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(54) Title: VARIATIONS ON PRINS-LIKE CHEMISTRY TO PRODUCE 2,5-DIMETHYLHEXADIENE FROM ISOBUTANOL

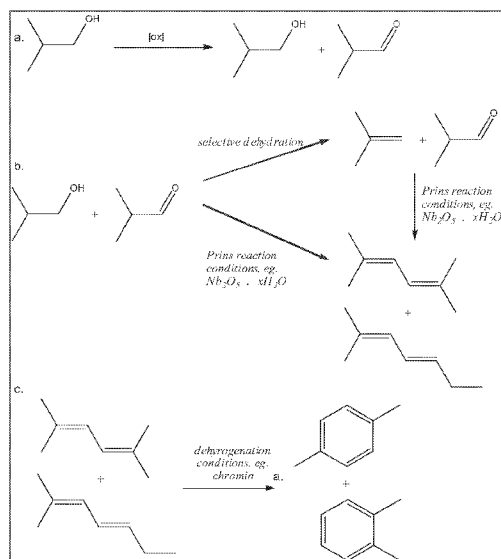


FIG. 3

(57) Abstract: The method of the present invention provides a high yield pathway to 2,5-dimethylhexadiene from renewable isobutanol, which enables economic production of renewable p-xylene (and subsequently, terephthalic acid, a key monomer in the production of PET) from isobutanol. In addition, the present invention provides methods for producing 2,5-dimethylhexadiene from a variety of feed stocks that can act as "equivalents" of isobutylene and/or isobutyraldehyde including isobutanol, isobutylene oxide, and isobutyl ethers and acetals. Catalysts employed in the present methods that produce 2,5-dimethylhexadiene can also catalyze alcohol dehydration, alcohol oxidation, epoxide rearrangement, and ether and acetal cleavage.



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Variations on Prins-like Chemistry to Produce 2,5-Dimethylhexadiene from Isobutanol

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 61/477,017, filed April 19, 2011, and U.S. Provisional Patent Application No. 61/478,607, filed April 25, 2011, each of which is incorporated herein by reference in its entirety.

Background

[0002] Aromatic compounds are conventionally produced from petroleum feedstocks in refineries by reacting mixtures of light hydrocarbons (C_1 - C_6) and naphthas over various catalysts at high heat and pressure. The mixture of light hydrocarbons available to a refinery is diverse, and provides a mixture of aromatic compounds suitable for use in fuel once the carcinogenic benzene is removed. Alternatively, the hydrocarbon feedstocks can be purified into single components to produce a purer aromatic product. For example, aromatization of pure isooctene selectively forms p-xylene over some catalysts. The state of the art for production of 2,5-dimethyl-2,4-hexadiene (which can subsequently be dehydrocyclized to form p-xylene) typically uses isobutylene (obtained primarily from gas and oil crackers) and isobutyraldehyde (obtained by hydroformylation of propylene with syngas) as feed stocks (see Figure 1).

[0003] Low molecular weight hydrocarbons can also be obtained by dehydration of low molecular weight alcohols produced via fermentation of biomass. For example, isobutanol can be dehydrated to provide isobutylene, a versatile 4 carbon synthon, which can then be dimerized under appropriate conditions to form 2,5-dimethylhexadiene.

[0004] However, conversion of low molecular weight alcohols (*e.g.*, isobutanol) to 2,5-dimethylhexadiene may be difficult. For example, current methods for converting isobutylene (*e.g.*, derived from isobutanol) to 2,5-dimethylhexadiene generally require high temperatures and oxygen co-feeds, which limit yields under typical conditions due to over oxidation of feedstock to carbon dioxide. Subsequent conversion of 2,5-dimethylhexadiene to p-xylene is typically a high yield, clean reaction over chromia (*e.g.*, U.S. Pat. Appl. No. 12/986,918, filed on Jan. 7, 2011, which is incorporated herein by reference in its entirety for all purposes) and other metal oxide catalysts. The reaction produces only p-xylene in the aromatic product and does so in high yield.

[0005] Further, using diisobutylene as a feedstock for the production of aromatic compounds (*e.g.*, xylenes) generally results in some cracking (which affects yield) and the production of less desirable xylene isomers (*e.g.*, *o*- and *m*- xylene) due to the presence of other and unavoidable isooctene isomers in the product stream from an isobutylene dimerization process.

[0006] The conversion of isobutylene and isobutyraldehyde over niobic oxide catalysts under acidic conditions to 2,5-dimethyl-2,4-hexadiene is known. Under similar conditions, *t*-butanol can be used in place of isobutylene since these conditions promote alcohol dehydration as well. For example, US 4,684,758 employs catalysts which may include niobic acid to produce 2,5-dimethyl-2,4-hexadiene from blends ranging from 1-10:1 isobutylene/*t*-butanol to isobutyraldehyde. However, this process requires a discrete isobutyraldehyde feed for coupling with the isobutylene and/or *t*-butanol feed component(s). In addition, the isobutyraldehyde feed is conventionally prepared from other starting materials, such as propylene and formaldehyde, so the overall process entails multiple processing steps from multiple, different raw materials.

Summary

[0007] The present disclosure provides various methods for producing isobutylene (or isobutylene equivalents) and isobutyraldehyde (or isobutyraldehyde equivalents) from isobutanol (which may be renewable isobutanol), either in separate reactions or *in situ* with an olefin-aldehyde condensation reaction to form 2,5-dimethylhexadiene and/or 2-methyl-2,4-heptadiene (see, *e.g.*, Figure 2). For example, isobutanol can be used as an isobutylene equivalent in the reaction and isobutylene oxide may be used as an isobutyraldehyde equivalent. These synthons can then be coupled to form the desired dienes, which can then be cyclized to form *o*- and *p*-xylene. State of the art conversion of isobutanol to *p*-xylene generally requires very high temperatures which may result in yield losses to coke and low value hydrocarbons due to feedstock cracking. In one embodiment, the present disclosure describes a route to *p*-xylene from isobutanol that minimizes yield losses and provides a higher overall yield than current state of the art. In some embodiments, the present methods may provide yields of *p*-xylene of at least 80%, at least 85%, at least 90%, at least 95% or greater.

[0008] The present invention advantageously provides for the direct use of isobutanol (including renewable isobutanol) as the sole input chemical. For example, a stream of isobutanol can be reacted under appropriate conditions to provide a product stream containing a desired fraction of isobutyraldehyde, e.g. via careful selection of oxidation catalysts and process conditions, and the partially oxidized product stream can then be reacted directly, eliminating the need for multiple feed stocks if so desired. Furthermore, the present invention provides for the conversion of isobutanol to isobutyraldehyde in the presence of water with slight modifications (e.g., excess water removal, acid catalysis, temperature, etc.). In addition, the presently described methods can produce *para*-xylene or *ortho*-xylene, amongst other products, as renewable high-value commodity chemicals in a final cyclization step.

[0009] The present invention includes a high yield pathway to 2,5-dimethylhexadiene from isobutanol. In some embodiments oxygen (or another inexpensive oxidant) may be employed, and because reaction temperatures are generally much milder, yield losses due to overoxidation are minimized. Accordingly, the relatively high yield enables economic production of renewable p-xylene (and subsequently, terephthalic acid, a key monomer in the production of PET) from biomass-derived isobutanol. Furthermore, the chemistry described herein is very flexible. For example, 2,5-dimethylhexadiene can be produced from a variety of feed stocks that can act as “equivalents” of isobutylene and/or isobutyraldehyde including isobutanol, isobutylene oxide, isobutyl isobutyrate, and isobutyl ethers and acetals, each of which may be derived from biomass-derived isobutanol.

[0010] Furthermore, certain catalysts described herein that can effect olefin-aldehyde coupling (or coupling of olefin and aldehyde equivalents) to produce 2,5-dimethylhexadiene can also catalyze alcohol dehydration, alcohol oxidation, esters to aldehydes and/or olefins, epoxide rearrangement, and ether and acetal cleavage (e.g., formation of coupling partners prior to a coupling reaction, or production of coupling partners *in situ*).

[0011] As described above, in conventional petrochemical refineries, isobutanol is typically obtained by reduction of isobutyraldehyde. However, there is no commercial process to reoxidize isobutanol back to isobutyraldehyde. Accordingly, any chemistry that favors starting with a more oxidized component – in this case, an aldehyde – typically starts with the aldehyde, not the alcohol. The chemistry and methods described herein use a single feedstock,

isobutanol (which may be renewable), as a source of both isobutylene and isobutyraldehyde, and in certain cases both components may be produced in the same reactor.

[00012] These and other advantages will be described below with reference to the various embodiments.

Brief Description of the Drawings

[00013] FIG. 1 shows a conventional aldehyde/olefin condensation reaction.

[00014] FIG. 2 shows an exemplary synthesis of 2,5,-dimethyl-2,4-hexadiene from isobutanol.

[00015] FIG. 3 shows exemplary routes for producing xylenes.

[00016] FIG. 4 shows exemplary routes for producing 2,5-dimethyl-2,4-hexadiene.

[00017] FIG. 5 shows exemplary routes for producing 2,5-dimethyl-2,4-hexadiene, 2-methyl-2,4-heptadiene and related alcohols.

[00018] FIG. 6 shows an exemplary route for conversion of isobutanol to isobutylene and isobutylene oxide and production of 2,5-dimethyl-2,4-hexadiene therefrom.

[00019] FIG. 7 shows an exemplary method for producing 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene.

[00020] FIG. 8 shows exemplary isobutyraldehyde and isobutanol/isobutylene equivalents.

[00021] FIG. 9 shows an exemplary method of producing 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene.

[00022] FIG. 10 shows an another exemplary method of producing 2,5-dimethyl-2,4-hexadiene.

[00023] FIG. 11 shows the GC/FID trace of the effluent resulting from 4 parts isobutanol and 1 part isobutyraldehyde passed over niobic acid on graphite, with molecular structures of the compounds corresponding to the relevant peaks, as set out in Example 9.

[00024] FIG. 12 shows the GC/FID trace of the effluent resulting from 2,5-dimethyl-2,4-hexadiene passed over chromia/alumina, with molecular structures of the compounds corresponding to the relevant peaks, as set out in Example 11.

Detailed Description

[00025] All documents cited herein are incorporated by reference in their entirety for all purposes to the same extent as if each individual document was specifically and individually indicated to be incorporated by reference.

[00026] "Renewably-based" or "renewable" as used herein denote that the carbon content of the renewable alcohol (and olefin, di-olefin, *etc.*, or subsequent products prepared from renewable alcohols, olefins, di-olefins, *etc.* as described herein), is from a "new carbon" source as measured by ASTM test method D 6866-05, "Determining the Biobased Content of Natural Range Materials Using Radiocarbon and Isotope Ratio Mass Spectrometry Analysis", incorporated herein by reference in its entirety. This test method measures the $^{14}\text{C}/^{12}\text{C}$ isotope ratio in a sample and compares it to the $^{14}\text{C}/^{12}\text{C}$ isotope ratio in a standard 100% biobased material to give percent biobased content of the sample. "Biobased materials" are organic materials in which the carbon comes from recently (on a human time scale) fixated CO_2 present in the atmosphere using sunlight energy (photosynthesis). On land, this CO_2 is captured or fixated by plant life (*e.g.*, agricultural crops or forestry materials). In the oceans, the CO_2 is captured or fixated by photosynthesizing bacteria or phytoplankton. For example, a biobased material has a $^{14}\text{C}/^{12}\text{C}$ isotope ratio greater than 0. Contrarily, a fossil-based material has a $^{14}\text{C}/^{12}\text{C}$ isotope ratio of about 0. The term "renewable" with regard to compounds such as alcohols or hydrocarbons (olefins, di-olefins, polymers, *etc.*) also refers to compounds prepared from biomass using thermochemical methods (*e.g.*, Fischer-Tropsch catalysts), biocatalysts (*e.g.*, fermentation), or other processes, for example as described herein.

[00027] A small amount of the carbon atoms of the carbon dioxide in the atmosphere is the radioactive isotope ^{14}C . This ^{14}C carbon dioxide is created when atmospheric nitrogen is struck by a cosmic ray generated neutron, causing the nitrogen to lose a proton and form carbon of atomic mass 14 (^{14}C), which is then immediately oxidized to carbon dioxide. A small but measurable fraction of atmospheric carbon is present in the form of $^{14}\text{CO}_2$. Atmospheric carbon dioxide is processed by green plants to make organic molecules during the process known as

photosynthesis. Virtually all forms of life on Earth depend on this green plant production of organic molecules to produce the chemical energy that facilitates growth and reproduction. Therefore, the ^{14}C that forms in the atmosphere eventually becomes part of all life forms and their biological products, enriching biomass and organisms which feed on biomass with ^{14}C . In contrast, carbon from fossil fuels does not have the signature ^{14}C : ^{12}C ratio of renewable organic molecules derived from atmospheric carbon dioxide. Furthermore, renewable organic molecules that biodegrade to CO_2 do not contribute to global warming as there is no net increase of carbon emitted to the atmosphere.

[00028] Assessment of the renewably based carbon content of a material can be performed through standard test methods, *e.g.* using radiocarbon and isotope ratio mass spectrometry analysis. ASTM International (formally known as the American Society for Testing and Materials) has established a standard method for assessing the biobased content of materials. The ASTM method is designated ASTM-D6866.

[00029] The application of ASTM-D6866 to derive "biobased content" is built on the same concepts as radiocarbon dating, but without use of the age equations. The analysis is performed by deriving a ratio of the amount of radiocarbon (^{14}C) in an unknown sample compared to that of a modern reference standard. This ratio is reported as a percentage with the units "pMC" (percent modern carbon). If the material being analyzed is a mixture of present day radiocarbon and fossil carbon (containing very low levels of radiocarbon), then the pMC value obtained correlates directly to the amount of biomass material present in the sample.

[00030] Throughout the present specification, reference to alcohols, olefins, di-olefins, *etc.*, and higher molecular weight materials (*e.g.*, isooctene/isooctane, polymers, copolymers, *etc.*) made from such compounds is synonymous with "renewable" alcohols, "renewable" olefins, "renewable" di-olefins, *etc.*, and "renewable" materials (*e.g.*, "renewable" isooctene/isooctane, "renewable" polymers, "renewable" copolymers, *etc.*) unless otherwise indicated. Unless otherwise specified, all such chemicals produced by the integrated processes described herein are renewable unless explicitly stated otherwise.

[00031] Throughout the present specification, the terms "olefin" and "alkene" are used interchangeably to refer to a hydrocarbon having at least one carbon-carbon double bond. Alkenes or olefins having two carbon-carbon double bonds can be referred to as dienes, and if

the two carbon-carbon double bonds are adjacent in the molecule (*e.g.*, four adjacent sp^2 carbon atoms), the molecule can be termed a conjugated diene.

[00032] The renewable alcohols, olefins, di-olefins, polymers, aliphatic and aromatic organic compounds, *etc.* of the present invention have pMC values of at least about 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, inclusive of all values and subranges therebetween.

[00033] Throughout the present specification, the term “about” may be used in conjunction with numerical values and/or ranges. The term “about” is understood to mean those values near to a recited value. For example, “about 40 [units]” may mean within $\pm 25\%$ of 40 (*e.g.*, from 30 to 50), within $\pm 20\%$, $\pm 15\%$, $\pm 10\%$, $\pm 9\%$, $\pm 8\%$, $\pm 7\%$, $\pm 6\%$, $\pm 5\%$, $\pm 4\%$, $\pm 3\%$, $\pm 2\%$, $\pm 1\%$, less than $\pm 1\%$, or any other value or range of values therein or therebelow. Furthermore, the phrases “less than about [a value]” or “greater than about [a value]” should be understood in view of the definition of the term “about” provided herein.

[00034] Throughout the present specification, numerical ranges are provided for certain quantities. It is to be understood that these ranges comprise all subranges therein. Thus, the range “from 50 to 80” includes all possible ranges therein (*e.g.*, 51-79, 52-78, 53-77, 54-76, 55-75, 60-70, *etc.*). Furthermore, all values within a given range may be an endpoint for the range encompassed thereby (*e.g.*, the range 50-80 includes the ranges with endpoints such as 55-80, 50-75, *etc.*).

[00035] Throughout the present specification, the words “a” or “an” are understood to mean “one or more” unless explicitly stated otherwise. Further, the words “a” or “an” and the phrase “one or more” may be used interchangeably.

[00036] In one embodiment of the present invention, isobutanol, which may be renewable, can be partially oxidized or dehydrogenated by a suitable catalyst to isobutyraldehyde (see, *e.g.*, Figure 3a). Suitable oxidation catalysts, oxidants and methods to effect selective oxidation of isobutanol to isobutyraldehyde are known in the art. A product stream can thus be obtained having a specific ratio of isobutanol to isobutyraldehyde, as desired. For example, the ratio of isobutyraldehyde to isobutanol may range from 1:100 to 100:1, 1:10 to 10:1, 1:5 to 5:1, 1:4 to 4:1, 1:3 to 3:1, 1:2 to 2:1, 1:1 (or any other ratio or range of ratios therein). A particular ratio may be selected as described herein depending on a desired product and/or reaction conditions.

[00037] The partially oxidized mixture comprising isobutyraldehyde and isobutanol can be then passed over a dehydration catalyst to yield a mixture of isobutylene and isobutyraldehyde (see Figure 3b). Typical dehydration catalysts that convert alcohols such as ethanol and isobutanol into ethylene and butene(s) include various acid treated and untreated alumina (*e.g.*, γ -alumina) and silica catalysts and clays including zeolites (*e.g.*, β -type zeolites, ZSM-5 or Y-type zeolites, fluoride-treated β -zeolite catalysts, fluoride-treated clay catalysts, etc.), sulfonic acid resins (*e.g.*, sulfonated styrenic resins such as Amberlyst® 15), strong acids such as phosphoric acid and sulfuric acid, Lewis acids such boron trifluoride and aluminum trichloride, and many different types of metal salts including metal oxides (*e.g.*, zirconium oxide or titanium dioxide) and metal chlorides (*e.g.*, Latshaw BE, Dehydration of Isobutanol to Isobutylene in a Slurry Reactor, Department of Energy Topical Report, February 1994).

[00038] The resultant mixture of isobutanol/isobutylene and isobutyraldehyde can be reacted over niobic acid (*e.g.*, $\text{Nb}_x\text{O}_y \cdot n\text{H}_2\text{O}$), (either “as is,” or primed with sulfuric or phosphoric acid or any other suitable mineral acid) on a support (which may include calcined transition or metalloid sulfates, or graphite, or any other suitable support) or a zeolite doped with a main-group or transition metal, or other suitable catalysts, at, *e.g.*, 200-400 °C. In the absence of excess water and acid, the reaction yields 2,5-dimethyl-2,4-hexadiene and/or 2-methyl-2,4-heptadiene (*e.g.*, if 1-butene is present) with high selectivity. Excess isobutanol/isobutylene can be recycled to one of the previous steps when isobutyraldehyde is held as the limiting reagent. Alternatively, excess isobutyraldehyde can be removed and utilized as a renewable component in other chemical routes described herein (see Figure 3b).

[00039] If coupling is performed in the presence of water and acid, more than 2 equivalents of isobutyraldehyde can be employed to favor acetal formation. The formed acetal can be further reacted over, *e.g.*, calcium phosphate or another suitable catalyst to yield 2,5-dimethyl-2,4-hexadiene (see Figure 4). It will be appreciated that more than one isomeric acetal may be possible. However, each isomeric acetal can be cleaved to form 2,5-dimethyl-2,4-hexadiene in a highly selective manner. Furthermore, reaction conditions can be selected to minimize formation of, or isomerization to, undesired products (*e.g.*, by varying temperature, acid catalyst identity and amount, mole ratios of feed components and or water, reaction time,

etc.). This is highly advantageous since subsequent cyclization of the preferred 2,5-dimethyl-2,4-hexadiene isomer can provide p-xylene in a highly selective manner.

[00040] In addition, while in certain embodiments, the present processes may be employed to produce 2,5,-dimethyl-2,4-hexadiene, and subsequently convert 2,5,-dimethyl-2,4-hexadiene to p-xylene, other isomers may also be produced. For example, in some embodiments, the present methods may be employed to produce other isomers of dimethylhexadiene, including 2,4-dimethyl-2,4-hexadiene, which may be subsequently dehydrocyclized to form m-xylene, 2,3-dimethyl-2,4-hexadiene, which may be subsequently dehydrocyclized to form o-xylene.

[00041] In other embodiments, the present processes may be employed to form other dimethylhexadiene isomers, including 2,5,-dimethyl-1,4-hexadiene, 2,4,-dimethyl-1,4-hexadiene, and 2,3,-dimethyl-1,4-hexadiene, each of which may be dehydrocyclized to form the corresponding xylene isomer. Furthermore, dimethylhexenes may also be produced by the present methods (e.g., 2,5-dimethyl-1-hexene, 2,5-dimethyl-2-hexene, 2,5-dimethyl-3-hexene, 2,5-dimethyl-4-hexene, 2,5-dimethyl-5-hexene, 2,4-dimethyl-1-hexene, 2,4-dimethyl-2-hexene, 2,3-dimethyl-3-hexene, 2,4-dimethyl-4-hexene, 2,4-dimethyl-5-hexene; 2,3-dimethyl-1-hexene, 2,3-dimethyl-2-hexene, 2,3-dimethyl-3-hexene, 2,3-dimethyl-4-hexene, 2,3-dimethyl-5-hexene).

[00042] In other embodiments, dimethylhexanes may also be produced (e.g., 2,5-dimethylhexane, 2,4-dimethylhexane, 2,3-dimethylhexane). These saturated compounds may be used as a transportation fuel or fuel additive, e.g., gasoline or a gasoline blendstock. Partially unsaturated (e.g., dimethylhexenes) compounds produced as described herein may find utility as chemical building blocks, may be employed in further chemical transformations, or may be hydrogenated (e.g., dimethylhexenes) to produce a material suitable for use as a transportation fuel or fuel additive, e.g., gasoline or a gasoline blendstock.

[00043] Furthermore, the 2,5-dimethyl-2,4-hexadiene and/or 2-methyl-2,4-heptadiene produced via the methods described herein can then be reacted over a dehydrogenation catalyst, for example Houdry-type chromia catalyst at, e.g., about 350- 550 °C to yield *para*-xylene and *ortho*-xylene, respectively, with high selectivity (see Figure 3c).

[00044] In another embodiment, controlled oxidation of isobutanol (which may be renewable isobutanol) to isobutyraldehyde is provided by coupling said isobutyraldehyde (which

may be produced as described herein from isobutanol) with isobutylene, without further oxidation to isobutyric acid. For example, isobutanol may be added directly over niobic acid (or any other suitable catalyst(s)) with an excess of isobutylene (which may be synthesized from isobutanol as described herein, and which may be renewable) in the presence of an oxidant (*e.g.*, O₂, peroxides, etc.; see Figure 5). As the isobutyraldehyde is formed it can directly react with excess isobutylene to yield the products mentioned above (*e.g.*, 2,5-dimethyl-2,4-hexadiene and/or 2-methyl-2,4-heptadiene). Potential side products such as methacrolein (*e.g.*, from oxidation of isobutylene), diisobutylene (*e.g.*, from dimerization of isobutylene) are valuable chemicals in their own right, and may be recovered.

[00045] In another embodiment, isobutylene oxide and isobutylene (both of which may be produced from isobutanol [which may be renewable] as described herein; see, *e.g.*, Figure 6) can be fed in tandem over niobic acid (or any other suitable catalyst(s)) and by regioselective epoxide ring-opening, the desired hexadiene backbone is created through dehydration, yielding 2,5-dimethyl-2,4-hexadiene (see Figure 7). Alternatively, isobutanol may be directly fed over a niobic acid catalyst (or any other suitable catalyst(s)) in the presence of oxygen. Both isobutylene and isobutyraldehyde (or isobutylene oxide) may thus be formed *in situ*, and then converted to 2,5-dimethylhexadiene. It may also be possible to use isobutylene oxide (in the absence of an oxygen feed stream) as the sole feed stock for the reaction to produce a similar results (*e.g.*, a similar product distribution with similar selectivity).

[00046] Renewable isobutylene oxide can be prepared by a variety of methods, including oxidation with cumene hydroperoxide (*e.g.*, as described in EP 1382602 or U.S. 7,273,941) or oxidation with hydrogen peroxide. For example, isobutylene oxide may be derived from isobutylene by oxidation over a suitable catalyst typically with a “sacrificial” hydroperoxide reactant. Exemplary sacrificial catalysts may include cumene hydroperoxide (*e.g.*, as described in EP 1382602 or U.S. 7,273,941) or tert-butyl hydroperoxide, which may provide valuable co-products after acting as an oxygen source for the formation of isobutylene oxide as described. Such valuable byproducts may be recovered. Alternatively, other oxidant may be employed (*e.g.*, other peroxides) including hydrogen peroxide (*e.g.*, in the presence of a titanium or vanadium silicalite catalyst as described in U.S. 7,273,941 or WO 97/47613). Other methods for oxidizing isobutylene to isobutylene oxide known in the art can also be used.

[00047] In another embodiment, isobutyl isobutyrate is used as an isobutyraldehyde equivalent since over metal oxide and Lewis acid catalysts, symmetrical esters are converted into two equivalents of corresponding aldehyde (*e.g.*, U.S. 4,320,229). Isobutyl isobutyrate can be produced from isobutyraldehyde using Lewis acid catalysts, (*e.g.*, the Tishchenko reaction), or isobutanol and isobutyric acid through conventional esterification chemistry. Isobutyl isobutyrate may be formed from isobutyraldehyde during the condensation of isobutyraldehyde with an isobutylene equivalent and may interconvert back to isobutyraldehyde *in situ* or removed and utilized as a renewable component in other chemical routes. Isobutyl isobutyrate may also act as an isobutylene equivalent since it may be converted into isobutylene and isobutyric acid over acidic catalysts or hydrolyzed to isobutanol and isobutyric acid.

[00048] Another unique feature of the invention is that isobutanol can be treated to produce single molecule feed stocks for the condensation reaction that contain stoichiometric equivalents of isobutylene and isobutyraldehyde (*e.g.*, enol ethers and acetals). Accordingly, in yet another embodiment, isobutanol and/or isobutene and isobutyraldehyde equivalents may be introduced to the reactor as a feedstock comprising a single compound. For example, if a one to one ratio of isobutanol/isobutene to isobutyraldehyde reactants is desired, the enol ether 1-(2-methyl-1-propoxy)-2-methylprop-1-ene can be the sole reactant in the reaction (see Figure 8). Acid catalyzed cleavage of the enol ether to form isobutylene (or isobutanol, that may be dehydrated *in situ* to form isobutylene as described herein) and isobutyraldehyde can occur in a first reaction, then the isobutylene and isobutyraldehyde can be condensed to form 2,5-dimethylhexadiene (*e.g.*, as described herein). If a two to one ratio of isobutanol/isobutene to isobutyraldehyde is desired, the diisobutyl acetal of isobutyraldehyde can be the sole reactant in the reaction (see Figure 8).

[00049] As described for the enol ether decomposition reaction above, the acetal may be cleaved *in situ* to form two equivalents of isobutene (or isobutanol, which may be dehydrated *in situ* to isobutene) and one equivalent of isobutyraldehyde, which may then be condensed to form 2,5-dimethylhexadiene. Excess isobutylene can be recovered for further use (*e.g.*, to form additional feedstock for ether synthesis). Both the enol ether and acetal described above may be produced from isobutanol and isobutyraldehyde in the presence of acid catalysts, with a suitable mechanism or apparatus for removing water produced in the reaction (*e.g.*, a Dean-Stark

apparatus; see, *e.g.*, Figure 9), or may be produced from a single feed consisting solely of isobutanol (see, *e.g.*, Figure 10).

[00050] Niobic acid may be used as the catalyst in the above described processes because it is known to promote conversion of isobutylene and isobutyraldehyde to 2,5-dimethylhexadiene in high yields. However, the present methods are not so limited, and other metal oxide and/or acid catalyst may be employed to perform the reactions described herein. In one embodiment, the niobic acid may be mixed with metal sulfates. In another embodiment, the metal oxide catalyst has a composition with the general formula X_aO_b wherein X is a metal or metalloid element and a and b are 0 to 6, with the proviso that a and b are not both 0 at the same time. In yet another embodiment the metal oxide catalyst contains multiple metal or metalloid elements and a corresponding amount of oxygen to balance the oxidation state of the metal/metalloid(s). In yet another embodiment, other non-metallic elements such as halogens, sulfur, nitrogen, and phosphorus may replace oxygen in the metal/metalloid oxide compositions described above. Catalysts comprised of primarily silicon and/or aluminum oxides (*e.g.*, zeolites, various alumina phases) as is or doped with metal or metalloid elements may also be used. Examples of catalysts that are known to catalyze the chemistry described herein include cation exchangers, metal halides, metal salts, phosphoric acid- and boric acid-derived materials, and 15 % sulfuric acid. Further heterogeneous catalysts include tungsten oxide with and without supports (such as titania, silica, alumina, niobia, and zirconia), chromia with alumina support, silver-oxide with and without silica support, sulfur trioxide on zirconia ("Olefin-aldehyde condensation reaction on solid acids" Yamaguchi, T.; Nishimichi, C. *Cat. Today*, **1993**, *16*, 555-562.), pentasil-type catalysts with at least one metal/metalloid selected from boron, gallium, iron and aluminum, and the H-form of ZSM-5. The heterogeneous catalysts may be treated with concentrated or dilute acid solutions, often sulfuric or orthophosphoric acids.

[00051] If isobutanol is used as the sole feedstock, then oxygen is typically used as an oxidant when possible, but other inexpensive sacrificial oxidants such as hydrogen peroxide may also be used.

[00052] Advantageously, isobutanol is the sole feed stock for the various processes and methods described herein. Furthermore, the present processes which comprise more than one chemical transformation (*e.g.*, conversion of isobutanol to isobutylene and to isobutyraldehyde)

may be comprised of a single and unique reaction zone where several different chemical steps occur simultaneously. As discussed above, the acidic metal oxide catalysts described herein (*e.g.*, niobic acid, etc.) can be used to catalyze multiple types of chemical reactions. For example, part of an isobutanol feed can be dehydrated to form isobutylene, while part of the same isobutanol feed stream can be oxidized to isobutyraldehyde, and then the isobutylene and isobutyraldehyde can be condensed to form, *e.g.*, 2,5-dimethylhexadiene. Another example is the decomposition of the enol ether 1-(2-methyl-1-propoxy)-2-methylprop-1-ene to form isobutylene and isobutyraldehyde as described herein can occur in a first reaction, then the isobutylene and isobutyraldehyde can be condensed. Yet another example is the decomposition of the acetal discussed herein to form two equivalents of isobutylene and one of isobutyraldehyde as described herein can occur in a first reaction, then the isobutylene and isobutyraldehyde can be condensed.

[00053] The present methods may also be conducted in more than one reaction zone to form the condensation reactants. However, the first or upstream processes in a multi-reaction zone arrangement can be operated in a desired, specific way to produce the appropriate type and stoichiometry of feedstocks for a subsequent condensation reaction (*e.g.*, to provide a desired ratio of isobutyraldehyde to isobutylene). For example, only a certain fraction of isobutanol may be oxidized to isobutyraldehyde to create a mixture of isobutanol and isobutyraldehyde that produces a desired product in a subsequent dehydration/condensation reaction.

[00054] The chemistry described herein may be performed neat with only the reactants being fed to the reactor or reactor zones. Alternatively, diluents may be used to aid in such functions such as controlling concentration, acting as a heat sink/carrier, moderating/eliminating unwanted side reactions, facilitating downstream processing, etc. Examples of diluents include inert gases or fluids such as nitrogen, argon, carbon dioxide, steam, methane, paraffins, acetonitrile, 1,4-dioxane, diethyl ether, tetrahydrofuran, etc. Typical temperatures for the reactions described above are between 100 – 400 °C. These reactions can be performed in the gas, liquid, or supercritical phase at pressures between 1 – 100 atm. Typical weight hour space velocities are between 0.1 – 100 hr⁻¹. The reaction may be performed strictly in the absence of oxygen if oxidation of a feedstock is not a requirement of the reaction. Alternatively a reducing environment may favor desired product formation and minimize side product formation. In these

cases a reducing diluent such as hydrogen or carbon monoxide may be used alone or in combination with other diluents.

[00055] In certain embodiments, the present reactions may be conducted at a pressures of from about 70 to about 570 psi; a temperature of from about 210 to about 315 °C, and a WHSV of from about 1-10. In certain embodiments, the reaction is conducted with a feed comprising minimal diluents, e.g., less than about 25%, less than about 20%, less than about 15%, less than about 10%, less than about 5%, less than about 4%, less than about 3%, less than about 2%, or less than about 1% (by weight, by volume, or by mol %). In some embodiments, the oxygen content of the feed is minimized (e.g., less than about 5%, less than about 4%, less than about 3%, less than about 2%, less than about 1%, less than about 0.5%, less than about 0.1% [by weight, by volume, or by mol %]). In some embodiments, the water content of the feed minimized (e.g., less than about 5%, less than about 4%, less than about 3%, less than about 2%, less than about 1%, less than about 0.5%, less than about 0.1% [by weight, by volume, or by mol %]).

[00056] The present methods will be further illustrated by the following non-limiting examples:

Examples

[00057] **Example 1.** Dry renewable isobutanol is fed over a copper chromite catalyst (activated over nitrogen according to the manufacturer) at 320 °C and the WHSV of the addition slowed to the rate where the proportion of isobutyraldehyde required is achieved upon testing the effluent by GC/FID and ¹H NMR. Proportions that would be potentially useful are 33% isobutyraldehyde/67% isobutanol, 50% isobutyraldehyde/50% isobutanol, 67% isobutyraldehyde/33% isobutanol, and above 99% isobutyraldehyde. During the reaction the material is tested often to monitor for excessive CO₂, propane, and/or isobutyric acid formation.

[00058] **Example 2.** The light phase azeotrope distilled from a mixture of water and renewable isobutanol is vaporized at 185 °C and diluted to 5% with helium. The stream is passed over a copper oxide catalyst on a particulate inert support. The oxidation proceeds stoichiometrically for 1 to 2 hours, then the reaction changes to endothermic as the CuO is exhausted and proceeds by anaerobic catalytic dehydrogenation over Cu⁰, reaching a final

temperature of 325 °C. Renewable isobutyraldehyde is formed with 95 % conversion and 98 % selectivity.

[00059] **Example 3.** One of the isobutanol/isobutyraldehyde mixtures from example 1 is passed over a mild dehydrogenation catalyst, selectively transforming the remaining isobutanol to isobutylene with 99% conversion and 96 % selectivity, which may then be further used according to the methods taught in US Patent 4,684,758 where isobutylene and isobutyraldehyde are reacted over a niobic acid catalyst to produce 2,5-dimethylhexadiene in 90 % yield.

[00060] **Example 4.** One of the isobutanol/isobutyraldehyde mixtures from example 1 is fed through a flow reactor charged with niobic acid catalyst at a rate of 40-60 g/hr at 225 °C. Enough pressure (about 600 psi) is applied to keep the reactants in the liquid phase. The gas is collected as isobutylene and is directly recycled back into the reactor. The liquid effluent is sampled for conversion to 2,5-dimethyl-2,4-hexadiene, which is normally 35% with the remainder being unreacted starting material and a minor portion (5%) of higher isobutylene oligomers. At optimal conditions the reactor is continually run for periods longer than 10 days.

[00061] **Example 5.** One of the isobutanol/isobutyraldehyde mixtures from example 1, 1 part isobutyraldehyde to 2 parts isobutanol, is reacted in the presence of a catalytic amount of strong acid to form both the 1,1-diisobutoxy-3-methyl-butane (acetal) and the isobutyl isobutenyl ether (enol ether), in Dean-Stark conditions to drive the reaction to completion, proceeding at 95% conversion. These compounds are fed through a flow reactor charged with niobic acid catalyst at a rate of 40-60 g/hr at temperatures ranging from 200 – 300 °C, most often 220 °C. Enough pressure (50 psi) is applied to keep the reactants in the liquid phase. All gas is collected as isobutylene and is directly recycled back into the reactor. The liquid effluent is sampled for conversion to 2,5-dimethyl-2,4-hexadiene which is normally 35% with the remainder being unreacted starting material and a minor portion (5%) of higher isobutylene oligomers. At optimal conditions the reactor is continually run for periods longer than 10 days.

[00062] **Example 6.** Example 5 is repeated but at 600 psi with all the components in the supercritical phase. The conversion slightly lower, 30%, but the difference is made up in isobutyl isobutyrate which is recycled and gently treated so as not to form isobutyric acid upon

disproportionation. The route taught by US Patent 4,320,229 is used to reform isobutyraldehyde from the ester in 90% conversion and recycled back to the reactor.

[00063] **Example 7.** Example 3 is repeated but in the presence of water, a catalytic amount of strong acid, and the mixture being in excess (2 equivalents to every equivalent isobutanol) of isobutyraldehyde. The secondary alcoholic carbocation formed *in situ* is trapped as an acetal by the excess isobutyraldehyde, specifically as 2,4-diisopropyl-6,6-dimethyl-1,3-dioxane, 80 % conversion. The reaction mixture is fractionated either by distillation with any remaining isobutyraldehyde being re-used and the acetal removed with the bottoms. Alternatively the reaction is further driven to acetal creation (90 %) by using Dean-Stark conditions. The collected acetal is introduced to a vessel charged with calcium phosphate, heated to 400 °C, and cooled to yield 80% 2,5-dimethyl-2,4-hexadiene with some additional (5%) 2-methyl-2,4-heptadiene.

[00064] **Example 8.** A mixture of renewable isobutylene and isobutanol, made from partial dehydrogenating a batch of renewable isobutanol over alumina at 10 psi and 45 WHSV at 350 °C, is fed through a flow reactor charged with niobic acid catalyst at a rate of 40-60 g/hr at temperatures ranging from 250 – 300 °C, preferably 220 °C. Enough pressure (about 600 psi) is applied to keep the reactants in the liquid phase. The liquid effluent is sampled for conversion to 2,5-dimethyl-2,4-hexadiene which is normally 35% with the remainder being unreacted starting material and a minor portion (5%) of higher isobutylene oligomers. At optimal conditions the reactor is continually run for periods longer than 10 days.

[00065] **Example 9.** Niobium oxide catalyst (Süd-Chemie, >5% graphite) was crushed to particles 1 to 2.8 mm in size, immersed in 0.1 N H₃PO₄ (aqueous) for 4 hours, washed 5 times in distilled water, then calcined at 350 °C overnight, similar to the catalyst preparation as taught by US Patent 4,684,758. The bottom of a stainless steel reactor with an inner diameter of ½" was filled with 4 mm borosilicate glass beads, then 15 g of the treated catalyst, and then filled with more beads. A solution of isobutyraldehyde and isobutanol (1:4 stoichiometry) was then flowed, 0.6 mL/min, through the reactor at 70 – 80 psi. Electrical tape was used to heat the reactor so that the material entering the catalyst region was about 215 °C and the product leaving the region was no more than 300 °C. Ample butenes, primarily isobutylene, were produced. The organic phase was colored a deep yellow, and GC/FID indicated 33% of the material was 2,5-dimethyl-

2,4-hexadiene, corresponding to a 25 % yield. 95+% of the isobutyraldehyde was converted. See Figure 12 for the GC/FID trace.

[00066] **Example 10.** 2,5-dimethyl-2,4-hexadiene and, occasionally, 2-methyl-2,4-heptadiene collected from the reactions in examples 3-6 are separated by fractional distillation. Both of the isolated compounds are fed neat over alkaline-assisted chromia catalyst at 1 WHSV at 450 °C at ambient pressure. The feed is halted after 30 mins to yield liquid fractions with 82 and 80 % of para and ortho-xylene, respectively, with an overall yield of 70 % xylene from a single-pass. The remaining starting material, as well as partially hydrogenated C₈s (e.g., 2,5-dimethyl-2-hexene), about 15% of the effluent, are promptly recycled back into the reactor after the respective xylene is removed by selective crystallization. At this point the original reactor is heated to 500 °C and exposed to air and regenerated for a period of 15 mins. Toluene is added during the feed to slow the deactivation of the catalyst, and this example can be applied to a battery of reactors running in tandem to allow continuous feed of the hydrocarbon while the deactivated reactors are regenerated.

[00067] **Example 11.** 2,5-dimethyl-2,4-hexadiene (96%, Acros) was diluted to 50% with a nitrogen stream and then passed over a chromia/alumina catalyst (SNAP III, BASF) at a WHSV of a 0.89 hr⁻¹, at a variety of temperatures. The effluent was analyzed by GC/FID to determine the proportion of starting material, para-xylene product, as well as the small proportion of partially hydrogenated starting material, as summarized in the table below. The GC/FID trace for the 450 °C effluent is included as Figure 11.

Temperature (°C)	DMH (%)	Various C ₈ saturates (%)	Para-xylene (%)	Meta-xylene (%)	Ortho-xylene (%)
250	91	9	1	-	-
300	78	16	4	-	-
350	49	33	19	>1	-

400	10	33	55	1	-
450	2	13	82	2	>1

FIGURE 11

[00068] **Example 12.** A stream of renewable isobutylene (95% from a dehydration reactor fed renewable isobutanol), is heated to 350 °C at 0.25 atm in the presence of 0.4 equivalents of ozone to produce a stream of 1 part isobutylene oxide and 2 parts isobutylene. The stream is partially cooled and fed through a flow reactor charged with niobic acid catalyst at a rate of 40-60 g/hr at 225 °C. Enough pressure (600 psi) is applied to keep the reactants in the liquid phase. The excess gas collected is primarily isobutylene and is recycled back to mix with an enriched isobutylene oxide stream to ensure the 1:2 stoichiometry detailed above. The liquid effluent is sampled for conversion to 2,5-dimethyl-2,4-hexadiene, which is normally 65% with the remainder being unreacted starting material and a minor portion (5%) of higher isobutylene oligomers. At optimal conditions the reactor is continually run for periods longer than 10 days.

[00069] The embodiments described herein and illustrated by the foregoing examples should be understood to be illustrative of the present invention, and should not be construed as limiting. On the contrary, the present disclosure embraces alternatives and equivalents thereof, as embodied by the appended claims.

What is claimed is:

1. A method for preparing xylenes, comprising:
 - a. providing a feedstock comprising isobutanol;
 - b. at least partially oxidizing a portion of said isobutanol to form a first stream comprising isobutyraldehyde and isobutanol;
 - c. coupling said isobutyraldehyde with isobutylene to form a second stream comprising 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene;
 - d. reacting said stream comprising 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene to form a product stream comprising said xylenes.
2. The method of claim 1, wherein said isobutanol feedstock comprises renewable isobutanol.
3. The method of claim 2, wherein said isobutanol feedstock is renewable isobutanol.
4. The method of claim 1, wherein said isobutylene is formed via selective dehydration of said isobutanol in said first stream prior to said reacting step c.
5. The method of claim 1, wherein said reacting step d comprises dehydrocyclization.
6. The method of claim 1, wherein said xylenes comprise o-xylene and p-xylene.
7. The method of claim 1, wherein the ratio of 2,5-dimethyl-2,4-hexadiene to 2-methyl-2,4-heptadiene in said second stream is greater than 1:1.
8. The method of claim 1, further comprising separating said xylenes from said product stream.
9. The method of claim 1, further comprising separating said 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene from said second stream prior to said reacting step d.
10. The method of claim 1, wherein oxidizing comprises treating said stream with an oxidizing agent.

11. The method of claim 1, wherein said reacting step b comprises contacting said reaction mixture with a catalyst.
12. The method of claim 11, wherein said catalyst comprises niobic acid and its hydrates.
13. The method of claim 1, wherein the ratio of isobutyraldehyde to isobutanol in said first stream is about 1:1.
14. The method of claim 1, further comprising conducting said coupling step c in the presence of water.
15. The method of claim 1, further comprising conducting said coupling step c in the absence of water.
16. The method of claim 14, further comprising conducting said coupling step in the presence of an acid.
17. The method of claim 1, wherein said second stream further comprises one or more saturated or unsaturated mono- or polyhydroxylated octanes.
18. The method of claim 17, wherein said one or more octanes comprise 2,5-dimethylhex-4-en-3-ol and 2,5-dimethylhexane-2,4-diol.
19. The method of claim 17, further comprising dehydrating said one or more saturated or unsaturated mono- or polyhydroxylated octanes.
20. A method for preparing 2,5-dimethyl-2,4-hexadiene, comprising:
 - a. providing a feedstock comprising isobutanol;
 - b. at least partially oxidizing a portion of said isobutanol to form a first stream comprising isobutyraldehyde and isobutanol;

- c. reacting isobutylene with said isobutyraldehyde to form a second stream comprising 2,6-diisopropyl-4,4-dimethyl-1,3-dioxane;
 - d. decomposing said 2,6-diisopropyl-4,4-dimethyl-1,3-dioxane in said second stream to form said 2,5-dimethyl-2,4-hexadiene; and
 - e. isolating said 2,5-dimethyl-2,4-hexadiene.
21. The method of claim 20, wherein a ratio of isobutyraldehyde to isobutylene in said reacting step c is at least 2:1.
22. The method of claim 20, wherein said isobutanol feedstock comprises renewable isobutanol.
23. The method of claim 20, wherein said isobutanol feedstock is renewable isobutanol.
24. The method of claim 20, wherein said isobutylene is formed via selective dehydration of said isobutanol in said first stream prior to said reacting step c.
25. The method of claim 20, wherein said reacting step d comprises dehydrating.
26. The method of claim 20, wherein selectively oxidizing comprises treating said stream with an oxidizing agent.
27. The method of claim 20, wherein said reacting step b comprises contacting said reaction mixture with an olefin-aldehyde coupling catalyst.
28. The method of claim 20, wherein said catalyst comprises niobic acid and its hydrates.
29. The method of claim 20, further comprising conducting said decomposing step in the presence of an acid.
30. The method of claim 1, wherein said second stream further comprises one or more saturated or unsaturated mono- or polyhydroxylated octanes.

31. The method of claim 30, wherein said one or more octanes comprise 2,5-dimethylhex-4-en-3-ol and 2,5-dimethylhexane-2,4-diol.

32. The method of claim 30, further comprising dehydrating said one or more saturated or unsaturated mono- or polyhydroxylated octanes.

33. A method for preparing 2,5-dimethyl-2,4-hexadiene, comprising:

- a. providing a feedstock comprising isobutanol;
- b. at least partially dehydrating a portion of said isobutanol to form a first stream comprising isobutylene and isobutanol;
- c. reacting said isobutylene with said isobutyraldehyde in the presence of an oxidant to form a product stream comprising one or more of 2,5-dimethyl-2,4-hexadiene and 2-methyl-2,4-heptadiene ; and
- d. separating said 2,5-dimethyl-2,4-hexadiene.

33. A method for preparing 2,5-dimethyl-2,4-hexadiene, comprising:

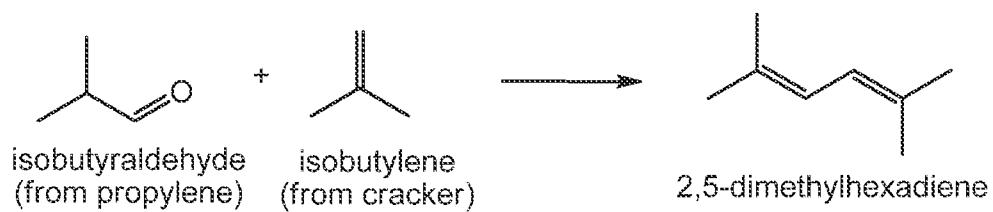
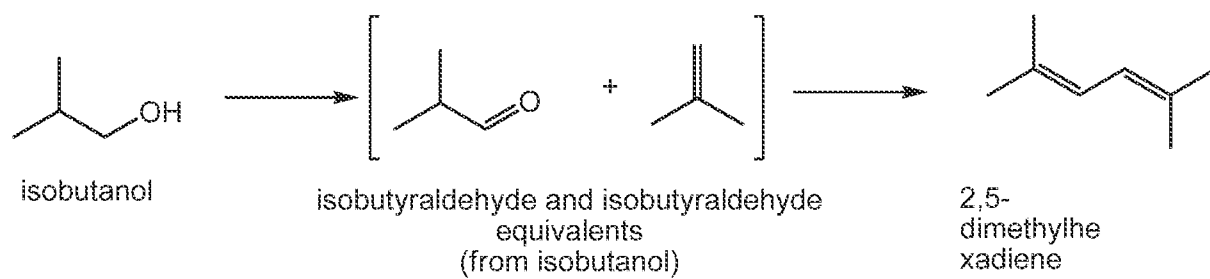
- a. providing a feedstock comprising isobutanol;
- b. at least partially dehydrating a portion of said isobutanol to form a first stream comprising isobutylene and isobutanol;
- c. reacting said isobutylene with isobutylene oxide to form a product stream comprising 2,5-dimethyl-2,4-hexadiene; and
- d. separating said 2,5-dimethyl-2,4-hexadiene.

34. The method of claim 33, further comprising oxidizing of at least a portion of isobutylene in said first stream to form said isobutylene oxide.

35. The method of claim 34, wherein oxidizing comprises treating said stream with an oxidizing agent.

36. The method of claim 33, wherein said reacting step is conducted in the presence of a catalyst.

37. The method of claim 36, wherein said catalyst comprises niobic acid and its hydrates.
38. A method for preparing 2,5-dimethyl-2,4-hexadiene, comprising:
- a. providing a feedstock comprising isobutanol;
 - b. at least partially oxidizing a portion of said isobutanol to form a first stream comprising isobutyraldehyde and isobutanol;
 - c. contacting said first stream comprising isobutyraldehyde and isobutanol with an acid catalyst to form a second stream comprising one or more of 1,1-diisobutoxy-2-methylpropane and 1-isobutoxy-2-methylprop-1-ene;
 - d. contacting said second stream with a second catalyst to produce a product stream comprising 2,5-dimethyl-2,4-hexadiene; and
 - e. separating said 2,5-dimethyl-2,4-hexadiene.
39. The method of claim 38, wherein said contacting step further comprises removing water.
40. The method of claim 38, wherein said second catalyst comprises niobic acid and its hydrates.
41. The method of claim 38, wherein said acid catalyst and said second catalyst are the same.

**FIG. 1****FIG. 2**

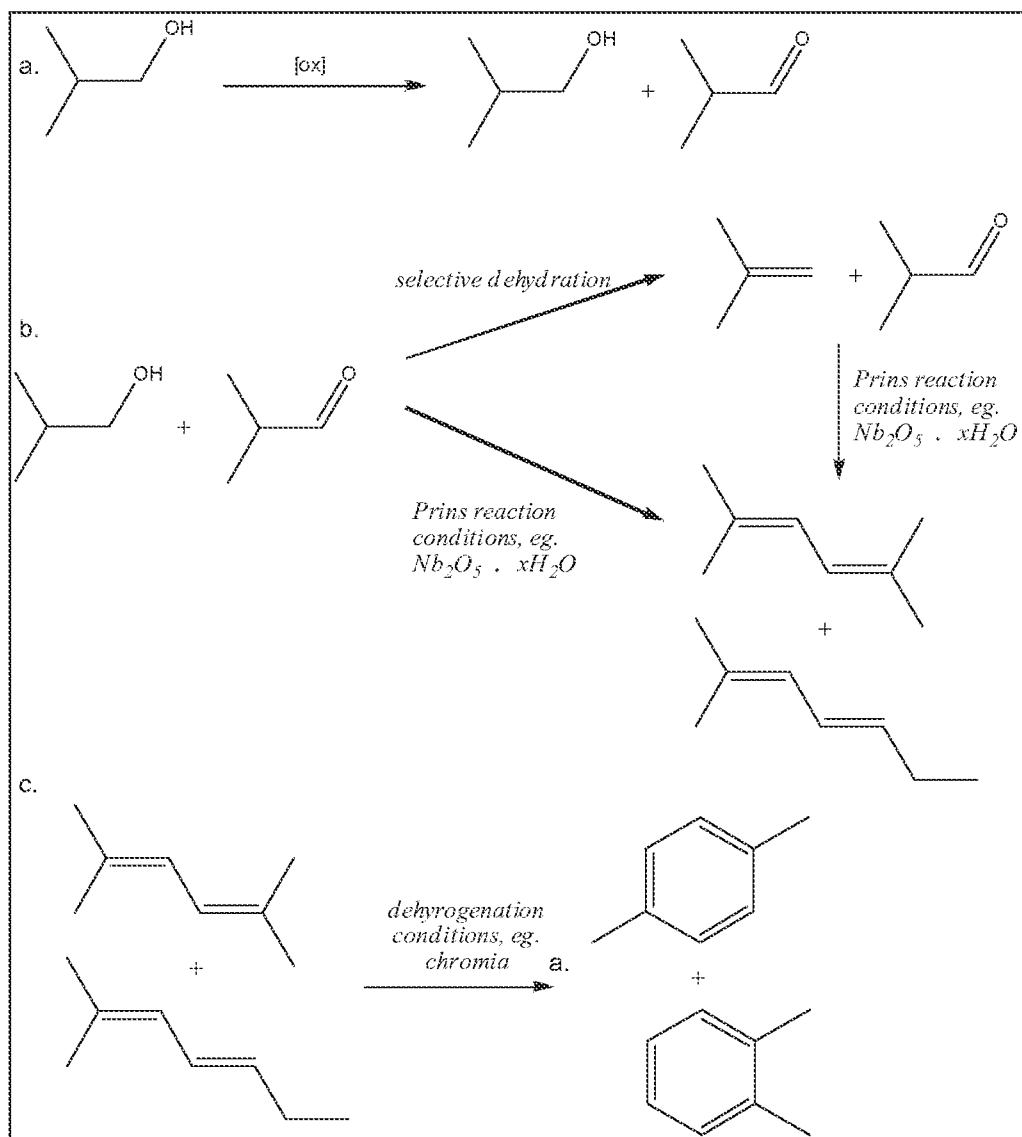


FIG. 3

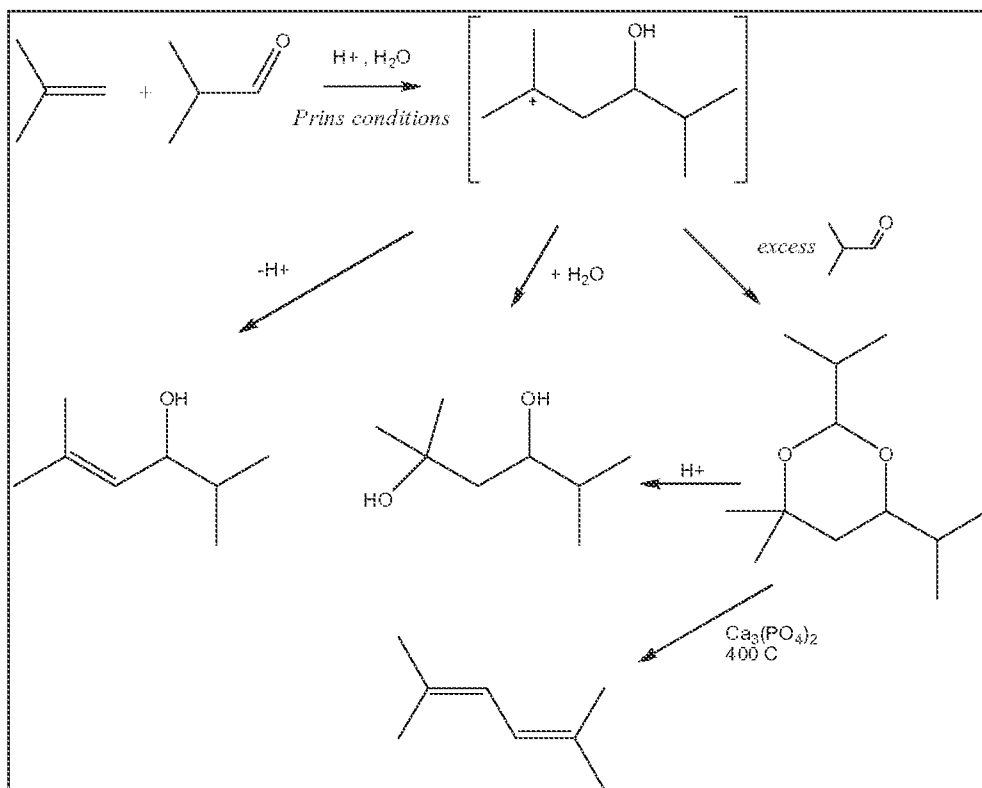


FIG. 4

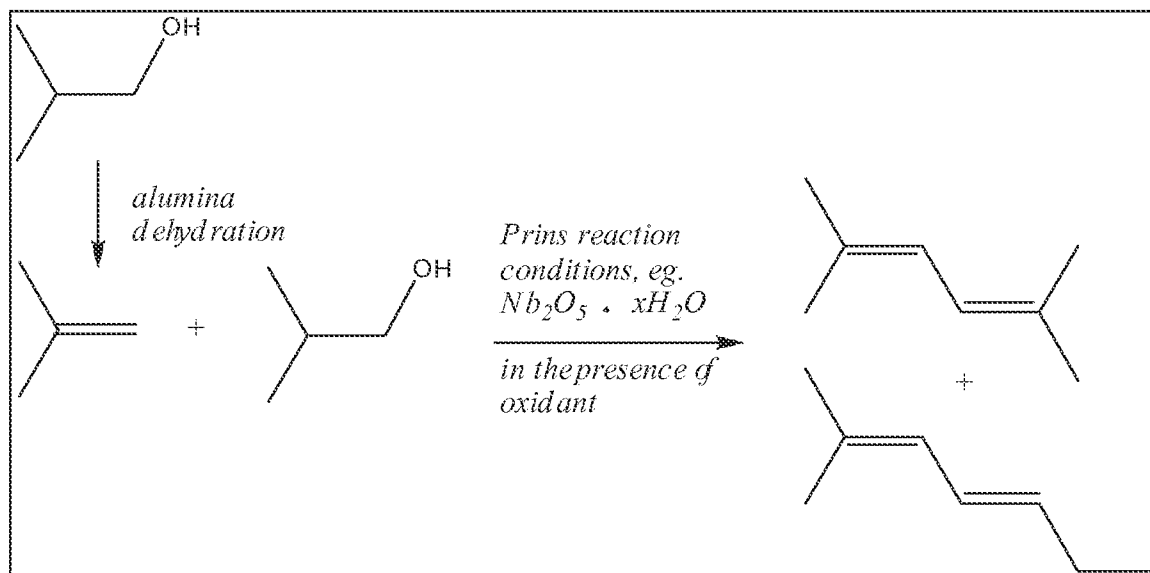


FIG. 5

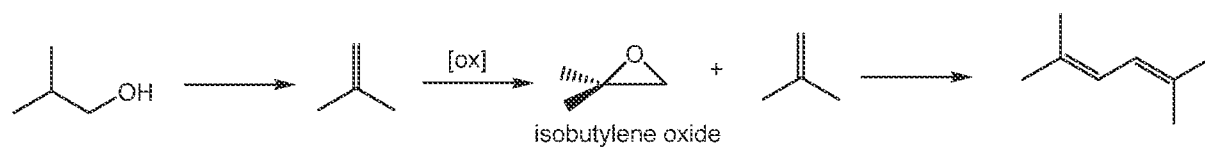


FIG. 6

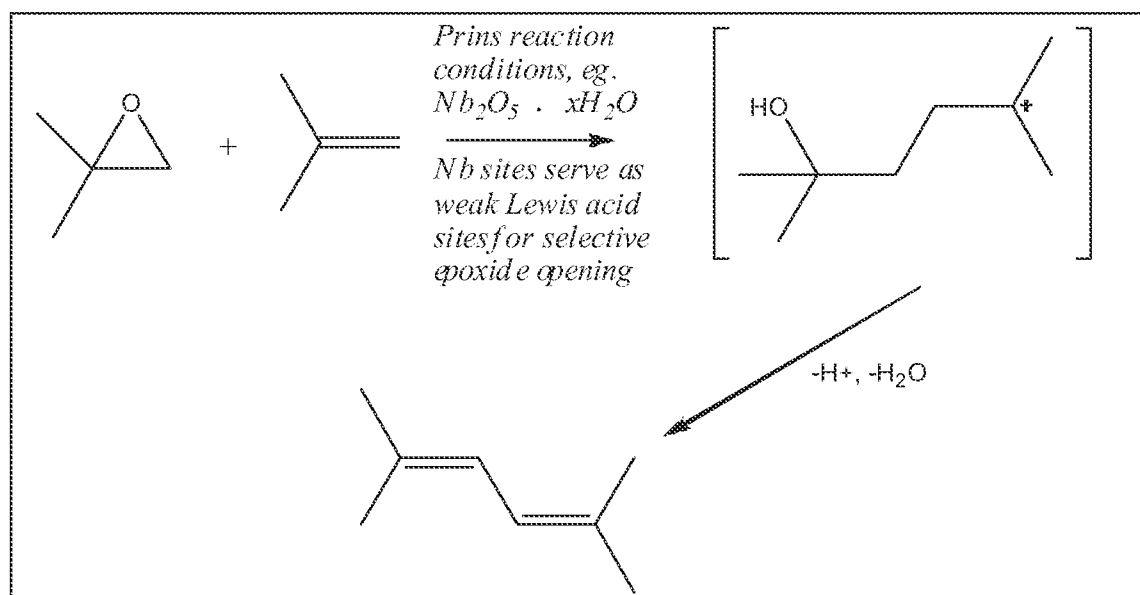
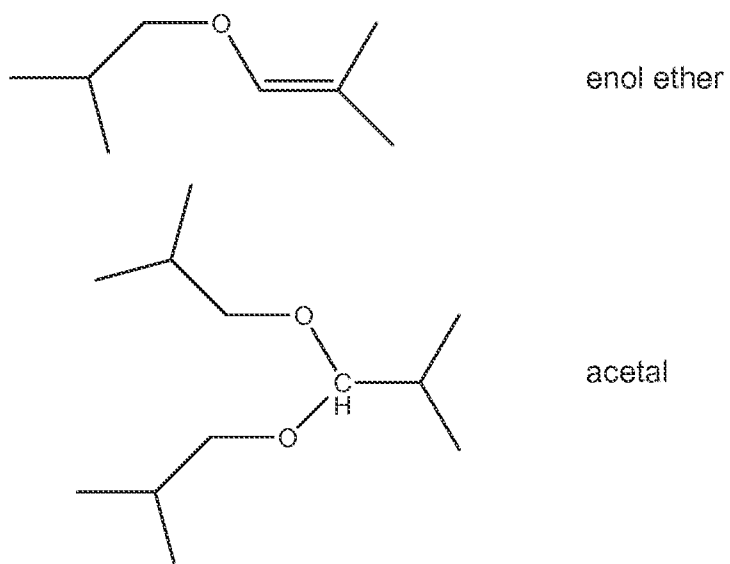


FIG. 7

**FIG. 8**

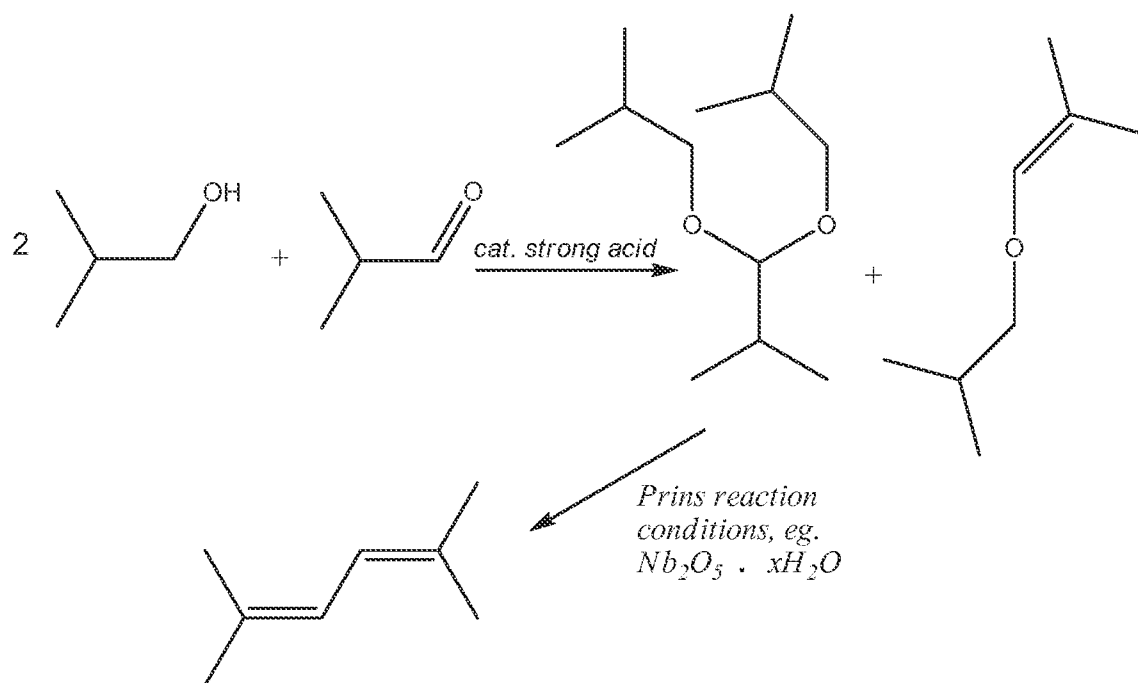


FIG. 9

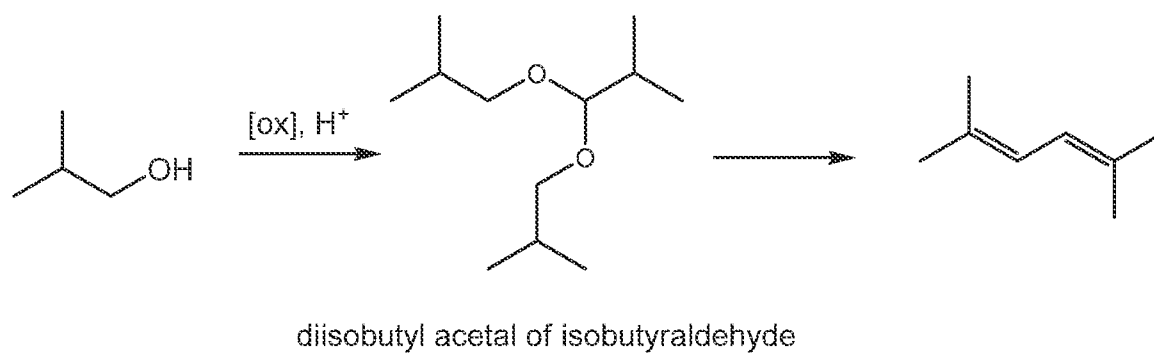


FIG. 10

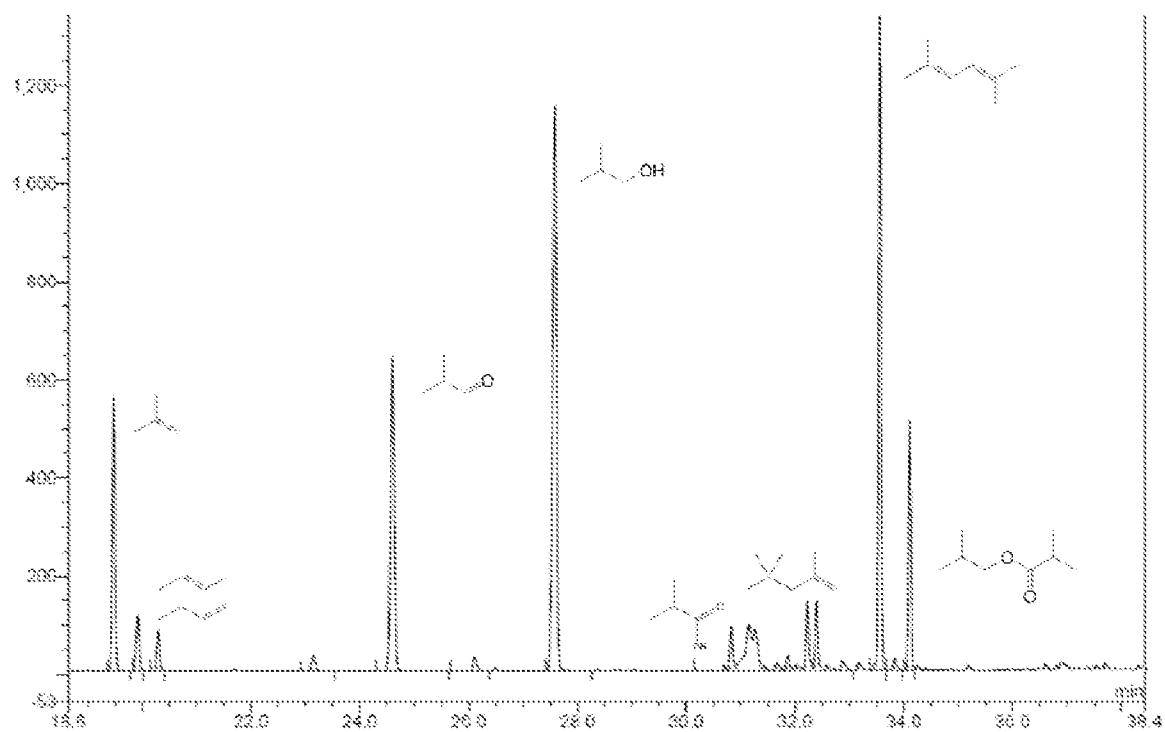


FIG. 11

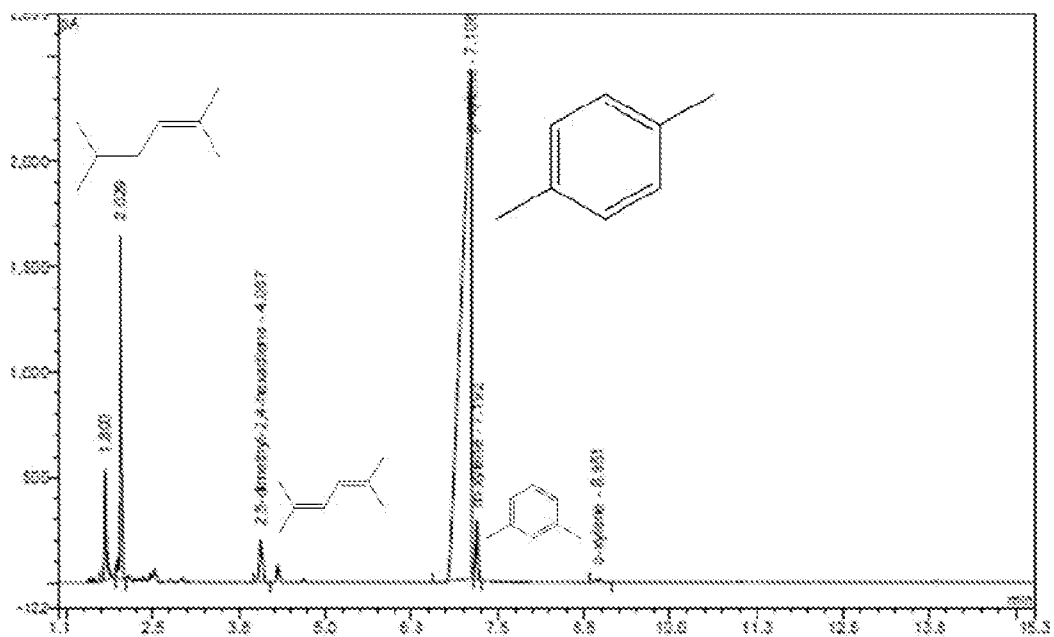


FIG. 12