a microporous crystalline structure, according to Corma *et al.*, Chem. Rev. 1995, 95 pp 559-614. The aluminum atoms of the zeolite material may be partly or
10 fully substituted by a metal (metal atoms) such as zirconium (Zr), titanium (Ti) and tin (Sn), these materials are known as zeotype materials.

Crystalline microporous material comprising a small-pore
15 structure means a crystalline microporous material comprising an eight-membered ring pore structure; crystalline microporous material comprising a medium-pore structure means a crystalline microporous material comprising a ten-membered ring pore structure. Examples of crystalline microporous materials with a small- or medium-pore structure
20 are provided in Chem. Rev. 1995, 95 pp 559-614 and include structures such as LTA, CHA, MFI (ZSM-5), MEL, MTT, MWW, TON, HEU, AEL, AFO, MWW and FER.

25 The crystalline microporous material with a structure of BEA comprises a large, twelve-membered ring pore structure (Chem. Rev. 1995, 95 pp 559-614), and is not considered a feature of the present invention.

Examples of zeotype materials with a medium pore size include structures such as Sn-MFI, Ti-MFI and Zr-MFI. An example of a zeotype material with a small pore size is Sn-LTA.
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Crystalline microporous materials comprising a small- or medium-pore structure may be considered to behave as a catalyst.

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The percentage yield of C₄ oxygenate compounds prepared by the process of the present invention is equal to or greater than 20%, equal to or greater than 24%, equal to or greater than 27%, equal to or greater than 30%, equal to or greater than 35%.

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The content of metal (metal atoms) in the crystalline microporous material comprising a small- or medium-pore structure is present from 0.1 to 15 wt%, from 0.5 to 5.0 wt%, from 0.5 to 1.5 wt%.

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The process may be carried out in a solvent; wherein the solvent may be selected from one or more of the group consisting of water, alcohol and a water and alcohol mixture (water and alcohol). Alcohol may be selected from one or more of the group consisting of methanol and ethanol.

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The process may be carried out at a temperature of from 25 to 150 °C, from 50 to 120 °C, and from 70 to 100 °C.

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The C₄ oxygenate compounds produced by the present invention may be converted to C₄-polyols by hydrogenation. Such hydrogenation reactions may be performed in the presence of a supported metal catalyst, wherein the metal is for example copper, nickel, molybdenum, cobalt, iron, chromium, zinc, and the platinum group metals. In a preferred embodiment the metal catalyst is selected from the group consist-

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ing of palladium or ruthenium supported on carbon or Raney nickel. Exemplary hydrogenation reaction conditions are disclosed in US 6,300,494 B1 and US 4,487,980 B1. Examples of further suitable metal catalysts and reaction conditions for use in hydrogenation reactions are disclosed in Ullmann's Encyclopaedia of Industrial Chemistry: Hydrogenation and Dehydrogenation.

The C₄ oxygenate compounds produced by the process of the present invention may be converted to methyl vinyl glycolate and 2-hydroxy-4-methoxybutanoic acid or salts or esters thereof. Science (2010) 328, pp 602 - 605 and Green Chemistry (2012) 14, pp 702-706 disclose appropriate synthetic procedures. Additionally, α -hydroxy- γ -butyrolactone may be prepared from the C₄ oxygenate compounds under the same conditions or conditions as described in ACS Catal., 2013, 3 (8), pp 1786-1800

The methyl vinyl glycolate compound may further react to form α -hydroxy methinonine analogues; an example of this transformation is disclosed in WO 98/32735. α -hydroxy methinonine analogues include compounds selected from the group consisting of 2-hydroxy-4-(C₁₋₅alkylthio)butanoic acid, salts and esters thereof.

C₁₋₅alkylthio means an alkyl thiol selected from the group consisting of methane thiol, ethane thiol, straight or branched chain propane thiol, straight or branched chain butane thiol and straight or branched chain pentane thiol.

C₁₋₈ alkyl esters means esters comprising the alkyl group selected from the group consisting of methyl, ethyl, propyl, butyl, isopropyl, isobutyl, pentyl, hexyl, heptyl, octyl and 2-ethylhexyl.

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In one embodiment of the invention the methionine α -hydroxy analogues is 2-hydroxy-4-(methylthio)butanoic acid.

In a second embodiment of the invention the methionine α -hydroxy analogues is selected from the group consisting of 2-hydroxy-4-(methylthio)butanoic acid methyl ester, 2-hydroxy-4-(methylthio)butanoic acid ethyl ester, 2-hydroxy-4-(methylthio)butanoic acid propyl ester, 2-hydroxy-4-(methylthio)butanoic acid butyl ester, 2-hydroxy-4-(methylthio)butanoic acid isopropyl ester, 2-hydroxy-4-(methylthio)butanoic acid pentyl ester, 2-hydroxy-4-(methylthio)butanoic acid hexyl ester, 2-hydroxy-4-(methylthio)butanoic acid heptyl ester, 2-hydroxy-4-(methylthio)butanoic acid octyl ester and 2-hydroxy-4-(methylthio)butanoic acid 2-ethylhexyl ester.

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The C₄ oxygenate compounds produced by the process of the present invention may be converted into butanediols as described in ChemSusChem (2012) 5, pp 1991-1999.

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The process for preparing C₄ oxygenate compounds from C₁₋₃ oxygenate compounds may also be carried out concomitantly with the hydrogenation reaction of the C₄ oxygenate compounds to form C₄ polyols. The reactions therefore may be conducted in one step, i.e. a 'one pot' reaction. A 'one-step' or 'one-pot' reaction means that the crystalline microporous material for the conversion of glycolaldehyde to

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C₄ oxygenate compounds and the metal catalyst for the hydrogenation of the C₄ oxygenate compounds are present in the reaction vessel simultaneously. The reaction is quenched when the hydrogenated product (C₄ polyols) is present.

C₄ polyol means C₄ oxygenate compounds that comprise compounds of a chain length of four carbon atoms and each carbon atom is bonded to an alcohol (OH) functional group. C₄ polyols may also be known as four carbon sugar alcohols and have the molecular formula of C₄H₁₀O₄. C₄ polyols are compounds selected from one or more of the group consisting of erythritol and threitol. Erythritol and threitol include all stereoisomers such as D- and L-threitol. Erythritol may be used as a foodstuff, a sweetener and for the preparation of butanediols. ChemSusChem (2012) 5, pp 1991-1999 illustrates the preparation of butanediols from erythritol.

Example 1:

Crystalline Microporous Material (Sn-MFI, Ti-MFI, Sn-BEA and Sn-LTA) Preparation:

Sn-MFI:

200 Sn-MFI (Si/Sn = 200) is prepared according to the method described by Mal et al. (Mal, N.K.; Ramaswamy, V.; Rajamohanam, P.R.; Ramaswamy, A.V. Sn-MFI molecular sieves: Synthesis methods, ²⁹Si liquid and solid MAS-NMR, ¹¹⁹Sn static and MAS NMR studies. Microporous Mater., 1997, 12, 331-340). According to this procedure NH₄F (5.35 g) is dissolved in demineralized water (25.0 g). A solution of SnCl₄.5H₂O (0.25 g) in H₂O (10.0 g) is added under rapid stirring. After this, of tetrapropylammonium bromide [TPABr

(9.8 g)] in H₂O (56.0 g) is added slowly. Fumed silica (8.6 g) is dissolved in the mixture. The mixture is stirred for 3 hours and the gel is then transferred to a Teflon lined autoclave and crystallized at 200°C for 6 days. The product is then suction filtrated with ample water and dried overnight at 80°C. Recovered powder is calcined at 550°C (2°C/min) for 6 hours. 400Sn-MFI (Si/Sn = 400) is prepared following the same procedure but adjusting the amount of SnCl₄.5H₂O.

Sn-MFI (Alternative preparation):

200 Sn-MFI (Si/Sn = 200) can be prepared from ZSM-5 (Ze-ochem, ZEOcat ® PZ-2 100H). ZSM-5 is treated under steam at 450°C for 6 h, acid washed with HCl 1 M at 100°C for 16 h, and washed with ample water. The solid is dried at 120°C for 16 h, impregnated with an aqueous solution of SnCl₂ and calcined at 550°C (2°C/min) for 6 h.

Ti-MFI:

200 Ti-MFI (Si/Ti = 200) is prepared according to a modification of the method described by Mal et al. (Mal, N.K.; Ramaswamy, V.; Rajamohanan, P.R.; Ramaswamy, A.V. Sn-MFI molecular sieves: Synthesis methods, ²⁹Si liquid and solid MAS-NMR, ¹¹⁹Sn static and MAS NMR studies. Microporous Mater., 1997, 12, 331-340). According to this procedure NH₄F (5.35 g) is dissolved in demineralized water (25.0 g). A solution of Ti (IV) ethoxide (0.17 g) in H₂O (3.5 g) and H₂O₂ (6.5 g) is added under rapid stirring. After this, a solution of tetrapropylammonium bromide [TPABr (9.8 g)] in H₂O (56.0 g) is added slowly. Fumed silica (8.6 g) is dissolved in the mixture. The mixture is stirred for 20 hours

and the gel is then transferred to a Teflon lined autoclave and crystallized at 200°C for 6 days. The product is then suction filtrated with ample water and dried overnight at 80°C. Recovered powder is calcined at 550°C (2°C/min) for 6 hours.

Sn-BEA:

Sn-BEA was prepared according to the method described in EP 2184270 B1.

Sn-LTA:

125 Sn-LTA with (Si/Sn = 125) can be prepared from LTA zeolite (Sigma-Aldrich, Molecular sieves, 4Å). LTA is treated under steam at 450°C for 6 h, acid washed with HCl 1 M at 100°C for 16 h, and washed with ample water. The solid is dried at 120°C for 16 h, impregnated with an aqueous solution of SnCl₂ and calcined at 550°C (2°C/min) for 6 h.

Preparation of C₄ oxygenate compounds from glycolaldehyde:

Example 2:

Crystalline microporous material (0.15 g) prepared according to Example 1, glycolaldehyde dimer [SAFC, 0.25 g] and deionized water (5 g) are added in a 20 mL vial (Ace pressure tube) and heated at 80°C under vigorous stirring (600 rpm). Samples of the reaction are taken at selected times (0.5-24 h). Analysis of the liquid samples after filtration is carried out using a HPLC Agilent 1200 equipped with a BIORAD Amminex HPX-87H column at 65°C and 0.004 M H₂SO₄ solution in water at 0.6 ml min⁻¹.

Table 1: The percentage yield of C₄ oxygenate compounds produced from an aqueous glycolaldehyde solution over time with various crystalline microporous materials.

	Percentage yield (%) of C₄-oxygenate compounds				
Time (h)	400Sn-MFI	200Sn-MFI	Ti-MFI	Sn-BEA	Sn-LTA
1	30.8	66.3	18.5	26.1	37.5
3	59.2	70.8	34.5	23.9	51.17
24	73.4	53.6	57.7	0	55.58

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Example 3:

Compositions comprising C₁₋₃ oxygenate compounds may be prepared by pyrolysis of biomass or C₅₋₆ sugars (C₅₋₆ oxygenate compounds) such as glucose, sucrose, fructose or xylose. Exemplary pyrolysis reactions are provided in US 7,094,932 B2 and PCT/EP2014/053587. The C₁₋₃ oxygenate compositions comprise 5 wt% glycolaldehyde or greater, such as between 5 wt % and 65 wt%.

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A composition comprising C₁₋₃ oxygenate compounds obtained from the pyrolysis of glucose according to US 7,094,932 B2 is diluted in water to obtain 5 g of a solution comprising 8 wt% glycolaldehyde. Crystalline microporous material (0.15 g), prepared according to Example 1 is added to the mixture in a 20 mL vial (Ace pressure tube) and the reaction is heated at 80°C under vigorous stirring (600 rpm). Samples of reaction are taken at selected times (0.5-24 h). Analysis of the liquid samples after filtration is carried out as previously explained.

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Table 2: The percentage yield of C₄ oxygenate compounds produced from an aqueous solution of a C₁₋₃ oxygenate mixture according to Example 2 versus time. Various crystalline microporous materials are shown.

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Time (h)	Percentage yield (%) of C ₄ oxygenate compounds			
	400Sn-MFI	200Sn-MFI	Ti-MFI	Sn-BEA
1	7.7	21.7	6.7	7.4
3	13.1	35.5	11.2	22.5
24	39.4	52.9	40.2	21.8

Example 4:

10 Hydrogenation of C₄ oxygenate compounds is carried out in an autoclave reactor at pressures 30-90 bar of H₂. The reaction is carried out by addition of a composition comprising C₄ oxygenate compounds (15 g), prepared according to Example 2 or 3, into a Parr autoclave (50 mL) together with
 15 of Ru/C catalyst (0.2 g; 5% on activated charcoal from Aldrich). The reactor is heated at 80 °C and stirred at 500 rpm for 3 h.

Example 5:

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Concomitant conversion of glycolaldehyde to C₄ oxygenate compounds and subsequent hydrogenation. ('one-pot' or 'one-step' conversion and hydrogenation).

25 Glycolaldehyde dimer (SAFC, 0.25 g), Sn-MFI (0.1 g) prepared according to Example 1, Ru/C catalyst (0.075 g; 5% on activated charcoal from Aldrich) and water (15 g) are added

in a 50 mL Parr autoclave. The first condensation reaction is carried out at 80 °C in air atmosphere. After 3 h of reaction, the autoclave is pressurized with hydrogen at 90 bar and the reaction is allowed to proceed for 3 h. Samples of the products are obtained after the condensation step and the hydrogenation and analyzed after filtration in an HPLC as previously explained.

Alternatively, vinyl glycolic acid or methyl vinyl glycolate (MVG) can be obtained by reaction of a composition comprising C₄ oxygenate compounds prepared according to Examples 1 or 2 with Sn-BEA catalyst in water or methanol respectively; Green Chemistry (2012) 14, pp 702-706.

Figure 1: The percentage yield of C₄ oxygenate compounds prepared according to Example 2 versus time. Various crystalline microporous materials are shown. The crystalline microporous materials are:

Squares: 200Sn-MFI;

Circles: Ti-MFI;

Triangles: Sn-BEA.

Figure 2: The percentage yield of C₄ oxygenate compounds prepared according to Example 3 versus time. Various crystalline microporous materials are shown.

The crystalline microporous materials are:

Squares: 200Sn-MFI;

Circles: Ti-MFI;

Triangles: Sn-BEA.

Claims:

1. A process for the preparation of one or more C₄ oxygenate compounds of the formula C₄H₈O₄ from a composition comprising C₁₋₃ oxygenate compounds, wherein the composition comprising C₁₋₃ oxygenate compounds comprises glycolaldehyde and wherein the C₄ oxygenates are selectively formed from glycolaldehyde in the presence of a solvent and a crystalline microporous material comprising a ring pore structure selected from one or more of the group consisting of an eight-membered ring pore structure and a ten-membered ring pore structure.
2. A process according to claim 1, wherein the C₄ oxygenate compounds are compounds selected from one or more of the group consisting of threose, erythrose and erythrulose.
3. A process according to claims 1 and 2, wherein the composition comprising C₁₋₃ oxygenate compounds comprises one or more compounds selected from the group consisting of formaldehyde, glycolaldehyde, glyoxal, pyruvaldehyde and acetol.
4. A process according to claim 3, wherein the composition comprising C₁₋₃ oxygenate compounds comprises glycolaldehyde at a concentration of at least 5 wt%.
5. A process according to claims 1 to 4, wherein the solvent is selected from one or more of the groups consisting of water, alcohol and a water and alcohol mixture.
6. A process according to claim 5, wherein the alcohol is selected from one or more of the group consisting of methanol and ethanol.
7. A process according to claims 1 to 6, wherein the crystalline microporous material comprising an eight-membered ring pore structure or a ten-membered ring pore structure,

comprises a metal selected from one or more of the group consisting of zirconium, aluminium, tin or titanium.

8. A process according to claim 7, wherein the crystalline microporous material comprising an eight-membered ring pore structure or a ten-membered ring pore structure, comprises from 0.1 wt % to 15 wt% of the metal.
9. A process according to claims 1 to 8, wherein the crystalline microporous material is a zeotype material which has a structure selected from the group consisting of CHA, LTA, MFI, MEL, MTT, MWW, TON, HEU, AEL, AFO, and FER structure.
10. A process according to claims 1 to 9, wherein the process is carried out at a temperature between 25 °C and 150 °C.
11. A process according to claims 1 to 10, wherein a prior step is performed of pyrolysing biomass or one or more oxygenate compounds selected from the group consisting of fructose, glucose, sucrose, xylose or isomers thereof, to produce a composition comprising the C₁₋₃ oxygenate compounds.
12. A process according to claims 1 to 11, wherein the C₄ oxygenate compounds are hydrogenated.
13. A process according to claim 12, wherein the process is a one-step process.
14. A process according to claims 1 to 11, wherein the C₄ oxygenate compounds are isomerised and esterified in the presence of Sn-BEA.
15. A process according to claims 1 to 11, wherein the C₄ oxygenate compounds are converted to one or more compounds selected from the group consisting of erythritol and threitol.

16. Use of C₄ oxygenate compounds prepared according to claims 1 to 11 for the preparation of one or more α -hydroxy methionine analogues.