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(54) Title: SEPARATION OF AROMATIC COMPOUNDS FROM CARBOHYDRATES USING METAL-ORGANIC FRAMEWORKS

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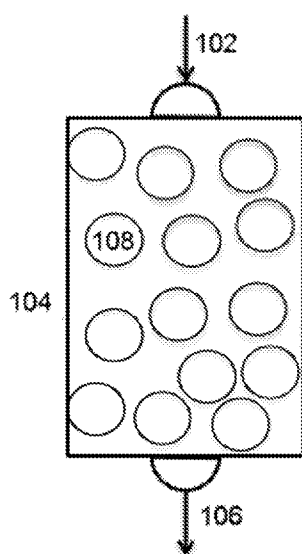


FIG. 1

(57) Abstract: Provided are methods of using metal-organic framework (MOF) that favorably separate aromatic compounds, such as furanic compounds, from carbohydrates, such as sugars.

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SEPARATION OF AROMATIC COMPOUNDS FROM CARBOHYDRATES USING METAL-ORGANIC FRAMEWORKS

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of US Ser No. 62/382,244, filed: Aug 31, 2017 and US Ser No. 62/349,986, filed: Jun 14, 2016, which are incorporated herein by reference in their entirety.

STATEMENT REGARDING FEDERALLY-SPONSORED RESEARCH

[0001] This invention was made with government support under Grants DE-FG02-05ER15696 and DE-SC0012702 awarded by the U.S. Department of Energy. The Government has certain rights to this invention.

BACKGROUND

[0002] In carbohydrate fermentation, aromatic compounds that are produced as byproducts can poison the enzymes which catalyze fermentation. In particular, the breakdown of carbohydrates in lignocellulosic biomass, a source of biomass on earth, may lead to the production of furanic or phenolic compounds, or combinations thereof. Aromatic compounds, including furanic and phenolic compounds, can poison catalysts, enzymes, and fermentation organisms used in the fermentation of carbohydrates (see Leonard, R. H., *et al.*, *Ind. Eng. Chem.* **1945**, 37, 390–395; Clark, T. A., *et al.*, *J. Chem. Technol. Biotechnol.* **1984**, 34, 101–110; Delgenes, J. P., *et al.*, *Enzyme Microb. Technol.* **1996**, 19, 220–225).

[0003] Furanic compounds, such as 5-hydroxymethylfurfural and furfural, are also green platform chemicals that may be derived from acid-catalyzed dehydration of carbohydrates. One challenge in synthesizing these compounds is to reduce possible decomposition as a result of sequential undesired reaction. These include decomposition to humins, which result from furanics polymerization; or to levulinic and formic acid, via rehydration. To increase furanics yield, various biphasic extraction strategies employing organic solvents have been tried, in tandem with aqueous-phase acid catalysis. However, these strategies often require costly downstream distillation. An alternative is the specific adsorption of the furanic onto a solid surface. However, the selectivity of adsorption has been a limitation, since carbohydrate reactants can also be adsorbed onto the solid surface.

[0004] Thus, it is desirable to separate aromatic compounds, such as furanic and phenolic compounds, from carbohydrates, including in fermentation mixtures. There is a need in the art for alternative methods to separate aromatic compounds from carbohydrates, such as sugars.

SUMMARY OF THE INVENTION

[0005] The present disclosure provides methods of separating aromatic compounds from carbohydrates using metal-organic frameworks (MOFs). Thus, in one aspect, provided is a method for separating an aromatic compound from a carbohydrate, wherein the carbohydrate is a monosaccharide or an alpha-linked disaccharide, or a combination thereof, by:

contacting a metal-organic framework with a solution comprising the aromatic compound and the carbohydrate; and

separating the aromatic compound from the carbohydrate in the solution by adsorbing at least a portion of the aromatic compound in the solution onto the metal-organic framework.

[0006] In some variations, the aromatic compound is a furanic compound.

[0007] In some variations, provided is a method that includes:

contacting a carbohydrate with a catalyst or an enzyme to produce a fermentation mixture, wherein the fermentation mixture comprises an aromatic compound and at least a portion of the carbohydrate;

contacting a metal-organic framework with the fermentation mixture; and

separating the aromatic compound from the carbohydrate in the fermentation mixture by adsorbing at least a portion of the furanic compound in the fermentation mixture onto the metal-organic framework.

[0008] In some variations, the aromatic compound is a furanic compound.

BRIEF DESCRIPTION OF THE FIGURES

[0009] The present application can be understood by reference to the following description taken in conjunction with the accompanying figures.

[0010] FIG. 1 depicts an exemplary system for separating carbohydrates from aromatic compounds using a metal-organic framework (MOF).

[0011] FIG. 2A depicts single-component adsorption isotherms of 5-hydroxymethylfurfural, glucose, and fructose on NU-1000 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 1 in Example 1).

[0012] FIG. 2B depicts single-component adsorption isotherms of furfural and xylose on NU-1000 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 1 in Example 1).

[0013] FIG. 3A depicts a Langmuir plot for 5-hydroxymethylfurfural adsorption on NU-1000 in a single mode at 297 K.

[0014] FIG. 3B depicts a Langmuir plot for furfural adsorption on NU-1000 in a single mode at 297 K.

[0015] FIG. 4A depicts competitive-mode adsorption isotherms of 5-hydroxymethylfurfural, glucose, and fructose on NU-1000 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 2 in Example 2).

[0016] FIG. 4B depicts competitive-mode adsorption isotherms of furfural and xylose on NU-1000 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 2 in Example 2).

[0017] FIG. 5A depicts a Langmuir plot for 5-hydroxymethylfurfural adsorption on NU-1000 in a competitive mode at 297 K.

[0018] FIG. 5B depicts a Langmuir plot for furfural adsorption on NU-1000 in a competitive mode at 297 K.

[0019] FIG. 6A depicts single-component adsorption isotherms of 5-hydroxymethylfurfural, glucose, and fructose on MSC-30 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 3 in Example 3).

[0020] FIG. 6B depicts single-component adsorption isotherms of furfural and xylose on MSC-30 at 297 K. The dashed lines represent the isotherm replicated by the Langmuir parameters (Table 3 in Example 3).

[0021] FIG. 7A depicts Langmuir plots for 5-hydroxymethylfurfural (HMF), glucose, and fructose adsorption on MSC-30 in a single mode at 297 K.

[0022] FIG. 7B depicts Langmuir plots for furfural and xylose adsorption on MSC-30 in a single mode at 297 K.

[0023] FIG. 8 depicts a graph of the competitive adsorption of HMF and glucose on NU-1000, MSC-30, and BP2000 at 297 K.

[0024] FIG. 9 depicts a graph of the competitive adsorption of HMF, glucose, and fructose on NU-1000, MSC-30, and BP2000 at 297 K.

DETAILED DESCRIPTION OF THE INVENTION

[0025] The following description sets forth exemplary methods, parameters and the like. It should be recognized, however, that such description is not intended as a limitation on the scope of the present disclosure but is instead provided as a description of exemplary embodiments.

[0026] In some aspects, provided herein are methods for separating aromatic compounds from carbohydrates, such as sugar, using metal-organic frameworks (MOFs). For example,

MOFs can be used to target aromatic compounds without adsorbing sugar during its acid-catalyzed synthesis in aqueous media, and can thus increase aromatic-compound yield as a result of selective sequestration of before degradation. The aromatic compounds may include, for example, furanics or phenolics, or combinations thereof.

[0027] In another example, MOFs can be used for the separation of aromatic compounds from aqueous carbohydrates in solutions for fermentation, where small amounts of aromatic compounds may be present as byproducts, and may poison enzymes that catalyze carbohydrate fermentation. In some variations, the aromatic compounds are furanics or phenolics, or combinations thereof. Thus, in one aspect, provided is a method that includes: contacting a carbohydrate with a catalyst or an enzyme to produce a fermentation mixture, wherein the fermentation mixture comprises an aromatic compound and at least a portion of the carbohydrate; contacting a metal-organic framework with the fermentation mixture; and separating the aromatic compound from the carbohydrate in the fermentation mixture by adsorbing at least a portion of the aromatic compound in the fermentation mixture onto the metal-organic framework. In some variations, the catalyst is an acid catalyst. In some variations, the aromatic compound is a furanic compound.

[0028] With reference to FIG. 1, exemplary system **100** depicts the methods described herein to separate one or more aromatic compounds from carbohydrates. Column **104** comprises MOF **108**. Solution **102** contains a carbohydrate and one or more aromatic compounds, is applied to column **104**, and output stream **106** exits the column. In other embodiments, a fermentation mixture containing a carbohydrate and a catalyst is provided to the column containing a metal-organic framework to produce an output stream. In some variations, the output stream **106** comprises a lower concentration of the one or more aromatic compounds than the input stream **102**. In other embodiments, the MOF is provided in a solution, and a filtration mechanism is used to produce an output stream. In some embodiments, the aromatic compound is a furanic compound.

[0029] In some embodiments, the MOF is recycled after the adsorption of aromatic compounds. In certain embodiments, the MOF is recycled by rinsing it with water.

[0030] In some embodiments, the carbohydrates in the output stream are used to further produce one or more aromatic compounds or other chemicals. In other embodiments, the carbohydrates in the output stream are in contact with a catalyst or an enzyme after isolation.

[0031] The separation method, including the types of aromatic compounds, carbohydrates, and MOFs used, are further described in detail below.

Metal-Organic Frameworks

Structure of metal-organic frameworks

[0032] Metal-organic frameworks (MOFs) are a class of materials formed by coordination bonds between metal-based nodes and organic linkers. The MOFs used in the methods described herein are selected based on various properties, including, for example, pore size, surface area, and choices of metal and linker.

[0033] Certain aspects of the present disclosure relate to methods of separating furanic compounds and carbohydrates using a MOF with an aromatic moiety. In some embodiments, the organic linker of the MOF has an aromatic moiety. In some variations, the aromatic moiety has one aromatic ring. In other variations, the aromatic moiety has two, three, four, five or six aromatic rings that are conjugated together. In certain variations, the aromatic moiety comprises two or more fused rings, for example two, three, four, five or six aromatic rings that are fused. In one variation, the organic linker includes a plurality of aromatic moieties conjugated together. In certain variations, the organic linker has two, three, four, five, or six aromatic rings conjugated with one another. In other variations, the organic linker has between three and six aromatic rings conjugated together. In other variations, the organic linker has four aromatic rings conjugated together, such as pyrene. In certain variations, the organic linker has two, three, four, five, or six fused aromatic rings. In other variations, the organic linker has between three and six fused aromatic rings. In other variations, the organic linker has four fused aromatic rings, such as pyrene.

[0034] In some variations, the organic linker has at least one aromatic heterocyclic ring. In other variations, the organic linker has two, three, four, five, or six aromatic heterocyclic rings that are conjugated with one another. In certain variations, the organic linker has two, three, four, five, or six fused aromatic heterocyclic rings.

[0035] In some variations, the organic linker has an aromatic moiety larger than that of one benzene ring.

[0036] In some embodiments, MOF comprises a plurality of aromatic domains that are connected to the metal. In one variation, the aromatic domain in a MOF refers to the portion of the MOF that has aromaticity. In another variation, the organic linker has an aromatic domain that is less than 5 nm, measured by end-to-end distance of the aromatic domain including a carbonyl group, if applicable. In other variations, the organic linker has an aromatic domain that is less than 2 nm.

[0037] In some variations, the MOF comprises hydrophobic repeating units. In another variation, the MOF comprises hydrophobic repeating units that exhibit π - π interactions with the one or more aromatic compounds to be separated from the carbohydrates. In some variations, the one or more aromatic compounds are one or more furanic compounds, one or more phenolic compounds, or a combination thereof. Without being bound by any theory, MOFs that exhibit

π - π interactions with the one or more aromatic compounds may achieve better selectivity for aromatic compounds than MOFs that do not have such interactions, because π - π interactions are absent when MOFs adsorb sugars.

[0038] In some embodiments, the organic linker has a pyrene moiety. In other embodiments, the organic linker has hydrophobic pyrene repeat units.

[0039] In some embodiments, the MOF has a surface area larger than 500 m²/g. In some variations, the MOF has a surface area smaller than 6000 m²/g.

[0040] In some embodiments, the MOF comprises a plurality of pores. In one variation, at least a portion of the pores have a diameter greater than 6 Å, greater than 7 Å, greater than 8 Å, greater than 9 Å, greater than 10 Å, or greater than 15 Å. In other variations, the MOF comprises a plurality of pores, wherein at least a portion of the pores have a diameter of less than 10 nm, less than 5 nm, or less than 1 nm. In certain variations, the MOF has pores between 6 Å and 10 nm, between 6 Å and 1 nm in diameter.

[0041] In some embodiments, the methods for separating carbohydrates and furanic compounds use a MOF with a Zr-based node.

[0042] In some variations, the MOF is hydrothermally stable.

[0043] In some embodiments, the methods for separating carbohydrates and furanic compounds use more than one MOF.

[0044] In some embodiments, the methods for separating carbohydrates and furanic compounds use NU-800, NU-901, NU-1000, NU-1001, NU-1102, or NU-1100, or a combination thereof.

[0045] The MOF may be provided in alternative formats, such as a multiple adsorption-desorption column format (i.e. as in pressure-swing adsorption) or a MOF-containing membrane. In some embodiments the MOF is incorporated into a membrane, preferably a membrane configured to operate on the principle of permeability - based on a ratio of partitioning and diffusivity; suitable MOF membrane are known in the art, e.g. Qiu et al., Chem. Soc. Rev., 2014, 43, 6116.

Selectivity

[0046] In some aspects, the MOF being used to separate one or more aromatic compounds from a carbohydrate has a higher adsorption capacity of the one or more aromatic compounds than the carbohydrate. In some variations, the MOF has a greater adsorption capacity for adsorbing the aromatic compound than the carbohydrate by 10-fold, 11-fold, 12-fold, 13-fold, 14-fold, or 15-fold; or at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or at least 100-fold; or between 10-fold and 100-fold, between 20-fold and 100-fold, between 10-fold and 50-fold, between 10-fold and 20-fold, or between 10-fold and 15-fold.

Such a comparison in adsorption capacity is observed in a competitive mode, when both the aromatic compound and the carbohydrate are at the same concentration in solution.

[0047] In some variations, the MOF adsorbs 10-fold, 11-fold, 12-fold, 13-fold, 14-fold, or 15-fold more of the aromatic compound than of the carbohydrate. In certain variations, the MOF adsorbs at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or at least 100-fold more of the aromatic compound than of the carbohydrate. In yet other variations, the MOF adsorbs between 10-fold and 100-fold, between 20-fold and 100-fold, between 10-fold and 50-fold, between 10-fold and 20-fold, or between 10-fold and 15-fold more of the aromatic compound than the carbohydrate. In some variations, the aromatic compound is a furanic compound. In some variations, the carbohydrate is glucose, fructose, xylose, or maltose, or any mixtures thereof. In certain variations, the MOF adsorbs one or more aromatic compounds without adsorbing one or more carbohydrates.

[0048] In some variations, the methods for separating carbohydrates and aromatic compounds use a MOF that can produce an output stream comprising the aromatic compound at a concentration of less than 25 mM, less than 24 mM, less than 23 mM, less than 22 mM, less than 21 mM, less than 20 mM, less than 19 mM, less than 18 mM, less than 17 mM, less than 16 mM, less than 15 mM, less than 10 mM, less than 9 mM, less than 8 mM, less than 7 mM, less than 6 mM, less than 5 mM, less than 4 mM, less than 3 mM, less than 2 mM, or less than 1 mM; or between 1 mM and 25 mM, between 5 mM and 25 mM, or between 10 mM and 16 mM. In other variations, the methods for separating carbohydrates and furanic compounds use a MOF that can produce an output stream containing more than 60%, more than 70%, more than 80%, more than 90%, or more than 95% by weight of the carbohydrate. In other variations, the methods for separating carbohydrates and aromatic compounds use a MOF that adsorbs less than 5%, less than 4%, less than 3%, less than 2%, or less than 1% by weight of the carbohydrate in the solution.

[0049] In some variations of the foregoing, the one or more aromatic compounds are one or more of the furanic compounds described herein.

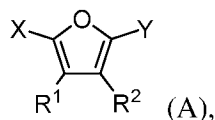
Aromatic Compounds

[0050] Biomass provides an abundant supply of carbohydrates that can be used to produce aromatic compounds via catalyzed dehydration of these carbohydrates. In some variations, the aromatic compounds are furanic compounds, in other variations the aromatic compounds are phenolic compounds. In still other variations, the aromatic compounds comprise a mixture of furanic and phenolic compounds. In certain fermentation reactions, the presence of aromatic compounds such as furanics and/or phenolics can be poisonous for enzymes that catalyze carbohydrate fermentation. Certain aspects of the present disclosure relate to the methods of

separating carbohydrates from one or more aromatic compounds that can be produced via carbohydrate fermentation. In some variations, the one or more aromatic compounds is one or more furanic compounds. Certain aspects of the present disclosure relate to the methods of separating carbohydrates from all aromatic compounds that can be produced via carbohydrate fermentation. In some embodiments, the methods disclosed herein can be used to separate the carbohydrates from all furanic compounds that can be produced via dehydration of saccharides.

[0051] In some embodiments, the aromatic compound is any compound containing aromaticity. In certain embodiments, the aromatic compound is a furanic compound. In some variations, the aromatic compound is a phenolic compound.

[0052] In some embodiments, the aromatic compound is a furanic compound of formula (A):



wherein:

R^1 and R^2 are H;

X and Y are independently H, alkyl, OH, C(O)H, C(O)OR^a, or CH₂OH, wherein R^a is H or alkyl.

[0053] In some variations, the furanic compound is furfural or 5-hydroxymethylfurfural.

[0054] In other variations, the furanic compound is furan, 2-hydroxymethylfuran, 2,5-dihydroxymethylfuran, 2,5-diformylfuran, 2-furoic acid, or 2,5-furandicarboxylic acid.

[0055] In some embodiments, a mixture of furanic compounds is separated from one or more carbohydrates.

[0056] In some embodiments, furanic compounds such as furfural and 5-hydroxymethylfurfural are separated from glucose, fructose, xylose, or maltose, or a combination thereof. In some embodiments, the furanic compounds are separated from the monosaccharides they are derived from. For example, 5-hydroxymethylfurfural and furfural can be separated from glucose, fructose, and xylose. In other embodiments, the furanic compounds are separated from alpha-linked disaccharides. For example, 5-hydroxymethylfurfural and furfural can be separated from maltose.

Carbohydrates

[0057] Carbohydrates are separated from the one or more aromatic compounds according to the methods described herein. In some variations, the one or more aromatic compounds are one or more furanic compounds.

[0058] In some embodiments, a carbohydrate has the formula $C_m(H_2O)_n$, where m and n are the same or different integer greater than or equal to 1.

[0059] In some variations, the carbohydrate is a monosaccharide, or an alpha-linked disaccharide, or a combination thereof. In one variation, the carbohydrate is a disaccharide formed by two monosaccharides joined with an alpha-glycosidic bond. In some variations, the carbohydrate is maltose.

[0060] In some variations, the carbohydrate includes simple sugars. For example, in some variations, the carbohydrate is fructose, glucose, or xylose, or any combinations thereof.

[0061] It should be understood that the methods described herein may be used to separate a mixture of carbohydrates from one or more aromatic compounds, including one or more furanic compounds.

Systems

[0062] In some embodiments, the methods for separating carbohydrates and aromatic compounds use a MOF provided in a column. In other embodiments, the MOF is provided in a reactor vessel. In other embodiments, the MOF is provided in the solution containing carbohydrates and aromatic compounds. In other embodiments, the MOF is provided in the fermentation mixture containing carbohydrates and aromatic compounds.

Processing Conditions

[0063] In some embodiments, the solution containing carbohydrates and aromatic compounds are in contact with the MOF for at least 1 minute, at least 5 minutes, at least 10 minutes, at least 15 minutes, at least 20 minutes, at least 30 minutes, or at least 60 minutes; or between 1 and 60 minutes, or between 15 and 45 minutes.

[0064] In some embodiments, the fermentation mixture containing carbohydrates and aromatic compounds are in contact with the MOF for at least 1 minute, at least 5 minutes, at least 10 minutes, at least 15 minutes, at least 20 minutes, at least 30 minutes, or at least 60 minutes; or between 1 and 60 minutes, between 15 and 45 minutes.

[0065] In some embodiments, the solution containing carbohydrates and aromatic compounds are in contact with the MOF at a temperature of at least 250 K, at least 260 K, or at least 270 K; or between 250 K and 310 K, or between 270 K and 280 K.

[0066] In some embodiments, the fermentation mixture comprising carbohydrates and aromatic compounds is in contact with the MOF at a temperature of at least 250 K, at least 260 K, or at least 270 K; or between 250 K and 310 K, or between 270 K and 280 K.

Recycling

[0067] In some embodiments, the methods for separating carbohydrates and aromatic compounds using a MOF comprise recycling of the MOF. In some variations, at least a portion

of the aromatic compounds adsorbed on the MOF can be removed by rinsing the MOF with water, and the MOF can be recycled. In some embodiments, the MOF can be used for separating carbohydrates and aromatic compounds after recycling.

[0068] In some embodiments, the methods for separating carbohydrates and aromatic compounds using a MOF produce an output stream comprising carbohydrates, and the output stream can be used for further fermentation reactions. In some variations, the output stream comprising carbohydrates can be used to produce aromatic compounds via dehydration.

EXAMPLES

[0069] The following Examples are merely illustrative and are not meant to limit any aspects of the present disclosure in any way.

Example 1

Adsorption of 5-hydroxymethylfurfural (HMF), furfural, glucose, fructose, and xylose on NU-1000 in a single mode

[0070] This example demonstrates the affinity of certain furanic compounds and certain carbohydrates with NU-1000 through single-component adsorption experiments in aqueous solution. The furanic compounds were 5-hydroxymethylfurfural (HMF) and furfural. The carbohydrates were glucose, fructose, and xylose. The furanic compounds and carbohydrates were all obtained from commercially available sources.

[0071] An aqueous stock solution containing a single component (for single-component adsorption) with high concentrations was prepared in a volumetric flask. The stock solution was used as-is or after dilution in water (18 MΩ cm). NU-1000 of 5 mg was dispersed in 1.5 mL of the aqueous solution. The suspension was ultrasonicated for 1 min to disperse the NU-1000, vortexed for at least 30 min at 297 K, and then filtered with a syringeless filter device equipped with a polytetrafluoroethylene membrane (0.2 μm mesh). The amount of residual compound in the liquid-phase filtrate was quantified by high-performance liquid chromatography (HPLC) equipped with a carbohydrate analysis column (ø7.8 × 300 mm, mobile phase 5 mM H₂SO₄ 0.6 mL min⁻¹, column temperature 323 K), with an absolute calibration method. The subtraction of mass of furanic/carbohydrate detected by HPLC from that of compound charged gave an uptake.

[0072] All isotherms for the furanic compounds tested exhibited Type I adsorption behavior, where uptakes increase steeply in the lower concentration range and plateau at higher concentrations. The adsorption was analyzed using the Langmuir equation. This is in contrast to glucose, fructose, or xylose on NU-1000. *See* FIGS. 2A and 2B. The Langmuir equation [Eq. (S1)] gives the adsorption equilibrium constant (K_{ads}) and adsorption capacity (Q_{max}) for each isotherm.

$$Q = \frac{CK_{\text{ads}}Q_{\text{max}}}{1 + CK_{\text{ads}}} \quad (\text{S1})$$

where C is the equilibrium concentration and Q is the uptake. This equation is transformed into Eq. (S2), which represents the Langmuir plot.

$$\frac{C}{Q} = \frac{C}{Q_{\text{max}}} + \frac{1}{K_{\text{ads}}Q_{\text{max}}} \quad (\text{S2})$$

[0073] The estimated Langmuir parameters for furanic compounds and carbohydrate adsorption on NU-1000 at 297 K in a single mode are summarized in Table 1.

Table 1. Langmuir parameters for furanic and carbohydrate adsorption on NU-1000 at 297 K in a single mode.

Adsorbate	Langmuir parameter	
	$K_{\text{ads}}^{[\text{a}]} / \text{M}^{-1}$	$Q_{\text{max}}^{[\text{b}]} / \text{mg g}_{\text{NU-1000}}^{-1}$
HMF	120	240
Glucose	0	0
Fructose	0	0
Furfural	28	467
Xylose	0	0

[a] Adsorption equilibrium constant. [b] Adsorption capacity.

[0074] These isotherms observed for the furanic compounds have high enthalpies of adsorption. Table 1 above summarizes the adsorption equilibrium constant (K_{ads}) and adsorption capacity (Q_{max}), which are obtained from a fit of the Langmuir plots. *See FIGS. 3A and 3B.* The K_{ads} values for HMF and furfural are calculated to be 120 M^{-1} and 28 M^{-1} , respectively, in Table 1. The adsorption capacity of NU-1000 MOF is high on a mass-fraction basis (Q_{max} values of $240 \text{ mg g}_{\text{NU-1000}}^{-1}$ for HMF and $467 \text{ mg g}_{\text{NU-1000}}^{-1}$ for furfural, Table 1), and comparable to other adsorbents of furan compounds consisting of carbon (*See Table 3*).

[0075] In contrast to HMF and furfural, NU-1000 showed no affinity for glucose, fructose or xylose in FIGS. 2A and 2B and Table 1 in single-component adsorption mode. These results indicate the lack of affinity of NU-1000 for simple monomeric sugars (including glucose, xylose and fructose), while exhibiting higher affinity toward furanic compounds (HMF and furfural).

[0076] Based the data in this Example, NU-1000 (an exemplary MOF) was observed to selectively adsorb furanic compounds rather than the monosaccharides tested.

Example 2

Adsorption of 5-hydromethylfurfural (HMF), furfural, glucose, fructose, and xylose on NU-1000 in a competitive mode

[0077] This example demonstrates the application of NU-1000 to separate furanic compounds from a multicomponent sugar-furanics aqueous mixture. Such separation may be applied, for example, in the purification of sugar solutions for fermentation, or in sequestration of the furanics product from the reaction mixture to increase the yield of furanics synthesis from

sugars, avoiding sequential reactions. A method similar to that detailed in Example 1 was used to demonstrate adsorption of HMF, furfural, glucose, fructose, and xylose on NU-1000 in a competitive mode at 297 K, where both the furanic compound and the carbohydrate are present at the same time in the aqueous solution mixture. FIGS. 4A and 4B show competitive-mode adsorption isotherms of different furanics and sugars on NU-1000. For C6 compounds, NU-1000 adsorbs only HMF from the aqueous solution mixture, with 100% retention of glucose and fructose in the solution, even at a high concentration of 0.2 M (FIG. 4A). Similarly, NU-1000 adsorbs furfural, with a lack of xylose uptake (FIG. 4B). These results demonstrate the lack of affinity of NU-1000 for simple monomeric sugars. This leads to an infinite calculated adsorption ratio of furanics to carbohydrates in a competitive mode, when using NU-1000 for both C6 and C5 compounds.

[0078] The Langmuir plots are presented in FIGS. 5A and 5B. The estimated Langmuir parameters for furanics and carbohydrate adsorption on NU-1000 at 297 K in a competitive mode are summarized in Table 2.

Table 2. Langmuir parameters for furanic and carbohydrate adsorption on NU-1000 at 297 K in a competitive mode.

Adsorbate	Langmuir parameter	
	$K_{\text{ads}}^{[a]} / \text{M}^{-1}$	$Q_{\text{max}}^{[b]} / \text{mg g}_{\text{NU-1000}}^{-1}$
HMF	96	292
Glucose	0	0
Fructose	0	0
Furfural	26	457
Xylose	0	0

[a] Adsorption equilibrium constant. [b] Adsorption capacity

[0079] The Example demonstrates that NU-1000 (an exemplary MOF) was observed to selectively adsorb furanic compounds from aqueous solution mixtures containing sugars.

Example 3

Adsorption of 5-hydromethylfurfural (HMF), furfural, glucose, fructose, and xylose on MSC-30 in a single mode

[0080] For comparison, commercial mesoporous carbon material MSC-30 was tested using the same method as described in Example 1. All isotherms observed in this study exhibited Type I behavior (i.e., Langmuir isotherm), except for glucose, fructose, or xylose on MSC-30 (FIGS. 6A and 6B). The Langmuir equation [Eq. (S1)] gives the adsorption equilibrium constant (K_{ads}) and adsorption capacity (Q_{max}) for each isotherm, which is transformed into Eq. (S2), representing the Langmuir plot (FIGS. 7A and 7B). The estimated Langmuir parameters for furanics and carbohydrate adsorption on MSC-30 at 297 K in a single mode are summarized in Table 3.

Table 3. Langmuir parameters for furanic and carbohydrate adsorption on MSC-30 in a single mode at 297 K.

Adsorbate	Langmuir parameter	
	$K_{\text{ads}}^{[a]} / \text{M}^{-1}$	$Q_{\text{max}}^{[b]} / \text{mg g}_{\text{MSC-30}}^{-1}$
HMF	714	716
Glucose	82	208
Fructose	43	170
Furfural	194	699
Xylose	47	134

[a] Adsorption equilibrium constant. [b] Adsorption capacity.

[0081] This Example demonstrates that MSC-30, a carbon material, exhibits high affinity for furanics, but it also adsorbs simple sugars. In contrast, NU-1000, as an exemplary MOF, exhibits high affinity for furanic compounds, but does not exhibit detectable adsorption capability for simple sugars, as shown in the data of Examples 1 and 2 above.

Example 4

Adsorption of HMF and Glucose on MOF NU-1000, MSC-30 and BP2000

[0082] This Example demonstrates the selective removal of HMF as a representative aromatic compound in fermentation mixtures, using MOF NU-1000.

[0083] This example was performed using a method similar to the procedure described in Example 2 above. An aqueous solution comprising 8 mM HMF and 11mM glucose was used. 1.5 mL this solution was then treated with 25 mg of MOF NU-1000, amorphous carbon MSC-30, or amorphous carbon BP2000 at 297 K. FIG. 8 is a graph depicting the amount of HMF and glucose removed from the solution by the NU-1000, MSC-30, or BP2000.

[0084] As shown in FIG. 8, NU-1000 removed 80% of the HMF originally present in the solution, while no glucose adsorption occurred on NU-1000. In contrast, amorphous carbon MSC-30 adsorbed 99% of HMF from solution (a higher amount relative to NU-1000), but also adsorbed more than 2.3-fold more glucose than HMF. This resulted in MSC-30 removing 18% of the sugar present in the 111 mM glucose solution mixture. Amorphous carbon BP2000 removed less HMF than MSC-30, and, like MSC-30, BP2000 also resulted in removal of sugar. BP2000 removed 12% of sugar originally present in the 111 mM glucose solution mixture. These data demonstrate the selective removal of aromatic compound HMF from an aqueous mixture of HMF and glucose with NU-1000, without the adsorption of sugar from the same aqueous solution mixture. Such selective removal was not observed with amorphous carbons MSC-30 and BP2000, since these also resulted in adsorption of sugar.

[0085] Without being bound by any theory, selective HMF removal (i.e. without also removing sugars from the feed solution) may involve π - π interactions with the NU-1000; such interactions are absent when adsorbing sugars. Thus, good selectivity of HMF adsorption in the

presence of sugars may indicate good selectivity with the other aromatic compounds present in lignocellulose-derived aqueous sugar-feed solutions.

Example 5

Adsorption of HMF, Glucose, and Fructose on MOF NU-1000, MSC-30 and BP2000

[0086] This Example demonstrates the selective removal of HMF in a mixture comprising two sugars, glucose and fructose.

[0087] This example was performed following the general procedure described in Example 3 above. An aqueous solution comprising 40 mM each of HMF, fructose, and glucose was used. 1.5 mL of this aqueous solution was treated with 50 mg of MOF NU-1000, amorphous carbon MSC-30, or amorphous carbon BP2000 at 297 K. FIG. 9 is a graph depicting the amount of HMF, glucose, and fructose removed from the solution by the NU-1000, MSC-30, or BP2000.

[0088] MOF NU-1000 removed 74% of the HMF originally present in solution (corresponding to an adsorbed HMF amount of $112 \text{ mg g}_{\text{adsorbent}}^{-1}$). No glucose adsorption occurred with NU-1000. In contrast, while amorphous carbon MSC-30 removed 98% of the HMF originally present in solution (corresponding to an adsorbed HMF amount of $148 \text{ mg g}_{\text{adsorbent}}^{-1}$), it also adsorbed 30% of the glucose and 21% of the fructose present in the original aqueous solution mixture. Using amorphous carbon BP2000, less HMF was removed compared to MSC-30 (corresponding to 96% of the HMF originally present in the aqueous solution mixture), but BP2000 also resulted in removal of 16% of the glucose and fructose that was originally present in the aqueous solution mixture.

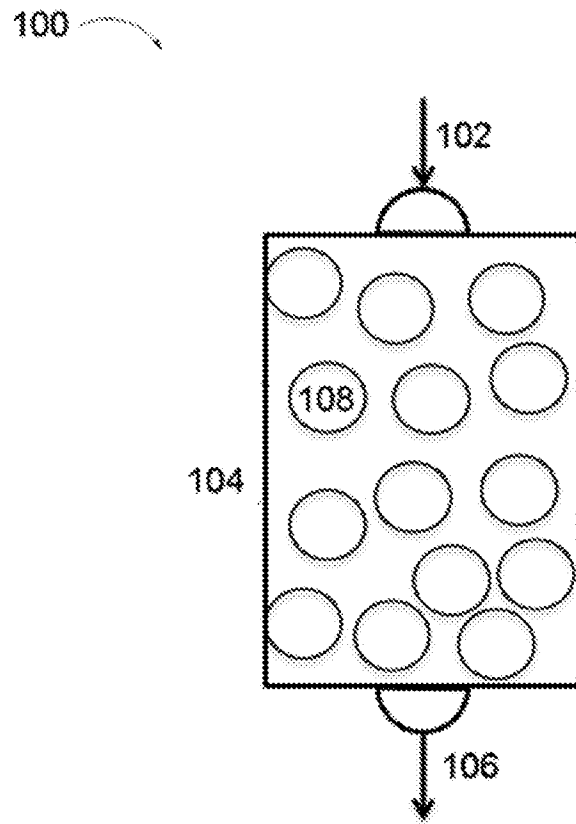
[0089] Again, these data demonstrate the selective removal of aromatic compound HMF from an aqueous mixture of HMF, glucose, and fructose with NU-1000, without the adsorption of sugar from the same aqueous solution mixture. Such selective removal was not observed with amorphous carbons MSC-30 and BP2000, since these also resulted in adsorption of sugar.

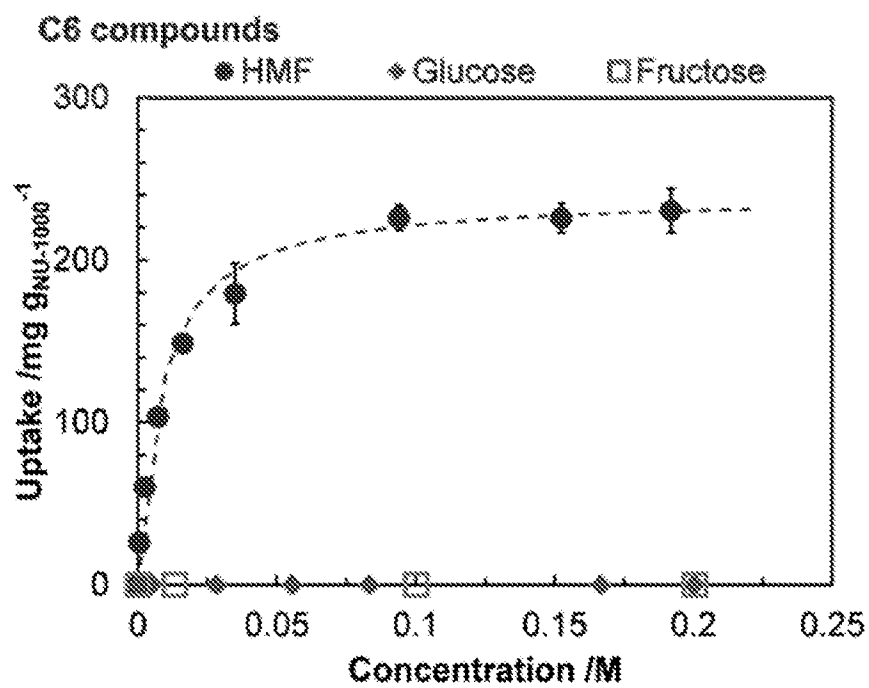
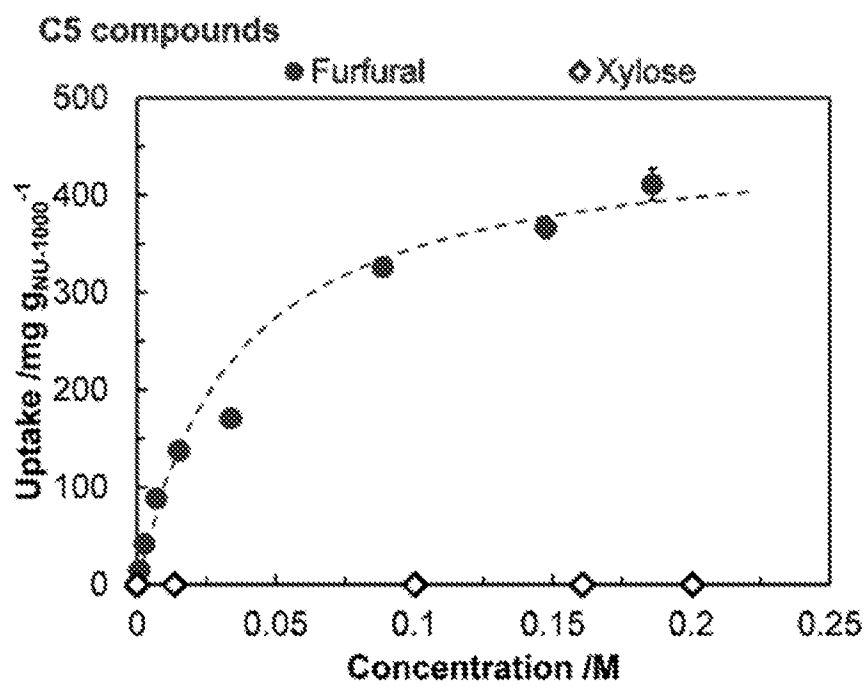
CLAIMS

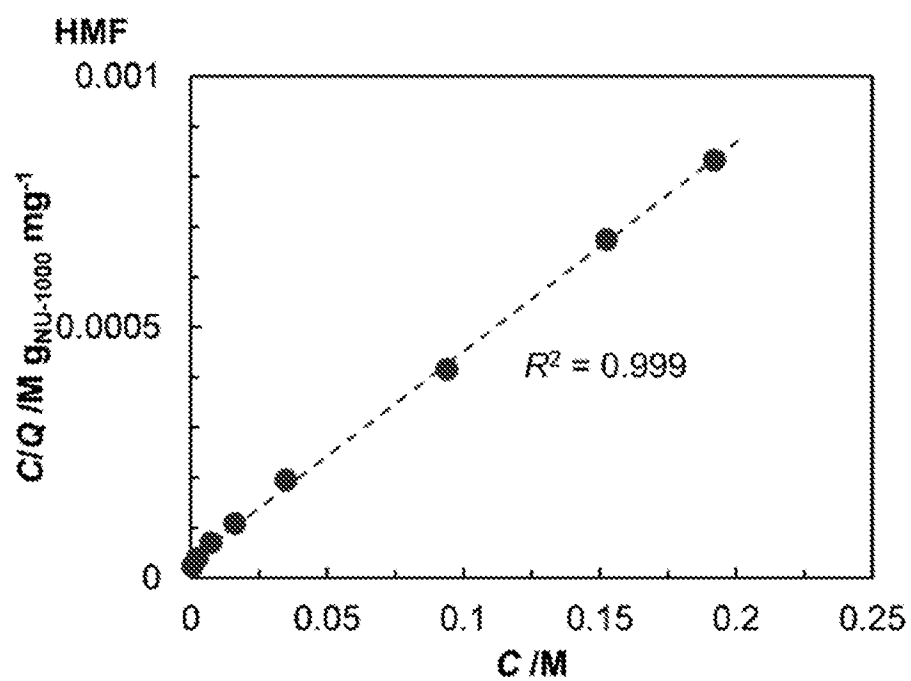
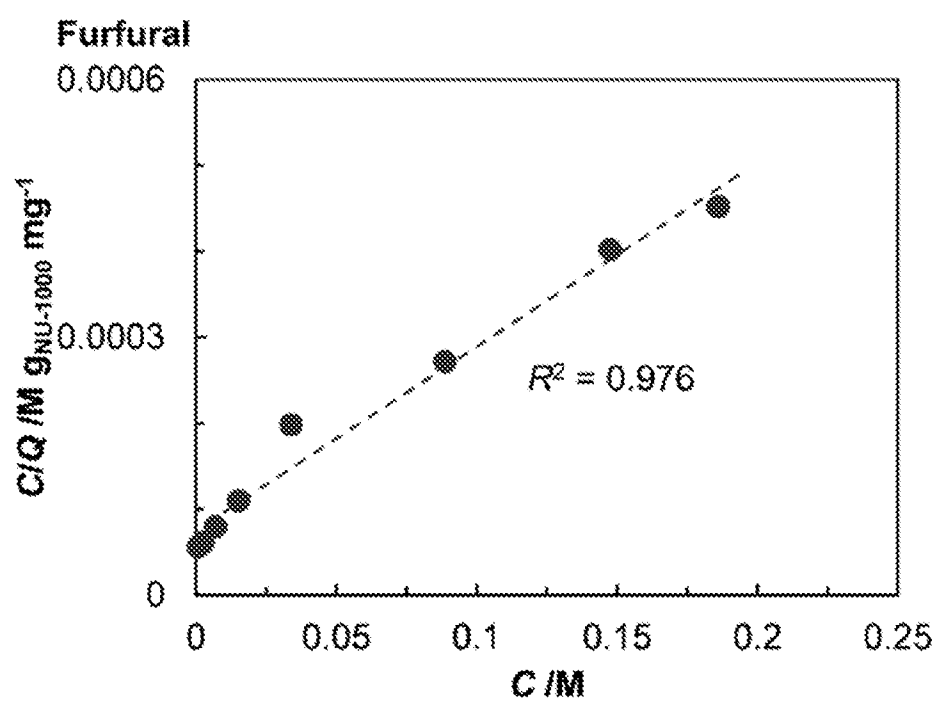
1. A method for separating an aromatic compound from a carbohydrate, wherein the carbohydrate is a monosaccharide or an alpha-linked disaccharide, or a combination thereof, the method comprising:
 - contacting a metal-organic framework with a solution comprising the aromatic compound and the carbohydrate; and
 - separating the aromatic compound from the carbohydrate in the solution by adsorbing at least a portion of the aromatic compound in the solution onto the metal-organic framework.
2. The method of claim 1, wherein the metal-organic framework comprises a metal and an organic linker.
3. The method of claim 2, wherein the organic linker comprises an aromatic moiety.
4. The method of claim 3, wherein the organic linker comprises a plurality of aromatic moieties conjugated together.
5. The method of claim 4, wherein the organic linker has an aromatic domain greater than a benzene ring.
6. The method of claim 5, wherein the aromatic domain is less than 5 nm.
7. The method of claim 2, wherein the organic linker comprises a pyrene.
8. The method of any one of claims 1 to 7, wherein the metal-organic framework has a surface area greater than 500 m²/g.
9. The method of claim 8, wherein the metal-organic framework has a surface area less than 6000 m²/g.
10. The method of any one of claims 1 to 9, wherein the metal-organic framework has a plurality of pores, and at least a portion of the pores have a diameter greater than 6 Å.
11. The method of claim 10, wherein at least a portion of the pores are less than 10 nm in diameter.

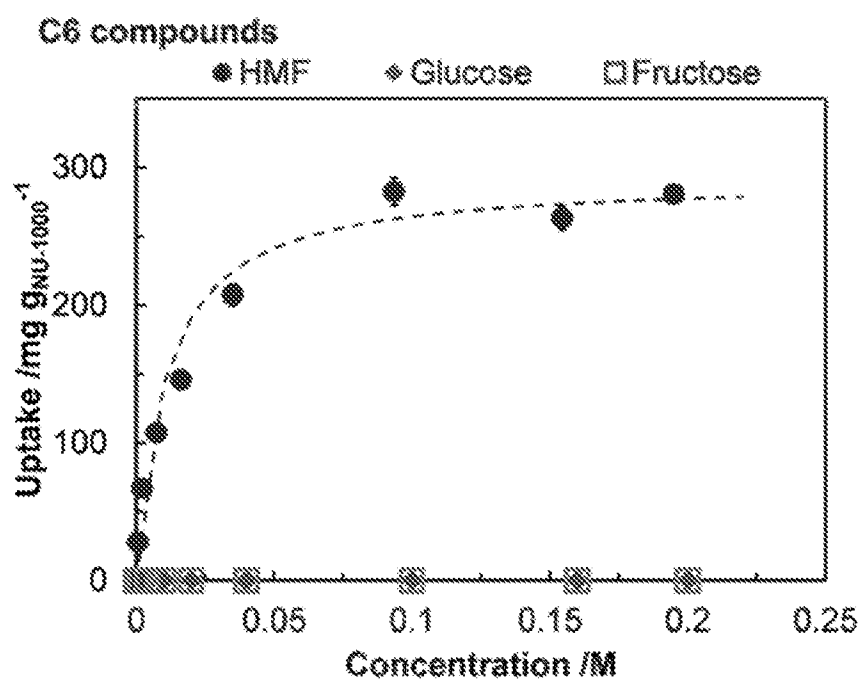
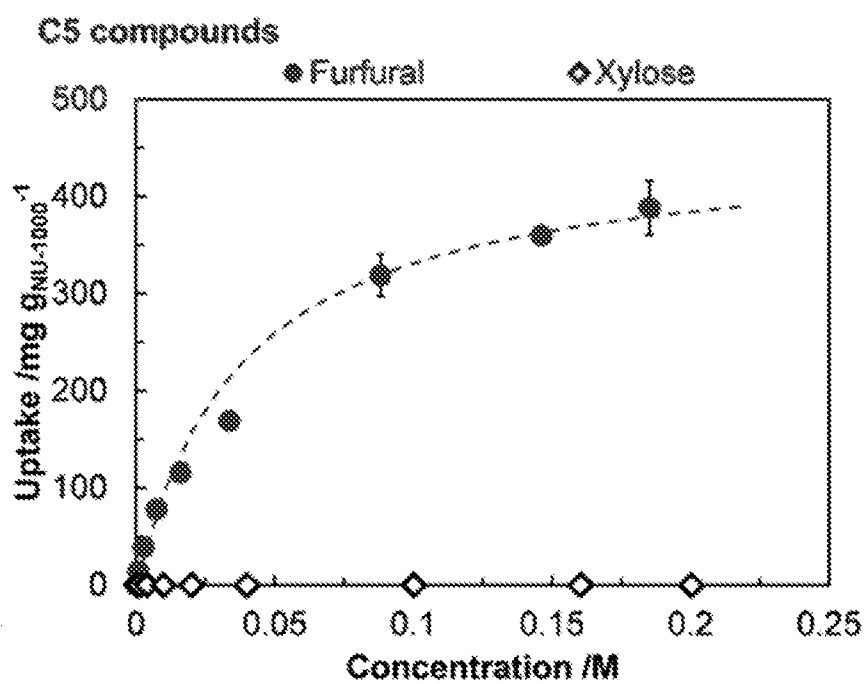
12. The method of any one of claims 2 to 11, wherein the metal is zirconium (Zr).
13. The method of any one of claims 1 to 12, wherein the metal-organic framework is NU-800, NU-901, NU-1000, NU-1001, NU-1102, or NU-1100, or a combination thereof.
14. The method of any one of claims 1 to 13, wherein the aromatic compound is derived from dehydration of saccharides.
15. The method of any one of claims 1 to 14, wherein the aromatic compound is a furanic compound.
16. The method of claim 15, wherein the furanic compound is 5-hydroxymethylfurfural or furfural, or a combination thereof.
17. The method of any one of claims 1 to 16, wherein the carbohydrate is glucose, fructose, xylose, or maltose, or any combinations thereof.
18. The method of any one of claims 1 to 17, wherein the metal-organic framework adsorbs at least 10-fold, at least 100-fold, or at least 1000-fold more aromatic compound than it adsorbs the carbohydrate.
19. The method of any one of claims 1 to 18, wherein the metal-organic framework adsorbs the aromatic compound without adsorbing the carbohydrate.
20. The method of any one of claims 1 to 19, wherein less than 5%, less than 4%, less than 3%, less than 2%, or less than 1% by weight of the carbohydrate in the solution adsorbs to the metal-organic framework.
21. The method of any one of claims 1 to 20, wherein the separating of the aromatic compound from the carbohydrate produces an output stream, wherein the output stream comprises the carbohydrate, and wherein the output stream has a concentration of less than 25 mM of the aromatic compound.
22. The method of any one of claims 1 to 21 wherein the metalorganic framework is incorporated into a membrane or into a chromatographic column for separations.

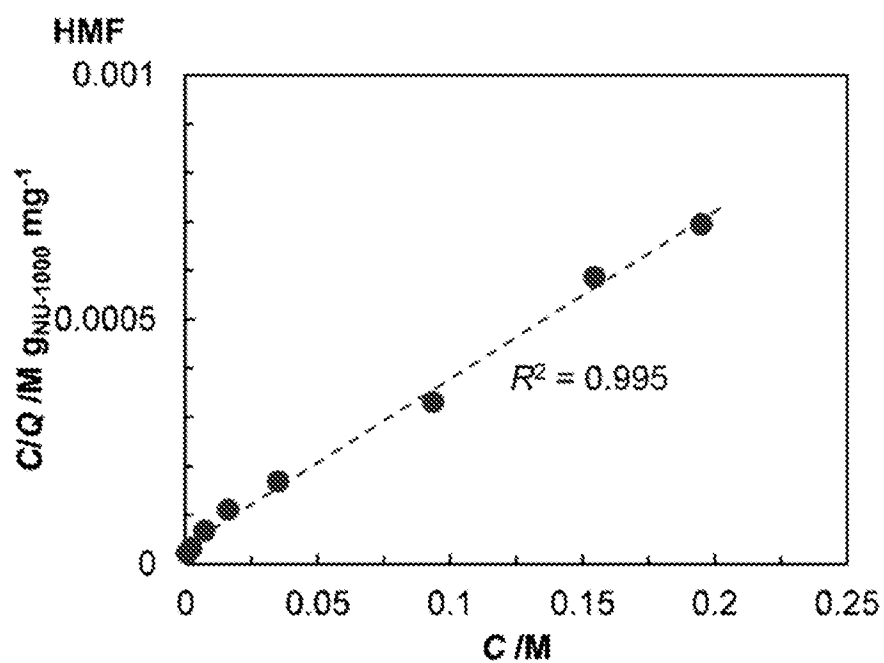
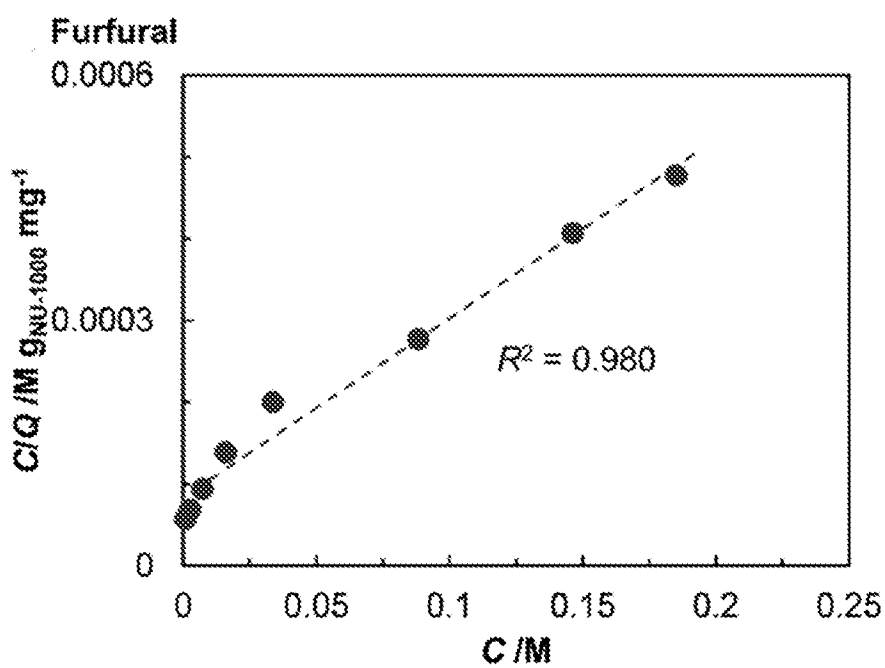
23. The method of any one of claims 1 to 22, further comprising recycling the metal-organic framework.
24. The method of claim 23, wherein the recycling of the metal-organic framework comprises:
contacting the metal-organic framework with water to remove the adsorbed aromatic compound.
25. A method, comprising:
contacting a carbohydrate with a catalyst or an enzyme to produce a fermentation mixture, wherein the fermentation mixture comprises an aromatic compound and at least a portion of the carbohydrate;
contacting a metal-organic framework with the fermentation mixture; and
separating the aromatic compound from the carbohydrate in the fermentation mixture by adsorbing at least a portion of the aromatic compound in the fermentation mixture onto the metal-organic framework.
26. The method of claim 25, further comprising:
isolating the carbohydrate separated from the aromatic compound; and
contacting the isolated carbohydrate with a catalyst or an enzyme.
27. The method of claim 25 or 26, wherein the carbohydrate is fructose, glucose, or xylose, or any combinations thereof.
28. The method of any one of claims 25 to 27, wherein the aromatic compound is a furanic compound.
29. The method of claim 28, wherein the furanic compound is 5-hydroxymethylfurfural or furfural, or a combination thereof.
30. The method of any one of claims 25 to 29, wherein the metal-organic framework is NU-800, NU-901, NU-1000, NU-1001, NU-1102, or NU-1100, or a combination thereof.
31. The method of any one of claims 25 to 30 wherein the metalorganic framework is incorporated into a membrane or into a chromatographic column for separations.

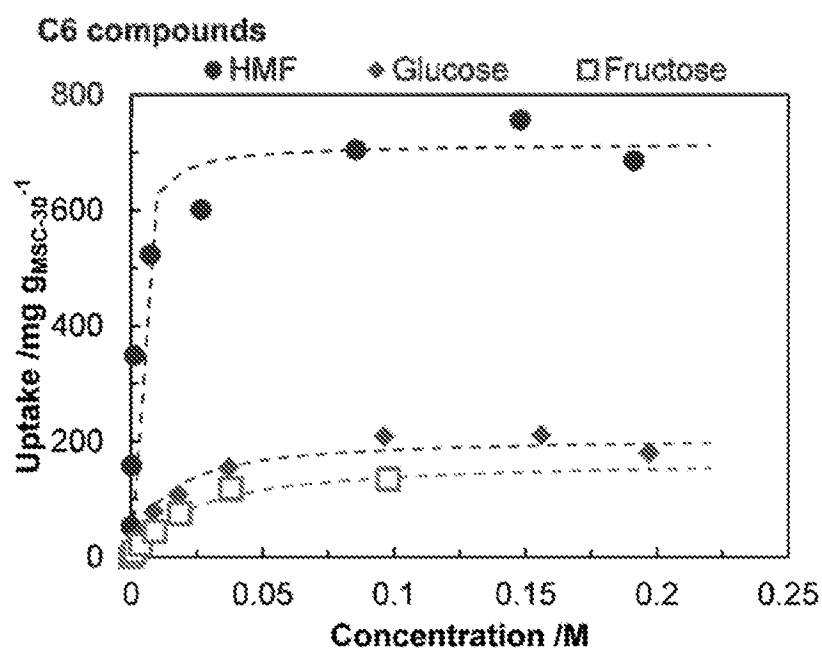
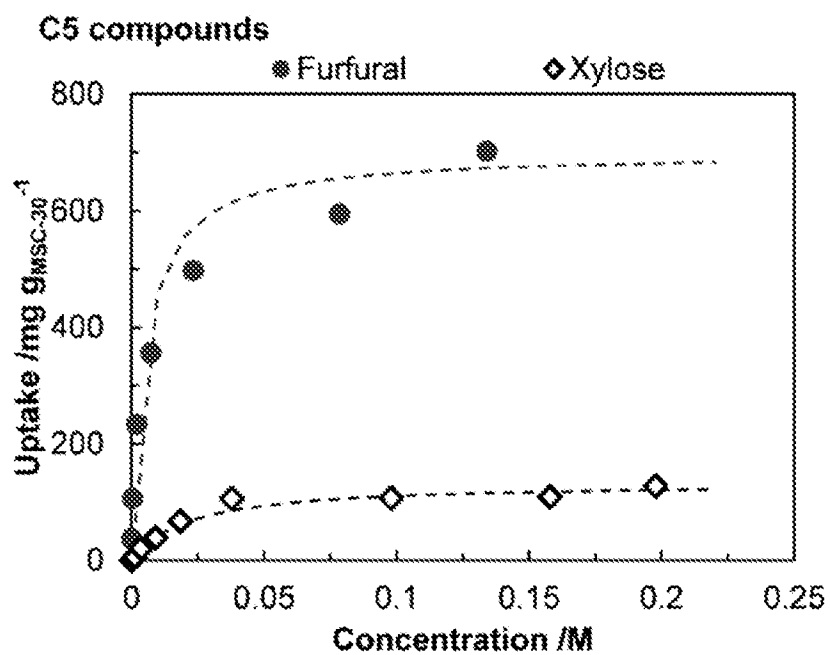
***FIG. 1***

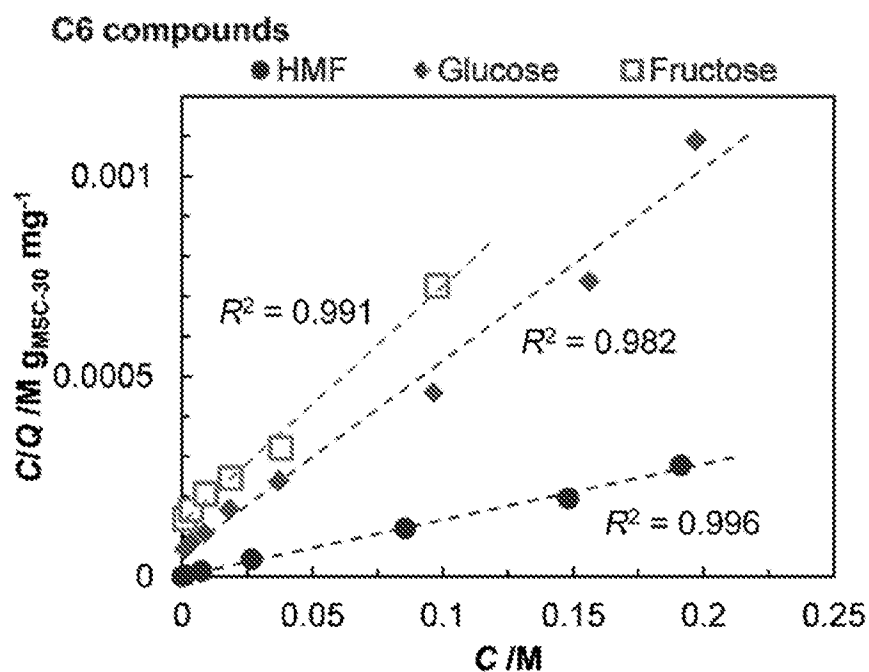
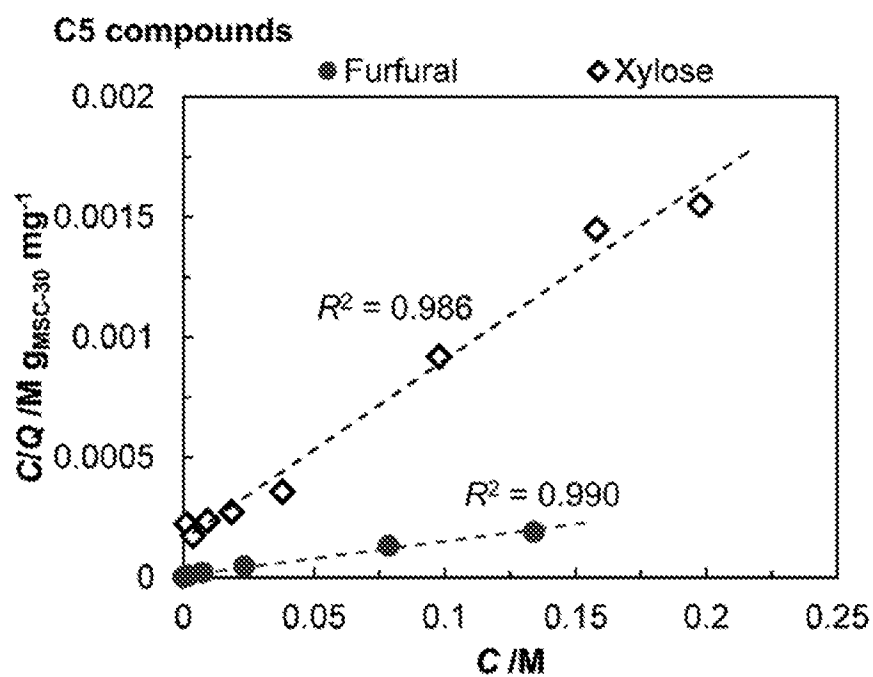
**FIG. 2A****FIG. 2B**

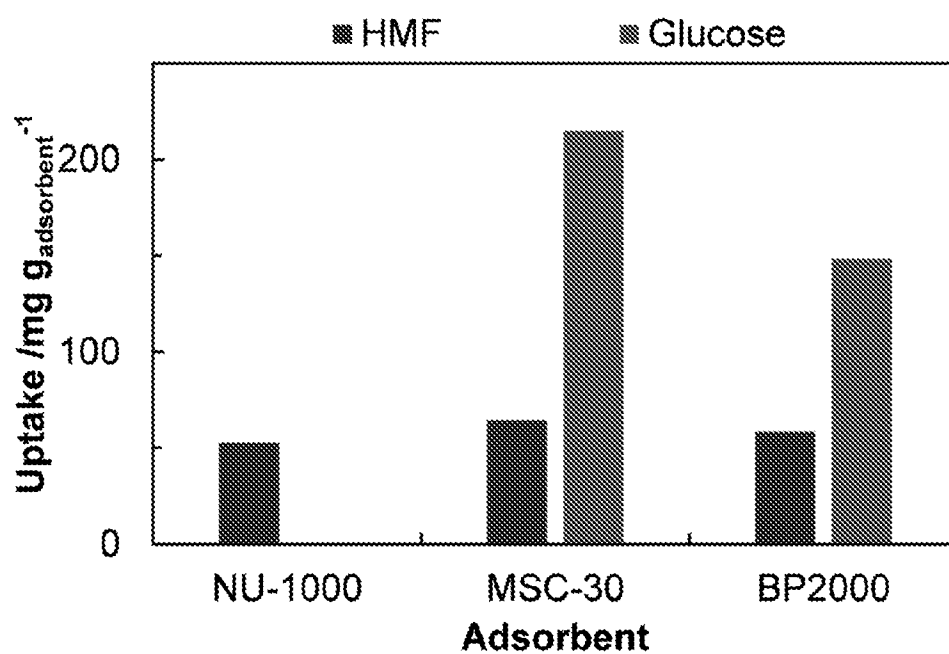
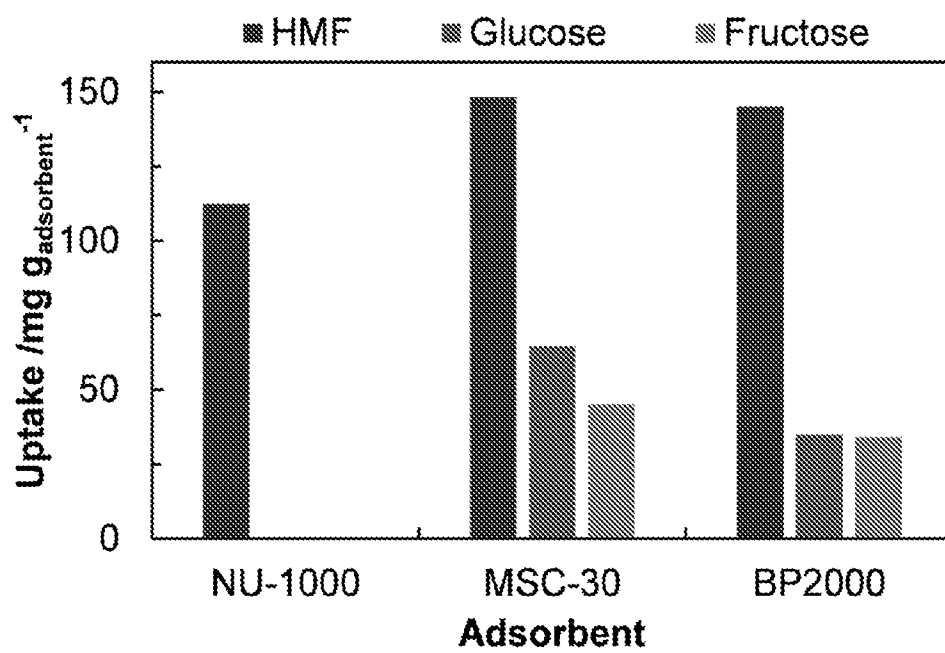
**FIG. 3A****FIG. 3B**

**FIG. 4A****FIG. 4B**

**FIG. 5A****FIG. 5B**

**FIG. 6A****FIG. 6B**

**FIG. 7A****FIG. 7B**

**FIG. 8****FIG. 9**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/037351

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - C07C 7/12; B01J 20/00; B01J 20/22; C07C 7/00; C12P 7/00; C12P 7/10 (2017.01)

CPC - B01J 20/226; B01J 20/00; B01J 20/22; B01J 20/223; C07C 7/00; C07C 7/12 (2017.05)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WEIL et al. Removal of Fermentation Inhibitors Formed during Pretreatment of Biomass by Polymeric Adsorbents. Industrial & Engineering Chemistry Research. Vol. 41, No. 24. 2002. [retrieved on 31 July 2017]. Retrieved from the Internet. <URL: https://pdfs.semanticscholar.org/4999/1165fa9c238dfa1e22e418df25b72695e8a2.pdf >. pp. 6132-6138. entire document	1-3, 25-27
Y	US 2016/0159713 A1 (THE REGENTS OF THE UNIVERSITY OF CALIFORNIA) 09 June 2016 (09.06.2016) entire document	1-3, 25-27
Y	US 5,508,183 A (SCOTT et al) 16 April 1996 (16.04.1996) entire document	26
P, X	YABUSHITA et al. Complete furanics-sugar separations with metal-organic framework NU-1000. Chemical Communications. Vol. 52, No. 79. 27 September 2016. [retrieved on 31 July 2017]. Retrieved from the Internet. <URL: https://www.researchgate.net/profile/Peng_Li64/publication/309067898_Complete_furanics-sugar_separations_with_metal-organic_framework_NU-1000/links/58068aa108ae5ad18816657b/C-omplete-furanics-sugar-separations-with-metal-organic-framework-NU-1000.pdf >. pp. 11791-11794. entire document	1-9, 25-27

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

31 July 2017

Date of mailing of the international search report

16 AUG 2017

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US2017/037351

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 10-24, 28-31
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.