

POLYMERIZATION OF ISOPRENE FROM RENEWABLE RESOURCES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/187,944, filed June 17, 2009, the disclosure of which is hereby incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] Isoprene (2-methyl-but-1,3-diene) is an important organic compound that is used in a wide array of applications. For instance, isoprene is employed as an intermediate or a starting material in the synthesis of numerous chemical compositions and polymers. Isoprene is also an important biological material that is synthesized naturally by many plants and animals, including humans. Isoprene is a colorless liquid at room temperature and is highly flammable.

[0003] Isoprene became an important monomer for utilization in the synthesis of *cis*-1,4-polybutadiene when its stereo-regulated polymerization became commercially possible in the early 1960s. *cis*-1,4-Polyisoprene made by such stereo-regulated polymerizations is similar in structure and properties to natural rubber. Even though it is not identical to natural rubber it can be used as a substitute for natural rubber in many applications. For instance, synthetic *cis*-1,4-polyisoprene rubber is widely used in manufacturing tires and other rubber products. This demand for synthetic *cis*-1,4-polyisoprene rubber consumes a majority of the isoprene available in the worldwide market. The remaining isoprene is used in making other synthetic rubbers, block copolymers, and other chemical products. For instance, isoprene is used in making butadiene-isoprene rubbers, styrene-isoprene copolymer rubbers, styrene-isoprene-butadiene rubbers, styrene-isoprene-styrene block copolymers, and styrene-isoprene block copolymers.

[0004] Over the years many synthesis routes for producing isoprene have been investigated. For instance, the synthesis of isoprene by reacting isobutylene with formaldehyde in the presence of a catalyst is described in United States Patent 3,146,278, United States Patent 3,437,711, United States Patent 3,621,072, United States Patent 3,662,016, United States Patent 3,972,955, United States Patent 4,000,209, United States

Patent 4,014,952, United States Patent 4,067,923, and United States Patent 4,511,751. United States Patent 3,574,780 discloses another process for the manufacture of isoprene by passing a mixture of methyl-*tert*-butyl ether and air over mixed oxide catalysts. The methyl-*tert*-butyl ether is then cracked into isobutylene and methanol over the catalyst. The methanol produced is oxidized into formaldehyde which then reacts with the isobutylene over the same catalyst to produce the isoprene. United States Patent 5,177,290 discloses a process for producing dienes, including isoprene, which involves reacting a reaction mixture of a tertiary alkyl ether and a source of oxygen over two functionally distinct catalysts under reaction conditions sufficient to produce high yields of the dienes with minimal recycle of the ether.

[0005] The isoprene used in industrial applications is typically produced as a by-product of the thermal cracking of petroleum or naphtha or is otherwise extracted from petrochemical streams. This is a relatively expensive energy-intensive process. With the worldwide demand for petrochemical based products constantly increasing, the cost of isoprene is expected to rise to much higher levels in the long-term and its availability is limited in any case. In other words, there is a concern that future supplies of isoprene from petrochemical based sources will be inadequate to meet projected needs and that prices will rise to unprecedented levels. Accordingly, there is a current need to procure a source of isoprene from a low cost, renewable source which is environmentally friendly.

[0006] In addition, isoprene produced from petrochemical feedstocks requires extensive purification before it can be converted to polymers. Cost effective methods are desirable for producing highly pure isoprene from renewable resources and converting it to polyisoprene products taking advantage of the high purity and/or the unique impurity profiles of bioisoprene compositions.

[0007] The invention described herein fulfills these needs and provides additional benefits as well.

BRIEF SUMMARY OF THE INVENTION

[0008] The invention provides, *inter alia*, compositions and methods for producing polymers of isoprene from renewable resources.

[0009] Accordingly, in one aspect, the invention provides systems for producing a copolymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with another non-isoprene molecule to produce a copolymer. In one embodiment, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises greater than or about 99.94% isoprene by weight compared to the total weight of all C5 hydrocarbons in the composition. In another embodiment, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms. In another embodiment, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more second compounds selected from the group consisting of ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol, 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, and 2,3-cycloheptenolpyridine; wherein the amount of the second compound relative to the amount of the isoprene is greater than or about 0.01 % (w/w). In another embodiment, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises less than or about 0.5 µg/L per compound for any compound in the composition that inhibits the polymerization of isoprene. In another embodiment, the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has $\delta^{13}\text{C}$ value of greater than -22‰ or which is within the range of -30‰ to -28.5‰. In another embodiment, the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the

blocks of repeat units that are derived from isoprene have a $d^{13}C$ value of greater than -22‰ or which is within the range of -32‰ to -24‰ . In another embodiment, the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}C$ value of greater than -22‰ or which is within the range of -34‰ to -24‰ . In another embodiment, the polymer is a copolymer selected from the group consisted of (i) copolymers of isoprene and 1,3-butadiene, (ii) copolymers of isoprene and styrene, (iii) copolymers of isoprene, 1,3-butadiene, and styrene, and (iv) copolymers of isoprene and α -methyl styrene. In another embodiment, the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has f_M value which is greater than 0.9. In another embodiment, the system further comprises one or more of: (i) a catalyst for polymerizing isoprene, (ii) a polymerization initiator, (iii) an ionic surfactant, (iv) a suitable organic solvent, and (v) a polymerization chain terminator.

[0010] In another aspect, the invention provides for systems for producing a polymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with other isoprene molecules to produce a polymer of isoprene with a molecular weight of about 5,000 to about 100,000.

[0011] In another aspect, the invention provides for methods for producing a copolymer of isoprene derived from renewable resources comprising: (a) culturing cells comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene; (b) producing the isoprene; and (c) polymerizing the isoprene derived from renewable resources with another non-isoprene molecules to produce a copolymer. In one embodiment, the method further comprises recovering the isoprene from the isoprene-producing cell culture prior to polymerization. In another embodiment, the method further comprises step (d) recovering the polymer produced.

[0012] In another aspect, the invention provides for methods for producing a polymer of isoprene derived from renewable resources comprising: (a) culturing cells comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene; (b) producing the isoprene; and (c) polymerizing the isoprene derived from renewable resources with other isoprene molecules to produce a polymer of isoprene with a molecular weight of about 5,000 to about 100,000.

[0013] In another aspect, the invention provides for polymers of isoprene derived from renewable resources produced by any of the methods described herein.

[0014] In one aspect, the invention provides for a system for producing a polymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; where at least a portion of the isoprene starting composition undergoes polymerization. In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises greater than or about 99.94% isoprene by weight compared to the total weight of all C5 hydrocarbons in the composition. In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms. In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more second compounds selected from the group consisting of ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinylloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol, 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, citronellol and geraniol; wherein the amount of the second compound relative to the amount of the isoprene is greater than or about 0.01 % (w/w). In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises less than or about 0.5

µg/L per compound for any compound in the composition that inhibits the polymerization of isoprene.

[0015] In some embodiments, the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has $\delta^{13}\text{C}$ value of greater than -22‰ or which is within the range of -30‰ to -28.5‰ . In some embodiments, the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $\delta^{13}\text{C}$ value of greater than -22‰ or which is within the range of -32‰ to -24‰ . In some embodiments, the the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $\delta^{13}\text{C}$ value of greater than -22‰ or which is within the range of -31‰ to -24‰ . In some embodiments, the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $\delta^{13}\text{C}$ value of greater than -22‰ or which is within the range of -34‰ to -24‰ . In some embodiments, the polymer is a copolymer selected from the group consisting of (i) copolymers of isoprene and 1,3-butadiene, (ii) copolymers of isoprene and styrene, (iii) copolymers of isoprene, 1,3-butadiene, and styrene, and (iv) copolymers of isoprene and α -methyl styrene. In some embodiments, the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has f_M value which is greater than 0.9.

[0016] In some embodiments, the system further comprises a catalyst for polymerizing isoprene. In some embodiments, the system further comprises a polymerization initiator. In some embodiments, the system further comprises an ionic surfactant. In some embodiments, the system further comprises a suitable organic solvent. In some embodiments, the system further comprises a polymerization chain terminator. In some embodiments, the system

further comprises one additional monomer selected from the group consisting of 1,3-butadiene and styrene. In some embodiments, the system further comprises additional monomers including both 1,3-butadiene and styrene.

[0017] In one aspect, provided is a method for producing a polymer of isoprene derived from renewable resources comprising: (a) obtaining isoprene from renewable resources; (b) polymerizing isoprene derived from renewable resources; and (c) recovering the polymer produced. In some embodiments, the isoprene from renewable resources is obtained by a method which comprises the steps of (i) culturing cells comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene, (ii) producing the isoprene, and (iii) recovering the isoprene from the culture. A polymer of isoprene derived from renewable resources produced by any of the methods described herein is also provided.

[0018] In one aspect, provided is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has $d^{13}C$ value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -34‰ to -24‰ . In various embodiments, the polyisoprene is free of protein. In some embodiments, the polyisoprene is a polyisoprene homopolymer.

[0019] In one aspect, provided is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a cis-1,4-microstructure content of less than 99.9%, wherein the polyisoprene polymer has a trans-1,4-microstructure content of less than 99.9%, and wherein the polyisoprene polymer has $d^{13}C$ value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}C$ value which is within the range of -34‰ to -24‰ .

[0020] In one aspect, provided is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a 3,4-microstructure content of greater than 2%, and wherein the polyisoprene polymer has $d^{13}C$

value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -34‰ to -24‰ .

[0021] In one aspect, provided is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a 1,2-microstructure content of greater than 2%, and wherein the polyisoprene polymer has $d^{13}\text{C}$ value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -34‰ to -24‰ .

[0022] In one aspect, provided is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}\text{C}$ value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -34‰ to -24‰ .

[0023] In one aspect, provided is a liquid polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the liquid polyisoprene polymer has a weight average molecular weight which is within the range of 5,000 to 100,000, and wherein the liquid polyisoprene polymer has $d^{13}\text{C}$ value of greater than -22‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -30‰ to -28.5‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -32‰ to -24‰ . In some embodiments, the polyisoprene polymer has $d^{13}\text{C}$ value which is within the range of -34‰ to -24‰ .

[0024] In one aspect, provided is a method for verifying that a polyisoprene homopolymer is from a sustainable renewable non-petroleum derived source which comprises: (I) determining the $d^{13}\text{C}$ value of the polyisoprene homopolymer; (II) if the polyisoprene homopolymer has a $d^{13}\text{C}$ value within the range of -34‰ to -30‰ or within the range of -

28.5‰ to -24‰ additionally analyzing the polyisoprene homopolymer to determine (1) its cis-microstructure content, (2) its 3,4-microstructure content, (3) its 1,2-microstructure content, (4) its a weight average molecular weight, or (5) the presence or absence of residual proteins, soaps, lipids, resins, or sugars indicative of natural rubber; and (III) verifying that the polyisoprene homopolymer is from a sustainable renewable non-petroleum derived source if it has (i) a $d^{13}C$ value of greater than -22‰, (ii) a $d^{13}C$ value which is within the range of -30‰ to -28.5‰, or (iii) a $d^{13}C$ value within the range of -34‰ to -30‰ or within the range of -28.5‰ to -24‰ and if it (a) has a cis-microstructure content of less than 100%, (b) contains 3,4-microstructure, (c) contains 1,2-microstructure, (d) has a weight average molecular weight of less than 100,000, or (e) is free of residual proteins, soaps, lipids, resins, or sugars indicative of natural rubber. In some embodiments, the method further comprises analyzing the ^{14}C content of the polymer and verifying that the f_M value is greater than 0.9.

[0025] In one aspect, provided is a method for verifying that a copolymer having repeat units that are derived from isoprene contains isoprene that is from a sustainable renewable non-petroleum derived source, said method comprising: (I) determining the $d^{13}C$ value of at least one polyisoprene block in the copolymer; and (II) verifying that the isoprene in the copolymer is from a sustainable renewable non-petroleum derived source if the polyisoprene block has (i) a $d^{13}C$ value of greater than -22‰, or (ii) a $d^{13}C$ value which is within the range of -34‰ to -28.5. In some embodiments, the method further comprises analyzing the ^{14}C content of the polymer and verifying that the f_M value is greater than 0.9.

[0026] In some embodiments of any of the aspects, the isoprene monomer is produced by cells in culture. In some embodiments, the cells in culture are capable of producing greater than about 400 nmole or about 1000 nmole of isoprene monomer/gram of cells for the wet weight of the cells/hour (nmole/g_{wcm}/hr) of isoprene monomer. In some embodiments, the cells have a heterologous nucleic acid that (i) encodes an isoprene synthase polypeptide and (ii) is operably linked to a promoter. In some embodiments, the cells are cultured in a culture medium that includes a carbon source, such as, but not limited to, a carbohydrate, glycerol, glycerine, dihydroxyacetone, one-carbon source, oil, animal fat, animal oil, fatty acid, lipid, phospholipid, glycerolipid, monoglyceride, diglyceride, triglyceride, renewable carbon source, polypeptide (*e.g.*, a microbial or plant protein or peptide), yeast extract, component from a yeast extract, or any combination of two or more of the foregoing. In some embodiments, the cells are cultured under limited glucose conditions.

[0027] In some embodiments, the cells in culture are capable of converting more than about 0.002% of the carbon in a cell culture medium into isoprene monomer. In some embodiments, the cells have a heterologous nucleic acid that (i) encodes an isoprene synthase polypeptide and (ii) is operably linked to a promoter. In some embodiments, the cells are cultured in a culture medium that includes a carbon source, such as, but not limited to, a carbohydrate, glycerol, glycerine, dihydroxyacetone, one-carbon source, oil, animal fat, animal oil, fatty acid, lipid, phospholipid, glycerolipid, monoglyceride, diglyceride, triglyceride, renewable carbon source, polypeptide (*e.g.*, a microbial or plant protein or peptide), yeast extract, component from a yeast extract, or any combination of two or more of the foregoing. In some embodiments, the cells are cultured under limited glucose conditions.

[0028] In some embodiments, the cells in culture comprise a heterologous nucleic acid encoding an isoprene synthase polypeptide. In some embodiments, the cells have a heterologous nucleic acid that (i) encodes an isoprene synthase polypeptide and (ii) is operably linked to a promoter. In some embodiments, the cells are cultured in a culture medium that includes a carbon source, such as, but not limited to, a carbohydrate, glycerol, glycerine, dihydroxyacetone, one-carbon source, oil, animal fat, animal oil, fatty acid, lipid, phospholipid, glycerolipid, monoglyceride, diglyceride, triglyceride, renewable carbon source, polypeptide (*e.g.*, a microbial or plant protein or peptide), yeast extract, component from a yeast extract, or any combination of two or more of the foregoing. In some embodiments, the cells are cultured under limited glucose conditions.

[0029] In some embodiments, the cells in culture are capable of producing an amount of isoprene monomer (such as the total amount of isoprene produced or the amount of isoprene produced per liter of broth per hour per OD₆₀₀) during stationary phase is greater than or about 2 or more times the amount of isoprene monomer produced during the growth phase for the same length of time. In some embodiments, the cells in culture are capable of producing isoprene monomer only in stationary phase. In some embodiments, the cells in culture are capable of producing isoprene monomer in both the growth phase and stationary phase. In various embodiments, the cells in culture are capable of producing an amount of isoprene monomer during stationary phase is greater than or about 2, 3, 4, 5, 10, 20, 30, 40, 50, or more times the amount of isoprene monomer produced during the growth phase for the same length of time.

[0030] In some embodiments of any of the aspects, isoprene of the isoprene monomer is from a composition. In some embodiments, the composition comprises greater than or about 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, or 1000 mg of isoprene monomer. In some embodiments, the composition comprises greater than or about 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 g of isoprene monomer (w/w) of the volatile organic fraction of the composition is isoprene monomer.

[0031] In some embodiments, the composition comprises greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene monomer by weight compared to the total weight of all C5 hydrocarbons in the composition. In some embodiments, the composition comprises less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% C5 hydrocarbons other than isoprene monomer (such 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the composition. In some embodiments, the composition has less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne by weight compared to the total weight of all C5 hydrocarbons in the composition. In particular embodiments, the composition has greater than about 2 mg of isoprene monomer and has greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene monomer by weight compared to the total weight of all C5 hydrocarbons in the composition.

[0032] In some embodiments, the composition has less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 $\mu\text{g/L}$ of a compound that inhibits the polymerization of isoprene monomer for any compound in the composition that inhibits the polymerization of isoprene monomer. In particular embodiments, the composition also has greater than about 2 mg of isoprene monomer.

[0033] In some embodiments, the composition has one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms. In some embodiments, the composition has greater than or about

0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 60, 80, 100, or 120 $\mu\text{g/L}$ of ethanol, acetone, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In particular embodiments, the composition has greater than about 2 mg of isoprene monomer and has one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms.

[0034] In some embodiments, the composition includes isoprene monomer and one or more second compounds selected from the group consisting of 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, citronellol and geraniol. In various embodiments, the amount of one of these second components relative to the amount of isoprene monomer in units of percentage by weight (*i.e.*, weight of the component divided by the weight of isoprene times 100) is at greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110% (w/w).

[0035] In some embodiments, the composition comprises (i) a gas phase that comprises isoprene monomer and (ii) cells in culture that produce greater than about 400 nmole/ $\text{g}_{\text{wcm}}/\text{hr}$ of isoprene. In some embodiments, the composition comprises a closed system, and the gas phase comprises greater than or about 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 $\mu\text{g/L}$ of isoprene monomer when normalized to 1 mL of 1 OD_{600} cultured for 1 hour. In some embodiments, the composition comprises an open system, and the gas phase comprises greater than or about 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 $\mu\text{g/L}$ of isoprene monomer when sparged at a rate of 1 vvm. In some embodiments, the volatile organic fraction of the gas phase comprises greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene monomer by weight compared to the total weight of all C5 hydrocarbons in the volatile organic fraction. In some embodiments, the volatile organic fraction of the gas phase comprises less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% C5 hydrocarbons other than isoprene monomer (such as 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-

pentynes, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the volatile organic fraction. In some embodiments, the volatile organic fraction of the gas phase has less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne by weight compared to the total weight of all C5 hydrocarbons in the volatile organic fraction. In particular embodiments, the volatile organic fraction of the gas phase has greater than about 2 mg of isoprene monomer and has greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene monomer by weight compared to the total weight of all C5 hydrocarbons in the volatile organic fraction.

[0036] In some embodiments, the volatile organic fraction of the gas phase of the composition has less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 µg/L of a compound that inhibits the polymerization of isoprene for any compound in the volatile organic fraction of the gas phase that inhibits the polymerization of isoprene monomer. In particular embodiments, the volatile organic fraction of the gas phase also has greater than about 2 mg of isoprene monomer.

[0037] In some embodiments, the volatile organic fraction of the gas phase of the composition has one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms. In some embodiments, the volatile organic fraction of the gas phase has greater than or about 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 60, 80, 100, or 120 µg/L of ethanol, acetone, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In particular embodiments, the volatile organic fraction of the gas phase has greater than about 2 mg of isoprene monomer and has one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms.

[0038] In some embodiments, the volatile organic fraction of the gas phase of the composition includes isoprene monomer and one or more second compounds selected from the group consisting of 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine,

2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, citronellol and geraniol. In various embodiments, the amount of one of these second components relative to amount of isoprene monomer in units of percentage by weight (*i.e.*, weight of the component divided by the weight of isoprene times 100) is at greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110% (w/w) in the volatile organic fraction of the gas phase.

[0039] In some embodiments of any of the compositions, at least a portion of the isoprene monomer is in a gas phase. In some embodiments, at least a portion of the isoprene monomer is in a liquid phase (such as a condensate). In some embodiments, at least a portion of the isoprene monomer is in a solid phase. In some embodiments, at least a portion of the isoprene monomer is adsorbed to a solid support, such as a support that includes silica and/or activated carbon. In some embodiments, the composition includes ethanol. In some embodiments, the composition includes between about 75 to about 90% by weight of ethanol, such as between about 75 to about 80%, about 80 to about 85%, or about 85 to about 90% by weight of ethanol. In some embodiments, the composition includes between about 4 to about 15% by weight of isoprene monomer, such as between about 4 to about 8%, about 8 to about 12%, or about 12 to about 15% by weight of isoprene monomer.

[0040] In some embodiments, the cells in culture are from a system that includes a reactor chamber wherein the cells are capable of producing greater than about 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, or more nmole/g_{wcm}/hr isoprene monomer. In some embodiments, the system is not a closed system. In some embodiments, at least a portion of the isoprene monomer is removed from the system. In some embodiments, the system includes a gas phase comprising isoprene monomer. In various embodiments, the gas phase comprises any of the compositions described herein.

[0041] In one aspect is provided a tire comprising any polyisoprene polymer described herein. For example, in one embodiment is provided tire comprising a polyisoprene polymer

which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has $d^{13}C$ value of greater than -22‰ , or a $d^{13}C$ value which is within the range of -30‰ to -28.5‰ , -32‰ to -24‰ , or -34‰ to -24‰ . In some of these embodiments, the polyisoprene is free of protein. In some embodiments, the polyisoprene is a polyisoprene homopolymer.

[0042] In some embodiments, the polyisoprene polymer described herein is produced by (i) polymerizing isoprene monomer in any of the compositions described herein or (ii) polymerizing isoprene recovered from any of the compositions described herein. In some embodiments are provided methods of producing any polyisoprene polymer described herein by (i) polymerizing isoprene monomer in any of the compositions described herein or (ii) polymerizing isoprene recovered from any of the compositions described herein.

[0043] In some embodiments of any of the compositions, systems, and methods described herein, a nonflammable concentration of isoprene monomer in the gas phase is produced. In some embodiments, the gas phase comprises less than about 9.5 % (volume) oxygen. In some embodiments, the gas phase comprises greater than or about 9.5 % (volume) oxygen, and the concentration of isoprene monomer in the gas phase is less than the lower flammability limit or greater than the upper flammability limit. In some embodiments, the portion of the gas phase other than isoprene monomer comprises between about 0% to about 100% (volume) oxygen, such as between about 10% to about 100% (volume) oxygen. In some embodiments, the portion of the gas phase other than isoprene monomer comprises between about 0% to about 99% (volume) nitrogen. In some embodiments, the portion of the gas phase other than isoprene monomer comprises between about 1% to about 50% (volume) CO_2 .

[0044] In some embodiments, the cells in culture produce isoprene monomer at greater than or about 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, or more nmole/ g_{wcm} /hr isoprene. In some embodiments, the cells in culture convert greater than or about 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.12, 0.14, 0.16, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6%, or more of the carbon in the cell culture medium into isoprene monomer. In some embodiments, the cells in culture produce isoprene monomer at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 100,000, or

more ng of isoprene monomer/gram of cells for the wet weight of the cells /hr (ng/g_{wcm}/h). In some embodiments, the cells in culture produce a cumulative titer (total amount) of isoprene monomer at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 50,000, 100,000, or more mg of isoprene/L of broth (mg/L_{broth}, wherein the volume of broth includes the volume of the cells and the cell medium). Other exemplary rates of isoprene monomer production and total amounts of isoprene monomer production are disclosed herein.

[0045] In some embodiments of any of the aspects, the cells in culture further comprise a heterologous nucleic acid encoding an IDI polypeptide. In some embodiments, the cells further comprise an insertion of a copy of an endogenous nucleic acid encoding an IDI polypeptide. In some embodiments, the cells further comprise a heterologous nucleic acid encoding a DXS polypeptide. In some embodiments, the cells further comprise an insertion of a copy of an endogenous nucleic acid encoding a DXS polypeptide. In some embodiments, the cells further comprise one or more nucleic acids encoding an IDI polypeptide and a DXS polypeptide. In some embodiments, one nucleic acid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some embodiments, one vector encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some embodiments, the vector comprises a selective marker, such as an antibiotic resistance nucleic acid.

[0046] In some embodiments, the heterologous isoprene synthase nucleic acid is operably linked to a T7 promoter, such as a T7 promoter contained in a medium or high copy plasmid. In some embodiments, the heterologous isoprene synthase nucleic acid is operably linked to a Trc promoter, such as a Trc promoter contained in a medium or high copy plasmid. In some embodiments, the heterologous isoprene synthase nucleic acid is operably linked to a Lac promoter, such as a Lac promoter contained in a low copy plasmid. In some embodiments, the heterologous isoprene synthase nucleic acid is operably linked to an endogenous promoter, such as an endogenous alkaline serine protease promoter. In some embodiments, the heterologous isoprene synthase nucleic acid integrates into a chromosome of the cells without a selective marker.

[0047] In some embodiments, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids are placed under the control of a promoter or factor that is more active in

stationary phase than in the growth phase. For example, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids may be placed under control of a stationary phase sigma factor, such as RpoS. In some embodiments, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids are placed under control of a promoter inducible in stationary phase, such as a promoter inducible by a response regulator active in stationary phase.

[0048] In some embodiments, at least a portion of the cells in culture maintain the heterologous isoprene synthase nucleic acid for at least or about 5, 10, 20, 40, 50, 60, 65, or more cell divisions in a continuous culture (such as a continuous culture without dilution). In some embodiments, the nucleic acid comprising the isoprene synthase, IDI, or DXS nucleic acid also comprises a selective marker, such as an antibiotic resistance nucleic acid.

[0049] In some embodiments, the cells in culture further comprise a heterologous nucleic acid encoding an MVA pathway polypeptide (such as an MVA pathway polypeptide from *Saccharomyces cerevisia* or *Enterococcus faecalis*). In some embodiments, the cells further comprise an insertion of a copy of an endogenous nucleic acid encoding an MVA pathway polypeptide (such as an MVA pathway polypeptide from *Saccharomyces cerevisia* or *Enterococcus faecalis*). In some embodiments, the cells comprise an isoprene synthase, DXS, and MVA pathway nucleic acid. In some embodiments, the cells comprise an isoprene synthase nucleic acid, a DXS nucleic acid, an IDI nucleic acid, and a MVA pathway nucleic acid (in addition to the IDI nucleic acid).

[0050] In some embodiments, the isoprene synthase polypeptide is a naturally-occurring polypeptide from a plant such as *Pueraria* (e.g., *Pueraria montana* or *Pueraria lobata*).

[0051] In some embodiments, the cells in culture are bacterial cells, such as gram-positive bacterial cells (e.g., *Bacillus* cells such as *Bacillus subtilis* cells or *Streptomyces* cells such as *Streptomyces lividans*, *Streptomyces coelicolor*, or *Streptomyces griseus* cells). In some embodiments, the cells in culture are gram-negative bacterial cells (e.g., *Escherichia* cells such as *Escherichia coli* cells or *Pantoea* cells such as *Pantoea citrea* cells). In some embodiments, the cells in culture are fungal, cells such as filamentous fungal cells (e.g., *Trichoderma* cells such as *Trichoderma reesei* cells or *Aspergillus* cells such as *Aspergillus oryzae* and *Aspergillus niger*) or yeast cells (e.g., *Yarrowia* cells such as *Yarrowia lipolytica* cells).

[0052] In some embodiments, the microbial polypeptide carbon source includes one or more polypeptides from yeast or bacteria. In some embodiments, the plant polypeptide carbon source includes one or more polypeptides from soy, corn, canola, jatropha, palm, peanut, sunflower, coconut, mustard, rapeseed, cottonseed, palm kernel, olive, safflower, sesame, or linseed.

[0053] In one aspect, the invention features a product produced by any of the compositions or methods of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0054] Figure 1 is the nucleotide sequence of a kudzu isoprene synthase gene codon-optimized for expression in *E. coli* (SEQ ID NO:1). The atg start codon is in italics, the stop codon is in bold and the added *PstI* site is underlined.

[0055] Figure 2 is a map of pTrcKudzu.

[0056] Figures 3A-3C are the nucleotide sequence of pTrcKudzu (SEQ ID NO:2). The RBS is underlined, the kudzu isoprene synthase start codon is in bold capital letters and the stop codon is in bold, capital, italics letters. The vector backbone is pTrcHis2B.

[0057] Figure 4 is a map of pETNHisKudzu.

[0058] Figures 5A-5C are the nucleotide sequence of pETNHisKudzu (SEQ ID NO:5).

[0059] Figure 6 is a map of pCL-lac-Kudzu.

[0060] Figures 7A-7C are the nucleotide sequence of pCL-lac-Kudzu (SEQ ID NO:7).

[0061] Figure 8A is a graph showing the production of isoprene in *E. coli* BL21 cells with no vector.

[0062] Figure 8B is a graph showing the production of isoprene in *E. coli* BL21 cells with pCL-lac-Kudzu

[0063] Figure 8C is a graph showing the production of isoprene in *E. coli* BL21 cells with pTrcKudzu.

[0064] Figure 8D is a graph showing the production of isoprene in *E. coli* BL21 cells with pETN-HisKudzu.

[0065] Figure 9A is a graph showing OD over time of fermentation of *E. coli* BL21/pTrcKudzu in a 14 liter fed batch fermentation.

[0066] Figure 9B is a graph showing isoprene production over time of fermentation of *E. coli* BL21/pTrcKudzu in a 14 liter fed batch fermentation.

[0067] Figure 10A is a graph showing the production of isoprene in *Pantaea citrea*. Control cells without recombinant kudzu isoprene synthase. Grey diamonds represent isoprene synthesis, black squares represent OD₆₀₀.

[0068] Figure 10B is a graph showing the production of isoprene in *Pantaea citrea* expressing pCL-lac Kudzu. Grey diamonds represent isoprene synthesis, black squares represent OD₆₀₀.

[0069] Figure 10C is a graph showing the production of isoprene in *Pantaea citrea* expressing pTrcKudzu. Grey diamonds represent isoprene synthesis, black squares represent OD₆₀₀.

[0070] Figure 11 is a graph showing the production of isoprene in *Bacillus subtilis* expressing recombinant isoprene synthase. BG3594comK is a *B. subtilis* strain without plasmid (native isoprene production). CF443-BG3594comK is a *B. subtilis* strain with pBSKudzu (recombinant isoprene production). IS on the y-axis indicates isoprene.

[0071] Figures 12A-12C are the nucleotide sequence of pBS Kudzu #2 (SEQ ID NO:57).

[0072] Figure 13 is the nucleotide sequence of kudzu isoprene synthase codon-optimized for expression in *Yarrowia* (SEQ ID NO:8).

[0073] Figure 14 is a map of pTrex3g comprising a kudzu isoprene synthase gene codon-optimized for expression in *Yarrowia*.

[0074] Figures 15A-15C are the nucleotide sequence of vector pSPZ1(MAP29Spb) (SEQ ID NO:11).

[0075] Figure 16 is the nucleotide sequence of the synthetic kudzu (*Pueraria montana*) isoprene gene codon-optimized for expression in *Yarrowia* (SEQ ID NO:12).

[0076] Figure 17 is the nucleotide sequence of the synthetic hybrid poplar (*Populus alba* x *Populus tremula*) isoprene synthase gene (SEQ ID NO:13). The ATG start codon is in bold and the stop codon is underlined.

[0077] Figure 18A (Figures 18A1 and 18A2) shows a schematic outlining construction of vectors pYLA 1, pYL1 and pYL2.

[0078] Figure 18B shows a schematic outlining construction of the vector pYLA(POP1).

[0079] Figure 18C shows a schematic outlining construction of the vector pYLA(KZ1)

[0080] Figure 18D shows a schematic outlining construction of the vector pYLI(KZ1)

[0081] Figure 18E shows a schematic outlining construction of the vector pYLI(MAP29)

[0082] Figure 18F shows a schematic outlining construction of the vector pYLA(MAP29)

[0083] Figure 19 (Figure 19A) shows the MVA and DXP metabolic pathways for isoprene (based on F. Bouvier *et al.*, Progress in Lipid Res. 44: 357-429, 2005). The following description includes alternative names for each polypeptide in the pathways and a reference that discloses an assay for measuring the activity of the indicated polypeptide (each of these references are each hereby incorporated by reference in their entirety, particularly with respect to assays for polypeptide activity for polypeptides in the MVA and DXP pathways).

Mevalonate Pathway: **AACT**; Acetyl-CoA acetyltransferase, MvaE, EC 2.3.1.9. Assay: J. Bacteriol., 184: 2116–2122, 2002; **HMGS**; Hydroxymethylglutaryl-CoA synthase, MvaS, EC 2.3.3.10. Assay: J. Bacteriol., 184: 4065–4070, 2002; **HMGR**; 3-Hydroxy-3-methylglutaryl-CoA reductase, MvaE, EC 1.1.1.34. Assay: J. Bacteriol., 184: 2116–2122, 2002; **MVK**; Mevalonate kinase, ERG12, EC 2.7.1.36. Assay: Curr Genet 19:9-14, 1991. **PMK**; Phosphomevalonate kinase, ERG8, EC 2.7.4.2, Assay: Mol Cell Biol., 11:620–631, 1991; **DPMDC**; Diphosphomevalonate decarboxylase, MVD1, EC 4.1.1.33. Assay: Biochemistry, 33:13355-13362, 1994; **IDI**; Isopentenyl-diphosphate delta-isomerase, IDI1, EC 5.3.3.2. Assay: J. Biol. Chem. 264:19169-19175, 1989. **DXP Pathway:** **DXS**; 1-Deoxyxylulose-5-phosphate synthase, dxs, EC 2.2.1.7. Assay: PNAS, 94:12857-62, 1997; **DXR**; 1-Deoxy-D-

xylulose 5-phosphate reductoisomerase, dxr, EC 2.2.1.7. Assay: Eur. J. Biochem. 269:4446–4457, 2002; **MCT**; 4-Diphosphocytidyl-2C-methyl-D-erythritol synthase, IspD, EC 2.7.7.60. Assay: PNAS, 97: 6451–6456, 2000; **CMK**; 4-Diphosphocytidyl-2-C-methyl-D-erythritol kinase, IspE, EC 2.7.1.148. Assay: PNAS, 97:1062-1067, 2000; **MCS**; 2C-Methyl-D-erythritol 2,4-cyclodiphosphate synthase, IspF, EC 4.6.1.12. Assay: PNAS, 96:11758-11763, 1999; **HDS**; 1-Hydroxy-2-methyl-2-(E)-butenyl 4-diphosphate synthase, ispG, EC 1.17.4.3. Assay: J. Org. Chem., 70:9168 -9174, 2005; **HDR**; 1-Hydroxy-2-methyl-2-(E)-butenyl 4-diphosphate reductase, IspH, EC 1.17.1.2. Assay: JACS, 126:12847-12855, 2004.

[0084] Figure 19 (Figure 19B) illustrates the classical and modified MVA pathways. 1, acetyl-CoA acetyltransferase (**AACT**); 2, HMG-CoA synthase (**HMGS**); 3, HMG-CoA reductase (**HMGR**); 4, mevalonate kinase (**MVK**); 5, phosphomevalonate kinase (**PMK**); 6, diphosphomevalonate decarboxylase (**MVD or DPMDC**); 7, isopentenyl diphosphate isomerase (**IDI**); 8, phosphomevalonate decarboxylase (**PMDC**); 9, isopentenyl phosphate kinase (**IPK**). The classical MVA pathway proceeds from reaction 1 through reaction 7 via reactions 5 and 6, while a modified MVA pathway goes through reactions 8 and 9. P and PP in the structural formula are phosphate and pyrophosphate, respectively. This figure was taken from Koga and Morii, *Microbiology and Mol. Biology Reviews*, 71:97-120, 2007, which is incorporated by reference in its entirety, particular with respect to nucleic acids and polypeptides of the modified MVA pathway. The modified MVA pathway is present, for example, in some archaeal organisms, such as *Methanosarcina mazei*.

[0085] Figure 20 (Figures 20A and 20B) shows graphs representing results of the GC-MS analysis of isoprene production by recombinant *Y. lipolytica* strains without (left) or with (right) a kudzu isoprene synthase gene. The arrows indicate the elution time of the authentic isoprene standard.

[0086] Figure 21 is a map of pTrcKudzu yIDI DXS Kan.

[0087] Figures 22A-22D are the nucleotide sequence of pTrcKudzu yIDI DXS Kan (SEQ ID NO:20).

[0088] Figure 23A is a graph showing production of isoprene from glucose in BL21/pTrcKudzukan. Time 0 is the time of induction with IPTG (400 μ mol). The x-axis is time after induction; the y-axis is OD₆₀₀ and the y2-axis is total productivity of isoprene (μ g/L).

headspace or specific productivity ($\mu\text{g/L headspace/OD}$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0089] Figure 23B is a graph showing production of isoprene from glucose in BL21/pTrcKudzu yIDI kan. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity } (\mu\text{g/L headspace/OD})$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0090] Figure 23C is a graph showing production of isoprene from glucose in BL21/pTrcKudzu DXS kan. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity } (\mu\text{g/L headspace/OD})$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0091] Figure 23D is a graph showing production of isoprene from glucose in BL21/pTrcKudzu yIDI DXS kan. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity } (\mu\text{g/L headspace/OD})$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0092] Figure 23E is a graph showing production of isoprene from glucose in BL21/pCL PtrcKudzu. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity } (\mu\text{g/L headspace/OD})$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0093] Figure 23F is a graph showing production of isoprene from glucose in BL21/pCL PtrcKudzu yIDI. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L}$

headspace or specific productivity ($\mu\text{g/L headspace/OD}$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0094] Figure 23G is a graph showing production of isoprene from glucose in BL21/pCL PtrcKudzu DXS. Time 0 is the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity}$ ($\mu\text{g/L headspace/OD}$). Diamonds represent OD_{600} , circles represent total isoprene productivity ($\mu\text{g/L}$) and squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0095] Figure 23H is a graph showing production of isoprene from glucose in BL21/pTrcKudzuIDIDXSk_{kan}. The arrow indicates the time of induction with IPTG (400 μmol). The x-axis is time after induction; the y-axis is OD_{600} and the y2-axis is total productivity of isoprene ($\mu\text{g/L headspace or specific productivity}$ ($\mu\text{g/L headspace/OD}$). Black diamonds represent OD_{600} , black triangles represent isoprene productivity ($\mu\text{g/L}$) and white squares represent specific productivity of isoprene ($\mu\text{g/L/OD}$).

[0096] Figure 24 is a map of pTrcKKDyIkIS_{kan}.

[0097] Figures 25A-25D are the nucleotide sequence of pTrcKKDyIkIS_{kan} (SEQ ID NO:33).

[0098] Figure 26 is a map of pCL PtrcUpperPathway.

[0099] Figures 27A-27D are the nucleotide sequence of pCL PtrcUpperPathway (SEQ ID NO:46).

[0100] Figure 28 shows a map of the cassette containing the lower MVA pathway and yeast *idi* for integration into the *B. subtilis* chromosome at the *nprE* locus. *nprE* upstream/downstream indicates 1 kb each of sequence from the *nprE* locus for integration. *aprE* promoter (alkaline serine protease promoter) indicates the promoter (-35, -10, +1 transcription start site, RBS) of the *aprE* gene. MVK1 indicates the yeast mevalonate kinase gene. RBS-PMK indicates the yeast phosphomevalonate kinase gene with a *Bacillus* RBS upstream of the start site. RBS-MPD indicates the yeast diphosphomevalonate decarboxylase gene with a *Bacillus* RBS upstream of the start site. RBS-IDI indicates the yeast *idi* gene

with a *Bacillus* RBS upstream of the start site. Terminator indicates the terminator alkaline serine protease transcription terminator from *B. amyliquefaciens*. SpecR indicates the spectinomycin resistance marker. “nprE upstream repeat for amp.” indicates a direct repeat of the upstream region used for amplification.

[0101] Figures 29A-29D are the nucleotide sequence of cassette containing the lower MVA pathway and yeast *idi* for integration into the *B. subtilis* chromosome at the *nprE* locus (SEQ ID NO:47).

[0102] Figure 30 is a map of p9796-poplar.

[0103] Figures 31A-31B are the nucleotide sequence of p9796-poplar (SEQ ID NO:48).

[0104] Figure 32 is a map of pTrcPoplar.

[0105] Figures 33A-33C are the nucleotide sequence of pTrcPoplar (SEQ ID NO:49).

[0106] Figure 34 is a map of pTrcKudzu yIDI Kan.

[0107] Figures 35A-35C are the nucleotide sequence of pTrcKudzu yIDI Kan (SEQ ID NO:50).

[0108] Figure 36 is a map of pTrcKudzuDXS Kan.

[0109] Figures 37A-37C are the nucleotide sequence of pTrcKudzuDXS Kan (SEQ ID NO:51).

[0110] Figure 38 is a map of pCL PtrcKudzu.

[0111] Figures 39A-39C are the nucleotide sequence of pCL PtrcKudzu (SEQ ID NO:52).

[0112] Figure 40 is a map of pCL PtrcKudzu A3.

[0113] Figures 41A-41C are the nucleotide sequence of pCL PtrcKudzu A3 (SEQ ID NO:53).

[0114] Figure 42 is a map of pCL PtrcKudzu yIDI.

[0115] Figures 43A-43C are the nucleotide sequence of pCL PtrcKudzu yIDI (SEQ ID NO:54).

[0116] Figure 44 is a map of pCL PtrcKudzu DXS.

[0117] Figures 45A-45D are the nucleotide sequence of pCL PtrcKudzu DXS (SEQ ID NO:55).

[0118] Figure 46A- 46E shows graphs representing isoprene production from biomass feedstocks. Panel A shows isoprene production from corn stover, Panel B shows isoprene production from bagasse, Panel C shows isoprene production from softwood pulp, Panel D shows isoprene production from glucose, and Panel E shows isoprene production from cells with no additional feedstock. Grey squares represent OD₆₀₀ measurements of the cultures at the indicated times post-inoculation and black triangles represent isoprene production at the indicated times post-inoculation.

[0119] Figure 47A shows a graph representing isoprene production by BL21 (λ DE3) pTrcKudzu yIDI DXS (kan) in a culture with no glucose added. Squares represent OD₆₀₀, and triangles represent isoprene produced (μ g/ml).

[0120] Figure 47B shows a graph representing isoprene production from 1% glucose feedstock invert sugar by BL21 (λ DE3) pTrcKudzu yIDI DXS (kan). Squares represent OD₆₀₀, and triangles represent isoprene produced (μ g/ml).

[0121] Figure 47C shows a graph representing isoprene production from 1% invert sugar feedstock by BL21 (λ DE3) pTrcKudzu yIDI DXS (kan). Squares represent OD₆₀₀, and triangles represent isoprene produced (μ g/ml).

[0122] Figure 47D shows a graph representing isoprene production from 1% AFEX corn stover feedstock by BL21 (λ DE3) pTrcKudzu yIDI DXS (kan). Squares represent OD₆₀₀, and triangles represent isoprene produced (μ g/ml).

[0123] Figure 48A-48C shows graphs demonstrating the effect of yeast extract of isoprene production. Panel A shows the time course of optical density within fermentors fed with varying amounts of yeast extract. Panel B shows the time course of isoprene titer within fermentors fed with varying amounts of yeast extract. The titer is defined as the amount of

isoprene produced per liter of fermentation broth. Panel C shows the effect of yeast extract on isoprene production in *E. coli* grown in fed-batch culture.

[0124] Figure 49A-49C shows graphs demonstrating isoprene production from a 500 L bioreactor with *E. coli* cells containing the pTrcKudzu + yIDI + DXS plasmid. Panel A shows the time course of optical density within the 500-L bioreactor fed with glucose and yeast extract. Panel B shows the time course of isoprene titer within the 500-L bioreactor fed with glucose and yeast extract. The titer is defined as the amount of isoprene produced per liter of fermentation broth. Panel C shows the time course of total isoprene produced from the 500-L bioreactor fed with glucose and yeast extract.

[0125] Figure 50 is a map of pJMupperpathway2.

[0126] Figures 51A-51C are the nucleotide sequence of pJMupperpathway2 (SEQ ID NO:56).

[0127] Figure 52 is a map of pBS Kudzu #2.

[0128] Figure 53A is a graph showing growth during fermentation time of *Bacillus* expressing recombinant kudzu isoprene synthase in 14 liter fed batch fermentation. Black diamonds represent a control strain (BG3594comK) without recombinant isoprene synthase (native isoprene production) and grey triangles represent *Bacillus* with pBSKudzu (recombinant isoprene production).

[0129] Figure 53B is a graph showing isoprene production during fermentation time of *Bacillus* expressing recombinant kudzu isoprene synthase in 14 liter fed batch fermentation. Black diamonds represent a control strain (BG3594comK) without recombinant isoprene synthase (native isoprene production) and grey triangles represent *Bacillus* with pBSKudzu (recombinant isoprene production).

[0130] Figure 54 is a time course of optical density within the 15-L bioreactor fed with glucose.

[0131] Figure 55 is a time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0132] Figure 56 is a time course of total isoprene produced from the 15-L bioreactor fed with glucose.

[0133] Figure 57 is a time course of optical density within the 15-L bioreactor fed with glycerol.

[0134] Figure 58 is a time course of isoprene titer within the 15-L bioreactor fed with glycerol. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0135] Figure 59 is a time course of total isoprene produced from the 15-L bioreactor fed with glycerol.

[0136] Figures 60A-60C are the time courses of optical density, mevalonic acid titer, and specific productivity within the 150-L bioreactor fed with glucose.

[0137] Figures 61A-61C are the time courses of optical density, mevalonic acid titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0138] Figures 62A-62C are the time courses of optical density, mevalonic acid titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0139] Figure 63A-63C are the time courses of optical density, isoprene titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0140] Figures 64A-64C are the time courses of optical density, isoprene titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0141] Figures 65A-65C are the time courses of optical density, isoprene titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0142] Figures 66A-66C are the time courses of optical density, isoprene titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0143] Figure 67A-67C are the time courses of optical density, isoprene titer, and specific productivity within the 15-L bioreactor fed with glucose.

[0144] Figure 68 is a graph of the calculated adiabatic flame temperatures for Series A as a function of fuel concentration for various oxygen levels. The figure legend lists the curves in the order in which they appear in the graph. For example, the first entry in the figure legend (isoprene in air at 40 °C) corresponds to the highest curve in the graph.

[0145] Figure 69 is a graph of the calculated adiabatic flame temperatures for Series B as a function of fuel concentration for various oxygen levels with 4% water. The figure legend lists the curves in the order in which they appear in the graph.

[0146] Figure 70 is a graph of the calculated adiabatic flame temperatures for Series C as a function of fuel concentration for various oxygen levels with 5% CO₂. The figure legend lists the curves in the order in which they appear in the graph.

[0147] Figure 71 is a graph of the calculated adiabatic flame temperatures for Series D as a function of fuel concentration for various oxygen levels with 10% CO₂. The figure legend lists the curves in the order in which they appear in the graph.

[0148] Figure 72 is a graph of the calculated adiabatic flame temperatures for Series E as a function of fuel concentration for various oxygen levels with 15% CO₂. The figure legend lists the curves in the order in which they appear in the graph.

[0149] Figure 73 is a graph of the calculated adiabatic flame temperatures for Series F as a function of fuel concentration for various oxygen levels with 20% CO₂. The figure legend lists the curves in the order in which they appear in the graph.

[0150] Figure 74 is a graph of the calculated adiabatic flame temperatures for Series G as a function of fuel concentration for various oxygen levels with 30% CO₂. The figure legend lists the curves in the order in which they appear in the graph.

[0151] Figure 75A is a table of the conversion of the CAFT Model results from weight percent to volume percent for series A.

[0152] Figure 75B is a graph of the flammability results from the CAFT model for Series A in Figure 68 plotted as volume percent.

[0153] Figure 76A is a table of the conversion of the CAFT Model results from weight percent to volume percent for series B.

[0154] Figure 76B is a graph of the flammability results from the CAFT model for Series B in Figure 69 plotted as volume percent.

[0155] Figure 77 is a figure of the flammability test vessel.

[0156] Figure 78A is a graph of the flammability Curve for Test Series 1: 0% Steam, 0 psig, and 40°C.

[0157] Figure 78B is a table summarizing the explosion and non-explosion data points for Test Series 1.

[0158] Figure 78C is a graph of the flammability curve for Test Series 1 compared with the CAFT Model.

[0159] Figure 79A is a graph of the flammability curve for Test Series 2: 4% Steam, 0 psig, and 40°C.

[0160] Figure 79B is a table summarizing the explosion and non-explosion data points for Test Series 2.

[0161] Figure 79C is a graph of the flammability curve for Test Series 2 compared with the CAFT Model.

[0162] Figures 80A and 80B are a table of the detailed experimental conditions and results for Test Series 1.

[0163] Figure 81 is a table of the detailed experimental conditions and results for Test Series 2.

[0164] Figure 82 is a graph of the calculated adiabatic flame temperature plotted as a function of fuel concentration for various nitrogen/oxygen ratios at 3 atmospheres of pressure.

[0165] Figure 83 is a graph of the calculated adiabatic flame temperature plotted as a function of fuel concentration for various nitrogen/oxygen ratios at 1 atmosphere of pressure.

[0166] Figure 84 is a graph of the flammability envelope constructed using data from Figure 82 and following the methodology described in Example 13. The experimental data

points (circles) are from tests described herein that were conducted at 1 atmosphere initial system pressure.

[0167] Figure 85 is a graph of the flammability envelope constructed using data from Figure 83 and following the methodology described in Example 13. The experimental data points (circles) are from tests described herein that were conducted at 1 atmosphere initial system pressure.

[0168] Figure 86A is a GC/MS chromatogram of fermentation off-gas.

[0169] Figure 86B is an expansion of Fig 86A to show minor volatiles present in fermentation off-gas.

[0170] Figure 87A is a GC/MS chromatogram of trace volatiles present in off-gas following cryo-trapping at -78 °C.

[0171] Figure 87B is a GC/MS chromatogram of trace volatiles present in off-gas following cryo-trapping at -196 °C.

[0172] Figure 87C is an expansion of Fig. 87B.

[0173] Figure 87D is an expansion of Fig. 87C.

[0174] Figures 88A and 88B are GC/MS chromatogram comparing C5 hydrocarbons from petroleum-derived isoprene (Fig. 88A) and biologically produced isoprene (Fig. 88B). The standard contains three C5 hydrocarbon impurities eluting around the main isoprene peak (Fig. 88A). In contrast, biologically produced isoprene contains amounts of ethanol and acetone (run time of 3.41 minutes) (Fig. 88A).

[0175] Figure 89 is a graph of the analysis of fermentation off-gas of an *E. coli* BL21 (DE3) pTrcIS strain expressing a Kudzu isoprene synthase and fed glucose with 3 g/L yeast extract.

[0176] Figure 90 shows the structures of several impurities that are structurally similar to isoprene and may also act as polymerization catalyst poisons.

[0177] Figure 91 is a map of pTrcHis2AUpperPathway (also called pTrcUpperMVA).

[0178] Figures 92A-92C are the nucleotide sequence of pTrcHis2AUpperPathway (also called pTrcUpperMVA) (SEQ ID NO:86).

[0179] Figure 93 is a time course of optical density within the 15-L bioreactor fed with glucose.

[0180] Figure 94 is a time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0181] Figure 95 is a time course of total isoprene produced from the 15-L bioreactor fed with glucose.

[0182] Figure 96 is a time course of optical density within the 15-L bioreactor fed with invert sugar.

[0183] Figure 97 is a time course of isoprene titer within the 15-L bioreactor fed with invert sugar. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0184] Figure 98 is a time course of total isoprene produced from the 15-L bioreactor fed with invert sugar.

[0185] Figure 99 is a time course of optical density within the 15-L bioreactor fed with glucose.

[0186] Figure 100 is a time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0187] Figure 101 is a time course of isoprene specific activity from the 15-L bioreactor fed with glucose.

[0188] Figure 102 is a map of pCLPtrcUpperPathwayHGS2.

[0189] Figures 103A-103C are the nucleotide sequence of pCLPtrcUpperPathwayHGS2 (SEQ ID NO:87).

[0190] Figure 104 is a time course of optical density within the 15-L bioreactor fed with glucose.

[0191] Figure 105 is a time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0192] Figure 106 is a time course of total isoprene produced from the 15-L bioreactor fed with glucose.

[0193] Figure 107 is a map of plasmid MCM330.

[0194] Figures 108A-108C are the nucleotide sequence of plasmid MCM330 (SEQ ID NO:90).

[0195] Figure 109 is a map of pET24D-Kudzu.

[0196] Figures 110A and 110B are the nucleotide sequence of pET24D-Kudzu (SEQ ID NO:101).

[0197] Figure 111A is a time course of optical density within the 15-L bioreactor fed with glucose.

[0198] Figure 111B is a time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0199] Figure 111C is a time course of specific productivity of isoprene in the 15-L bioreactor fed with glucose.

[0200] Figure 112 is a map of plasmid pET24 P.alba HGS.

[0201] Figures 113A and 113B are the nucleotide sequence of plasmid pET24 P.alba HGS (SEQ ID NO:102).

[0202] Figure 114 is a schematic diagram showing restriction sites used for endonuclease digestion to construct plasmid EWL230 and compatible cohesive ends between BspHI and NcoI sites.

[0203] Figure 115 is a map of plasmid EWL230.

[0204] Figures 116A and 116B are the nucleotide sequence of plasmid EWL230 (SEQ ID NO:103).

[0205] Figure 117 is a schematic diagram showing restriction sites used for endonuclease digestion to construct plasmid EWL244 and compatible cohesive ends between NsiI and PstI sites.

[0206] Figure 118 is a map of EWL244.

[0207] Figures 119A and 119B are the nucleotide sequence of plasmid EWL244 (SEQ ID NO:104).

[0208] Figure 120 is a map of plasmids MCM484-487.

[0209] Figures 121A-121C are the nucleotide sequence of plasmid MCM484 (SEQ ID NO:105).

[0210] Figures 122A-122C are the nucleotide sequence of plasmid MCM485 (SEQ ID NO:106).

[0211] Figures 123A-123C are the nucleotide sequence of plasmid MCM486 (SEQ ID NO:107).

[0212] Figures 124A-124C are the nucleotide sequence of plasmid MCM487 (SEQ ID NO:108).

[0213] Figures 125A-125D are graphs of isoprene production by *E. coli* strain (EWL256) expressing genes from the MVA pathway and grown in fed-batch culture at the 15-L scale without yeast extract feeding. Figure 125A shows the time course of optical density within the 15-L bioreactor fed with glucose. Figure 125B shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth. Figure 125C shows the time course of total isoprene produced from the 15-L bioreactor fed with glucose. Figure 125D shows the total carbon dioxide evolution rate (TCER), or metabolic activity profile, within the 15-L bioreactor fed with glucose.

[0214] Figures 126A-126E are graphs of isoprene production by *E. coli* strain (EWL256) expressing genes from the MVA pathway and grown in fed-batch culture at the 15-L scale with yeast extract feeding. Figure 126A shows the time course of optical density within the 15-L bioreactor fed with glucose. Figure 126B shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth. Figure 126C shows the time course of total isoprene produced from the 15-L bioreactor fed with glucose. Figure 126D shows the volumetric productivity within the 15-L bioreactor fed with glucose. An average value of 1.1 g/L/hr was maintained for a 40-hour period (23-63 hours) with yeast extract feeding. Figure 126E shows the carbon dioxide evolution rate (CER), or metabolic activity profile, within the 15-L bioreactor fed with glucose.

[0215] Figures 127A-127D shows production of isoprene from different carbon sources via the MVA (pathway). Figure 127A shows growth of *E. coli* EWL256, which contains both the MVA pathway and isoprene synthase, on either glucose, biomass hydrolysate, glycerol, or acetate as the only carbon source. The different carbon sources were added to a concentration of 1% in the media. A negative control with no added carbon source was included. Growth was measured as optical density at 600 nM. Figure 127B shows specific productivity of isoprene from *E. coli* EWL256 containing both the MVA pathway and isoprene synthase when grown on either glucose, biomass hydrolysate, glycerol, or acetate as only carbon source. The different carbon sources were added to a concentration of 1% in the media. A negative control with no added carbon source was included. Samples were taken 190 minutes, 255 minutes and 317 minutes after inoculation and isoprene produced by the bacteria was measured using GC-MS. Figure 127C shows growth of *E. coli* EWL256 on either glucose or xylose as the only carbon source. The different carbon sources were added to a concentration of 1% in the media. A negative control with no added carbon source was included. Growth was measured as optical density at 600nM. Figure 127D shows specific productivity of isoprene from *E. coli* EWL256 when grown on either glucose or xylose as only carbon source. The carbon sources were added to a concentration of 1% in the media. A negative control with no added carbon source was included. Samples were taken 260 minutes, 322 minutes and 383 minutes after inoculation and isoprene produced by the bacteria was measured using GC-MS.

[0216] Figures 128A and 128B show the production of isoprene by *E. coli* strains from glucose and from fatty acid, respectively. For Figure 128A, eleven colonies from the transformation of WW4 with pMCM118, the plasmid bearing the lower mevalonic acid pathway, were picked to verify the presence of the lower pathway. Cells from the colonies were cultured in TM3 medium containing 0.1% yeast extract and 2% glucose. Aliquots of induced culture were assayed for isoprene production after 4 hours of induction. All colonies showed the production of isoprene. The inducer IPTG had a strong growth inhibitory effect as was evident from the 3 to 4.6-fold reduced cell density in going from 50 to 900 μ M concentration of the inducer (data not shown). The graph shows that higher induction, yields a higher specific titer of isoprene. For Figure 128B, the production culture was inoculated from a washed overnight culture at 1 to 10 dilution. The culture was grown for several hours and induced with 50 μ M IPTG. The left bar shows isoprene assay results four hours after induction followed by a one hour isoprene accumulation assay. The middle bar shows the one hour normalized value for the same culture with the same induction period but analyzed by a 12 hour isoprene accumulation assay. The right bar shows the value for a one hour isoprene accumulation assay of the culture that was induced for 13 hours.

[0217] Figure 129 is a map of the *E. coli*-*Streptomyces* shuttle vector pUWL201PW (6400 bp) used for cloning isoprene synthase from Kudzu. Tsr, thiostrepton resistance gene. Picture is taken from Doumith et al., Mol. Gen. Genet. 264: 477-485, 2000.

[0218] Figure 130 shows isoprene formation by *Streptomyces albus* wild type strain ("wt") and strains harboring plasmid pUWL201PW (negative control) or pUWL201_iso (encoding isoprene synthase from Kudzu).

[0219] Figure 131A is a map of the *M. mazei* archaeal Lower Pathway operon.

[0220] Figures 131B and 131C are the nucleotide sequence of the *M. mazei* archaeal lower Pathway operon (SEQ ID NO:127).

[0221] Figure 132A is a map of MCM376 - MVK from *M. mazei* archaeal Lowerin pET200D.

[0222] Figures 132B and 132C are the nucleotide sequence of MCM376 - MVK from *M. mazei* archaeal Lowerin pET200D (SEQ ID NO:128).

[0223] Figures 133A-133D show growth and specific productivity of isoprene production for EWL256 compared to RM11608-2. Growth (OD550) is represented by the white diamonds; specific productivity of isoprene is represented by the solid bars. The x-axis is time (hours) post-induction with either 200 (Figures 133A and 133B) or 400 (Figures 133C and 133D) μ M IPTG. Y-1 axis is productivity of isoprene (μ g/L/OD/hr) and Y-2 is arbitrary units of optical density at a wavelength of 550. These values for the OD550 must be multiplied by 6.66 to obtain the actual OD of the culture.

[0224] Figure 134 is a map of plasmid pBBRCMPGI1.5-pgl.

[0225] Figures 135A and 135B are the nucleotide sequence of plasmid pBBRCMPGI1.5-pgl (SEQ ID NO:136).

[0226] Figures 136A-136F are graphs of isoprene production by *E. coli* strain expressing *M. mazei* mevalonate kinase, *P. alba* isoprene synthase, and pgl (RHM111608-2), and grown in fed-batch culture at the 15-L scale. Figure 136A shows the time course of optical density within the 15-L bioreactor fed with glucose. Figure 136B shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth. Method for calculating isoprene: cumulative isoprene produced in 59 hrs, g/Fermentor volume at 59 hrs, L [=] g/L broth. Figure 136C also shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. Method for calculating isoprene: $\int$ (Instantaneous isoprene production rate, g/L/hr)dt from t = 0 to 59 hours [=] g/L broth. Figure 136D shows the time course of total isoprene produced from the 15-L bioreactor fed with glucose. Figure 136E shows volumetric productivity within the 15-L bioreactor fed with glucose. Figure 136F shows carbon dioxide evolution rate (CER), or metabolic activity profile, within the 15-L bioreactor fed with glucose.

[0227] Figure 137A is a map of plasmid pJ201:19813.

[0228] Figures 137B and 137C are the nucleotide sequence of pJ201:19813 (SEQ ID NO:137).

[0229] Figure 138 shows the time course of optical density within the 15-L bioreactor fed with glucose.

[0230] Figure 139 shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0231] Figure 140 shows the time course of total isoprene produced from the 15-L bioreactor fed with glucose.

[0232] Figure 141 is a graph illustrating the time course of optical density within the 500-L bioreactor fed with glucose and yeast extract.

[0233] Figure 142 is a graph illustrating the time course of isoprene titer within the 500-L bioreactor fed with glucose and yeast extract. The titer is defined as the amount of isoprene produced per liter of fermentation broth.

[0234] Figure 143 is a graph illustrating the time course of total isoprene produced from the 500-L bioreactor fed with glucose and yeast extract.

DETAILED DESCRIPTION OF THE INVENTION

[0235] The invention provides, *inter alia*, compositions and methods for producing a polymer of isoprene from renewable resources. In one embodiment, provided herein are compositions and methods for making copolymers of isoprene and other non-isoprene molecules. In another embodiment, provided herein is a polymer of isoprene derived from renewable resources of various molecular weights, for example, a cis-1,4-polyisoprene homopolymer rubber. The polymer is produced by polymerizing isoprene derived from renewable resources. The synthetic isoprene containing polymers of this invention offer the benefit of being verifiable as to being derived from non-petrochemical based resources. In one aspect, the isoprene from renewable resources comprises isoprene from bioisoprene compositions. In another aspect, isoprene derived from renewable resources can be isoprene from bioisoprene compositions. In another aspect, the isoprene derived from renewable resources can be a bioisoprene composition produced by culturing cells expressing a heterologous isoprene synthase enzyme. In some aspects, the isoprene derived from renewable resources undergoes polymerization to produce polyisoprene such as cis-1,4-polyisoprene. In other aspects, the isoprene derived from renewable resources undergoes polymerization with one or more of other monomers to produce co-polymers comprising repeating units that are derived from isoprene monomer.

Definitions

[0236] Unless defined otherwise herein, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention pertains. Although any methods and materials similar or equivalent to those described herein find use in the practice of the present invention, the preferred methods and materials are described herein. Accordingly, the terms defined immediately below are more fully described by reference to the Specification as a whole. All documents cited are, in relevant part, incorporated herein by reference. However, the citation of any document is not to be construed as an admission that it is prior art with respect to the present invention.

[0237] As used herein, “renewable resources” refers to resources that are not fossil fuels. Generally, renewable resources are derived from living organisms or recently living organisms that can be replenished as they are consumed. Renewable resources can be replaced by natural ecological cycles or sound management practices. Non-limiting examples include biomass (e.g., switchgrass, hemp, corn, poplar, willow, sorghum, sugarcane), trees, and other plants. Renewable resources, renewable carbon sources and bio-renewable resources are generally interchangeable herein.

[0238] As used herein, “at least a portion of the isoprene starting composition” can refer to at least about 1%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, 99.5%, 99.6%, 99.7%, 99.8%, 99.9%, or 100% of the isoprene starting composition undergoing polymerization.

[0239] The term “isoprene” or “isoprene monomer” refers to 2-methyl-1,3-butadiene (CAS# 78-79-5), which is the direct and final volatile C5 hydrocarbon product from the elimination of pyrophosphate from 3,3-dimethylallyl pyrophosphate (DMAPP), and does not involve the linking or polymerization of [an] IPP molecule(s) to [a] DMAPP molecule(s). The term “isoprene” is not generally intended to be limited to its method of production unless indicated otherwise herein.

[0240] As used herein, “biologically produced isoprene” or “bioisoprene” is isoprene produced by any biological means, such as produced by genetically engineered cell cultures, natural microbials, plants or animals.

[0241] A “bioisoprene composition” refers to a composition that can be produced by biological mean, such as systems (e.g., cells) that are engineered to produce isoprene. It contains isoprene and other compounds that are co-produced (including impurities) and/or isolated together with isoprene. A bioisoprene composition usually contains fewer hydrocarbon impurities than isoprene produced from petrochemical sources and often requires minimal treatment in order to be of polymerization grade. A bioisoprene composition also has a different impurity profile from a petrochemically produced isoprene composition.

[0242] Bioisoprene derived from renewable carbon can be converted to a variety of polymers by chemical polymerization. Provided herein are methods for recovering isoprene from fermentation and subsequent conversion to polymers comprising repeating units that are derived from isoprene monomer. These methods include, but are not limited to, recovering and purifying isoprene from fermentation off-gas and subsequent gas or liquid phase polymerization. Both continuous and batch mode processes are contemplated within the scope of the invention.

[0243] As further detailed herein, bioisoprene compositions are distinguished from petroleum-based isoprene (herein referred to as “petro-isoprene”) compositions in that bioisoprene compositions are substantially free of any contaminating unsaturated C5 hydrocarbons that are usually present in petro-isoprene compositions, such as, but not limited to, 1,3-cyclopentadiene, *trans*-1,3-pentadiene, *cis*-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, and *cis*-pent-3-ene-1-yne. If any contaminating unsaturated C5 hydrocarbons are present in the bioisoprene starting material composition described herein, they are present in lower levels than that in petro-isoprene compositions. Several of these impurities are particularly problematic given their structural similarity to isoprene and the fact that they can act as polymerization catalyst poisons. As detailed below, biologically produced isoprene compositions can be substantially free of any contaminating unsaturated C5 hydrocarbons without undergoing extensive purification.

[0244] Bioisoprene composition is distinguished from petro-isoprene composition in that bioisoprene composition contains other bio-byproducts (compounds derived from the biological sources and/or associated the biological processes that are obtained together with

bioisoprene) that are not present or present in much lower levels in petro-isoprene compositions, such as alcohols, aldehydes, ketone and the like. The bio-byproducts may include, but are not limited to, ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, 2,3-cycloheptenolpyridine, 3-hexen-1-ol, 3-hexen-1-yl acetate, limonene, geraniol (trans-3,7-dimethyl-2,6-octadien-1-ol), citronellol (3,7-dimethyl-6-octen-1-ol) or a linear isoprene polymer (such as a linear isoprene dimer or a linear isoprene trimer derived from the polymerization of multiple isoprene units). In some aspects, one or more of these compounds are removed from the bioisoprene composition prior to polymerization. In other aspects, one or more of these compounds are included in the polymerization reaction.

[0245] Further, bioisoprene is distinguished from petro-isoprene by carbon finger-printing. In one aspect, bioisoprene has a higher radioactive carbon-14 (^{14}C) content or higher $^{14}\text{C}/^{12}\text{C}$ ratio than petro-isoprene. Bioisoprene is produced from renewable carbon sources, thus the ^{14}C content or the $^{14}\text{C}/^{12}\text{C}$ ratio in bio-isoprene is the same as that in the present atmosphere. Petro-isoprene, on the other hand, is derived from fossil fuels deposited thousands to millions of years ago, thus the ^{14}C content or the $^{14}\text{C}/^{12}\text{C}$ ratio is diminished due to radioactive decay. As discussed in greater detail herein, the fuel products derived from bioisoprene has higher ^{14}C content or $^{14}\text{C}/^{12}\text{C}$ ratio than fuel products derived from petro-isoprene. In one embodiment, a fuel product derived from bioisoprene described herein has a ^{14}C content or $^{14}\text{C}/^{12}\text{C}$ ratio similar to that in the atmosphere. In another aspect, bioisoprene can be analytically distinguished from petro-isoprene by the stable carbon isotope ration ($^{13}\text{C}/^{12}\text{C}$), which can be reported as “delta values” represented by the symbol $\delta^{13}\text{C}$. For examples, for isoprene derived from extractive distillation of C₅ streams from petroleum refineries, $\delta^{13}\text{C}$ is about -22‰ to about -24‰. This range is typical for light, unsaturated hydrocarbons derived from petroleum, and products derived from petroleum-based isoprene typically contain

isoprenic units with the same $\delta^{13}\text{C}$. Bioisoprene produced by fermentation of corn-derived glucose ($\delta^{13}\text{C}$ -10.73‰) with minimal amounts of other carbon-containing nutrients (e.g., yeast extract) produces isoprene which can be polymerized into polyisoprene with $\delta^{13}\text{C}$ -14.66‰ to -14.85‰. Products produced from such bioisoprene are expected to have $\delta^{13}\text{C}$ values that are less negative than those derived from petroleum-based isoprene.

[0246] While isoprene can be obtained by fractionating petroleum, the purification of this material is expensive and time-consuming. Petroleum cracking of the C5 stream of hydrocarbons produces only about 15% isoprene. Isoprene is also naturally produced by a variety of microbial, plant, and animal species. In particular, two pathways have been identified for the biosynthesis of isoprene: the mevalonate (MVA) pathway and the non-mevalonate (DXP) pathway. Genetically engineered cell cultures in bioreactors have produced isoprene more efficiently, in larger quantities, in higher purities and/or with unique impurity profiles, e.g. as described in U.S. provisional patent application Nos. 61/013,386 and 61/013,574, filed on December 13, 2007, WO 2009/076676, U.S. provisional patent application Nos. 61/134,094, 61/134,947, 61/134,011 and 61/134,103, filed on July 2, 2008, WO 2010/003007, U.S. provisional patent application No. 61/097,163, filed on September 15, 2008, WO 2010/031079, U.S. provisional patent application No. 61/097,186, filed on September 15, 2008, WO 2010/031062, U.S. provisional patent application No. 61/097,189, filed on September 15, 2008, WO 2010/031077, U.S. provisional patent application No. 61/097,200, filed on September 15, 2008, WO 2010/031068, U.S. provisional patent application No. 61/097,204, filed on September 15, 2008, WO 2010/031076, U.S. provisional patent application No. 61/141,652, filed on December 30, 2008, PCT/US09/069862, U.S. patent application No. 12/335,071, filed December 15, 2008 (US 2009/0203102 A1) and U.S. patent application No. 12/429,143, filed April 23, 2009 (US 2010/0003716 A1), which are incorporated by reference in their entireties.

[0247] In one aspect, the invention features compositions and systems for producing a polymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; where at least a portion of the isoprene starting composition undergoes polymerization. An isoprene starting material derived from renewable resources is subjected to chemical polymerization to produce a polymer comprising repeating units that are derived from isoprene monomer from renewable sources. In one aspect, an isoprene starting

composition derived from renewable resources can be a bioisoprene composition derived from renewable carbon sources.

Exemplary starting isoprene compositions

[0248] In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than or about 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, or 1000 mg of isoprene. In some embodiments, the starting isoprene composition comprises greater than or about 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 g of isoprene. In some embodiments, the starting isoprene composition comprises greater than or about 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 200, 500, 1000 kg of isoprene. In some embodiments, the amount of isoprene in the starting composition is between about 2 to about 5,000 mg, such as between about 2 to about 100 mg, about 100 to about 500 mg, about 500 to about 1,000 mg, about 1,000 to about 2,000 mg, or about 2,000 to about 5,000 mg. In some embodiments, the amount of isoprene in the starting composition is between about 20 to about 5,000 mg, about 100 to about 5,000 mg, about 200 to about 2,000 mg, about 200 to about 1,000 mg, about 300 to about 1,000 mg, or about 400 to about 1,000 mg. In some embodiments, the amount of isoprene in the starting composition is between about 2 to about 5,000 g, such as between about 2 to about 100 g, about 100 to about 500 g, about 500 to about 1,000 g, about 1,000 to about 2,000 g, or about 2,000 to about 5,000 g. In some embodiments, the amount of isoprene in the starting composition is between about 2 to about 5,000 kg, about 10 to about 2,000 kg, about 20 to about 1,000 kg, about 20 to about 500 kg, about 30 to about 200 kg, or about 40 to about 100 kg. In some embodiments, greater than or about 20, 25, 30, 40, 50, 60, 70, 80, 90, or 95% (w/w) of the volatile organic fraction of the starting composition is isoprene.

[0249] In some embodiments, the isoprene starting composition derived from renewable resources comprises greater than or about 98.0, 98.5, 99.0, 99.5, or 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the starting composition. In some embodiments, the highly pure isoprene starting composition comprises greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the starting composition. In some embodiments, the starting composition has a relative detector response of greater than or about 98.0, 98.5, 99.0, 99.5, or 100% for isoprene compared to the detector response for all C5 hydrocarbons in the starting

composition. In some embodiments, the starting composition has a relative detector response of greater than or about 99.90, 99.91, 99.92, 99.93, 99.94, 99.95, 99.96, 99.97, 99.98, 99.99, or 100% for isoprene compared to the detector response for all C5 hydrocarbons in the starting composition. In some embodiments, the starting isoprene composition comprises between about 98.0 to about 98.5, about 98.5 to about 99.0, about 99.0 to about 99.5, about 99.5 to about 99.8, about 99.8 to 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the starting composition. In some embodiments, the starting isoprene composition comprises between about 99.90 to about 99.92, about 99.92 to about 99.94, about 99.94 to about 99.96, about 99.96 to about 99.98, about 99.98 to 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the starting composition.

[0250] In some embodiments, the isoprene starting composition derived from renewable resources comprises less than or about 2.0, 1.5, 1.0, 0.5, 0.2, 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% C5 hydrocarbons other than isoprene (such 1,3-cyclopentadiene, *cis*-1,3-pentadiene, *trans*-1,3-pentadiene, , 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, or *cis*-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the starting composition. In some embodiments, the starting composition has a relative detector response of less than or about 2.0, 1.5, 1.0, 0.5, 0.2, 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for C5 hydrocarbons other than isoprene compared to the detector response for all C5 hydrocarbons in the starting composition. In some embodiments, the starting composition has a relative detector response of less than or about 2.0, 1.5, 1.0, 0.5, 0.2, 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for 1,3-cyclopentadiene, *cis*-1,3-pentadiene, *trans*-1,3-pentadiene, , 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, or *cis*-pent-3-ene-1-yne compared to the detector response for all C5 hydrocarbons in the starting composition. In some embodiments, the highly pure isoprene starting composition comprises between about 0.02 to about 0.04%, about 0.04 to about 0.06%, about 0.06 to 0.08%, about 0.08 to 0.10%, or about 0.10 to about 0.12% C5 hydrocarbons other than isoprene (such 1,3-cyclopentadiene, *cis*-1,3-pentadiene, *trans*-1,3-pentadiene, , 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, or *cis*-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the starting composition.

[0251] In some embodiments, the isoprene starting composition derived from renewable resources comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 µg/L of a compound that inhibits the polymerization of isoprene for any compound in the starting composition that inhibits the polymerization of isoprene. In some embodiments, the starting isoprene composition comprises between about 0.005 to about 50, such as about 0.01 to about 10, about 0.01 to about 5, about 0.01 to about 1, about 0.01 to about 0.5, or about 0.01 to about 0.005 µg/L of a compound that inhibits the polymerization of isoprene for any compound in the starting composition that inhibits the polymerization of isoprene. In some embodiments, the starting isoprene composition comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 µg/L of a hydrocarbon other than isoprene (such as 1,3-cyclopentadiene, *cis*-1,3-pentadiene, *trans*-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, or *cis*-pent-3-ene-1-yne). In some embodiments, the starting isoprene composition comprises between about 0.005 to about 50, such as about 0.01 to about 10, about 0.01 to about 5, about 0.01 to about 1, about 0.01 to about 0.5, or about 0.01 to about 0.005 µg/L of a hydrocarbon other than isoprene. In some embodiments, the starting isoprene composition comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 µg/L of a protein or fatty acid (such as a protein or fatty acid that is naturally associated with natural rubber).

[0252] In some embodiments, the isoprene starting composition derived from renewable resources comprises less than or about 10, 5, 1, 0.8, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of alpha acetylenes, piperynes, acetonitrile, or 1,3-cyclopentadiene. In some embodiments, the starting isoprene composition comprises less than or about 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of sulfur or allenes. In some embodiments, the starting isoprene composition comprises less than or about 30, 20, 15, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of all acetylenes (such as 1-pentyne, 2-pentyne, 3-methyl-1-butyne, pent-4-ene-1-yne, *trans*-pent-3-ene-1-yne, and *cis*-pent-3-ene-1-yne). In some embodiments, the starting isoprene composition comprises less than or about 2000, 1000, 500, 200, 100, 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of isoprene dimers, such as cyclic isoprene dimers (*e.g.*, cyclic C10 compounds derived from the dimerization of two isoprene units).

[0253] In some embodiments, the isoprene starting composition derived from renewable resources includes ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl

ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In particular embodiments, the starting isoprene composition comprises greater than or about 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 60, 80, 100, or 120 µg/L of ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In some embodiments, the isoprene composition comprises between about 0.005 to about 120, such as about 0.01 to about 80, about 0.01 to about 60, about 0.01 to about 40, about 0.01 to about 30, about 0.01 to about 20, about 0.01 to about 10, about 0.1 to about 80, about 0.1 to about 60, about 0.1 to about 40, about 5 to about 80, about 5 to about 60, or about 5 to about 40 µg/L of ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol, or any two or more of the foregoing.

[0254] In some embodiments, the isoprene starting composition derived from renewable resources includes one or more of the following components: 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, 2,3-cycloheptenolpyridine, or a linear isoprene polymer (such as a linear isoprene dimer or a linear isoprene trimer derived from the polymerization of multiple isoprene units). In various embodiments, the amount of one of these components relative to amount of isoprene in units of percentage by weight (*i.e.*, weight of the component divided by the weight of isoprene times 100) is greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110% (w/w). In some embodiments, the relative detector response for the second compound compared to the detector response for isoprene is greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110%. In various embodiments, the amount of one of these components relative to amount of isoprene in units of percentage by weight (*i.e.*, weight of the component divided by the weight of isoprene times 100) is between about 0.01 to about 105 % (w/w), such as about 0.01 to about 90, about 0.01 to about 80, about 0.01 to about 50,

about 0.01 to about 20, about 0.01 to about 10, about 0.02 to about 50, about 0.05 to about 50, about 0.1 to about 50, or 0.1 to about 20% (w/w).

[0255] In some embodiments, at least a portion of the isoprene starting composition derived from renewable resources is in a gas phase. In some embodiments, at least a portion of the isoprene starting composition derived from renewable resources is in a liquid phase (such as a condensate). In some embodiments, at least a portion of the isoprene starting composition derived from renewable resources is in a solid phase. In some embodiments, at least a portion of the isoprene starting composition derived from renewable resources is absorbed to a solid support, such as a support that includes silica and/or activated carbon. In some embodiments, the starting isoprene composition is mixed with one or more solvents. In some embodiments, the starting isoprene composition is mixed with one or more gases.

[0256] Techniques for producing isoprene in cultures of cells that produce isoprene are described in U.S. provisional patent application Nos. 61/013,386 and 61/013,574, filed on December 13, 2007, WO 2009/076676, U.S. provisional patent application Nos. 61/134,094, 61/134,947, 61/134,011 and 61/134,103, filed on July 2, 2008, WO 2010/003007, U.S. provisional patent application No. 61/097,163, filed on September 15, 2008, WO 2010/031079, U.S. provisional patent application No. 61/097,186, filed on September 15, 2008, WO 2010/031062, U.S. provisional patent application No. 61/097,189, filed on September 15, 2008, WO 2010/031077, U.S. provisional patent application No. 61/097,200, filed on September 15, 2008, WO 2010/031068, U.S. provisional patent application No. 61/097,204, filed on September 15, 2008, WO 2010/031076, U.S. provisional patent application No. 61/141,652, filed on December 30, 2008, PCT/US09/069862, U.S. patent application No. 12/335,071, filed December 15, 2008 (US 2009/0203102 A1) and U.S. patent application No. 12/429,143, filed April 23, 2009 (US 2010/0003716 A1), the teachings of which are incorporated herein by reference for the purpose of teaching techniques for producing and recovering isoprene by such a process. In any case, U.S. provisional patent application Nos. 61/013,386 and 61/013,574, filed on December 13, 2007, WO 2009/076676, U.S. provisional patent application Nos. 61/134,094, 61/134,947, 61/134,011 and 61/134,103, filed on July 2, 2008, WO 2010/003007, U.S. provisional patent application No. 61/097,163, filed on September 15, 2008, WO 2010/031079, U.S. provisional patent application No. 61/097,186, filed on September 15, 2008, WO 2010/031062, U.S. provisional patent application No. 61/097,189, filed on September 15, 2008, WO 2010/031077, U.S. provisional

patent application No. 61/097,200, filed on September 15, 2008, WO 2010/031068, U.S. provisional patent application No. 61/097,204, filed on September 15, 2008, WO 2010/031076, U.S. provisional patent application No. 61/141,652, filed on December 30, 2008, PCT/US09/069862, U.S. patent application No. 12/335,071, filed December 15, 2008 (US 2009/0203102 A1) and U.S. patent application No. 12/429,143, filed April 23, 2009 (US 2010/0003716 A1) teach compositions and methods for the production of increased amounts of isoprene in cell cultures. U.S. patent application No. 12/335,071, filed December 15, 2008 (US 2009/0203102 A1) further teaches compositions and methods for co-production of isoprene and hydrogen from cultured cells. In particular, these compositions and methods increase the rate of isoprene production and increase the total amount of isoprene that is produced. For example, cell culture systems that generate 4.8×10^4 nmole/g_{wcm}/hr of isoprene have been produced (Table 1). The efficiency of these systems is demonstrated by the conversion of about 2.2% of the carbon that the cells consume from a cell culture medium into isoprene. As shown in the Examples and Table 2, approximately 3 g of isoprene per liter of broth was generated. If desired, even greater amounts of isoprene can be obtained using other conditions, such as those described herein. In some embodiments, a renewable carbon source is used for the production of isoprene. In some embodiments, the production of isoprene is decoupled from the growth of the cells. In some embodiments, the concentrations of isoprene and any oxidants are within the nonflammable ranges to reduce or eliminate the risk that a fire may occur during production or recovery of isoprene. The compositions and methods are desirable because they allow high isoprene yield per cell, high carbon yield, high isoprene purity, high productivity, low energy usage, low production cost and investment, and minimal side reactions. This efficient, large scale, biosynthetic process for isoprene production provides an isoprene source for synthetic isoprene-based products such as rubber and provides a desirable, low-cost alternative to using natural rubber.

[0257] As discussed further below, the amount of isoprene produced by cells can be greatly increased by introducing a heterologous nucleic acid encoding an isoprene synthase polypeptide (*e.g.*, a plant isoprene synthase polypeptide) into the cells. Isoprene synthase polypeptides convert dimethylallyl diphosphate (DMAPP) into isoprene. As shown in the Examples, a heterologous *Pueraria Montana* (kudzu) or *Populus alba* (Poplar) isoprene synthase polypeptide was expressed in a variety of host cells, such as *Escherichia coli*, *Pantoea citrea*, *Bacillus subtilis*, *Yarrowia lipolytica*, and *Trichoderma reesei*. As also shown in the Examples, a heterologous *Methanosarcina mazei* (*M. mazei*) mevalonate kinase

(MVK) was expressed in host cells such as *Escherichia coli* to increase isoprene production. All of these cells produced more isoprene than the corresponding cells without the heterologous isoprene synthase polypeptide. As illustrated in Tables 1 and 2, large amounts of isoprene are produced using the methods described herein. For example, *B. subtilis* cells with a heterologous isoprene synthase nucleic acid produced approximately 10-fold more isoprene in a 14 liter fermentor than the corresponding control *B. subtilis* cells without the heterologous nucleic acid (Table 2). The production of 60.5 g of isoprene per liter of broth (mg/L, wherein the volume of broth includes both the volume of the cell medium and the volume of the cells) by *E. coli* and 30 mg/L by *B. subtilis* in fermentors indicates that significant amounts of isoprene can be generated (Table 2). If desired, isoprene can be produced on an even larger scale or other conditions described herein can be used to further increase the amount of isoprene. The vectors listed in Tables 1 and 2 and the experimental conditions are described in further detail below and in the Examples section.

Table 1: Exemplary yields of isoprene from a shake flask using the cell cultures and methods of the invention. The assay for measuring isoprene production is described in Example I, part II. For this assay, a sample was removed at one or more time points from the shake flask and cultured for 30 minutes. The amount of isoprene produced in this sample was then measured. The headspace concentration and specific rate of isoprene production are listed in Table 1 and described further herein.

Strain	Isoprene Production in a Headspace vial*	
	Headspace concentration $\mu\text{g/L}_{\text{gas}}$	Specific Rate $\mu\text{g/L}_{\text{broth}}/\text{hr}/\text{OD}$ ($\text{nmol/g}_{\text{wcm}}/\text{hr}$)
<i>E. coli</i> BL21/ pTrcKudzu IS	1.40	53.2 (781.2)
<i>E. coli</i> BL21/ Pcl DXS yidi Kudzu IS	7.61	289.1 (4.25×10^3)
<i>E. coli</i> BL21/MCM127 with kudzu IS and entire MVA pathway	23.0	874.1 (1.28×10^4)

<i>E. coli</i> BL21/ Pet N-HisKudzu IS	1.49	56.6 (831.1)
<i>Pantoea citrea</i> /pTrcKudzu IS	0.66	25.1 (368.6)
<i>E. coli</i> w/ <i>Poplar IS</i> [Miller (2001)]	-	5.6 (82.2)
<i>Bacillus licheniformis</i> Fall US 5849970	-	4.2 (61.4)
<i>Yarrowia lipolytica</i> with kudzu isoprene synthase	~0.05 µg/L	~2 (~30)
<i>Trichoderma reesei</i> with kudzu isoprene synthase	~0.05 µg/L	~2 (~30)
<i>E. coli</i> BL21/ pTrcKKD _{yIk} IS with kudzu IS and lower MVA pathway	85.9	3.2 x 10 ³ (4.8 x 10 ⁴)

*Normalized to 1 mL of 1 OD₆₀₀, cultured for 1 hour in a sealed headspace vial with a liquid to headspace volume ratio of 1:19.

Table 2: Exemplary yields of isoprene in a fermentor using the cell cultures and methods of the invention. The assay for measuring isoprene production is described in Example I, part II. For this assay, a sample of the off-gas of the fermentor was taken and analyzed for the amount of isoprene. The peak headspace concentration (which is the highest headspace concentration during the fermentation), titer (which is the cumulative, total amount of isoprene produced per liter of broth), and peak specific rate of isoprene production (which is the highest specific rate during the fermentation) are listed in Table 2 and described further herein.

Strain	Isoprene Production in Fermentors		
	Peak Headspace concentration** ($\mu\text{g/L}_{\text{gas}}$)	Titer ($\text{mg/L}_{\text{broth}}$)	Peak Specific rate $\mu\text{g/L}_{\text{broth}}/\text{hr}/\text{OD}$ ($\text{nmol/g}_{\text{wcm}}/\text{hr}$)
<i>E. coli</i> BL21 /pTrcKudzu with Kudzu IS	52	41.2	37 (543.3)
<i>E. coli</i> FM5/pTrcKudzu IS	3	3.5	21.4 (308.1)
<i>E. coli</i> BL21/ triple strain (DXS, yidi, IS)	285	300	240 (3.52×10^3)
<i>E. coli</i> FM5/ triple strain (DXS, yidi, IS)	50.8	29	180.8 (2.65×10^3)
<i>E. coli</i> /MCM127 with Kudzu IS and entire MVA pathway	1094	250	875 (1.28×10^4)
<i>E. coli</i> BL21/pCLPtrc UpperPathway gi1.2 integrated lower pathway pTrcKudzu	2418	1640	1248 (1.83×10^4)
<i>E. coli</i> BL21/pCLPtrc UpperPathwayHGS2 -pTrcKKDyIkIS	3500	3300	1088 (1.60×10^4)
<i>Bacillus subtilis</i> wild-type	1.5	2.5	0.8 (11.7)

<i>Bacillus pBS Kudzu IS</i>	16.6	~30 (over 100 hours)	5 (73.4)
<i>Bacillus Marburg 6051 [Wagner and Fall (1999)]</i>	2.04	0.61	24.5 (359.8)
<i>Bacillus Marburg 6051 Fall US 5849970</i>	0.7	0.15	6.8 (100)
<i>E. coli</i> BL21/pCLP _{trc} Upper Pathway and gil.2KKDyI and pTrcAlba-mMVK	2.03×10^4	3.22×10^4	5.9×10^3 (8.66×10^4)
<i>E. coli</i> BL21/pCLP _{trc} Upper Pathway and gil.2KKDyI and pTrcAlba-mMVK plus pBBRCMPGI1.5pgl	3.22×10^4	6.05×10^4	1.28×10^4 (1.88×10^5)

**Normalized to an off-gas flow rate of 1 vvm (1 volume off-gas per 1 L_{broth} per minute).

[0258] Additionally, isoprene production by cells that contain a heterologous isoprene synthase nucleic acid can be enhanced by increasing the amount of a 1-deoxy-D-xylulose-5-phosphate synthase (DXS) polypeptide and/or an isopentenyl diphosphate isomerase (IDI) polypeptide expressed by the cells. For example, a DXS nucleic acid and/or an IDI nucleic acid can be introduced into the cells. The DXS nucleic acid may be a heterologous nucleic acid or a duplicate copy of an endogenous nucleic acid. Similarly, the IDI nucleic acid may be a heterologous nucleic acid or a duplicate copy of an endogenous nucleic acid. In some embodiments, the amount of DXS and/or IDI polypeptide is increased by replacing the endogenous DXS and/or IDI promoters or regulatory regions with other promoters and/or

regulatory regions that result in greater transcription of the DXS and/or IDI nucleic acids. In some embodiments, the cells contain both a heterologous nucleic acid encoding an isoprene synthase polypeptide (*e.g.*, a plant isoprene synthase nucleic acid) and a duplicate copy of an endogenous nucleic acid encoding an isoprene synthase polypeptide.

[0259] The encoded DXS and IDI polypeptides are part of the DXP pathway for the biosynthesis of isoprene (Figure 19A). DXS polypeptides convert pyruvate and D-glyceraldehyde-3-phosphate into 1-deoxy-D-xylulose-5-phosphate. While not intending to be bound by any particular theory, it is believed that increasing the amount of DXS polypeptide increases the flow of carbon through the DXP pathway, leading to greater isoprene production. IDI polypeptides catalyze the interconversion of isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP). While not intending to be bound by any particular theory, it is believed that increasing the amount of IDI polypeptide in cells increases the amount (and conversion rate) of IPP that is converted into DMAPP, which in turn is converted into isoprene.

[0260] For example, fermentation of *E. coli* cells with a kudzu isoprene synthase, *S. cerevisia* IDI, and *E. coli* DXS nucleic acids was used to produce isoprene. The levels of isoprene varied from 50 to 300 µg/L over a time period of 15 hours (Example 7, part VII). As another example, fermentation of *E. coli* with *M. mazei* mevalonate kinase (MVK), *P. alba* isoprene synthase, the upper MVA pathway, and the integrated lower MVA pathway was used to produce isoprene. The levels of isoprene varied from 32 to 35.6 g/L over a time period of 67 hours (Example 14, part III).

[0261] In yet another example, fermentation of *E. coli* with *M. mazei* mevalonate kinase (MVK), *P. alba* isoprene synthase, *pgl* over-expression (RHM111608-2), the upper MVA pathway, and the integrated lower MVA pathway were used to produce isoprene. The levels of isoprene vary from 33.2 g/L to 40.0 g/L over a time period of 40 hours or 48.6 g/L to 60.5 g/L over a time period of 59 hours (Example 17, part (ii)).

[0262] In some embodiments, the presence of heterologous or extra endogenous isoprene synthase, IDI, and DXS nucleic acids causes cells to grow more reproducibly or remain viable for longer compared to the corresponding cell with only one or two of these heterologous or extra endogenous nucleic acids. For example, cells containing heterologous isoprene synthase, IDI, and DXS nucleic acids grew better than cells with only heterologous

isoprene synthase and DXS nucleic acids or with only a heterologous isoprene synthase nucleic acid. Also, heterologous isoprene synthase, IDI, and DXS nucleic acids were successfully operably linked to a strong promoter on a high copy plasmid that was maintained by *E. coli* cells, suggesting that large amounts of these polypeptides could be expressed in the cells without causing an excessive amount of toxicity to the cells. While not intending to be bound to a particular theory, it is believed that the presence of heterologous or extra endogenous isoprene synthase and IDI nucleic acids may reduce the amount of one or more potentially toxic intermediates that would otherwise accumulate if only a heterologous or extra endogenous DXS nucleic acid was present in the cells.

[0263] In some embodiments, the production of isoprene by cells that contain a heterologous isoprene synthase nucleic acid is augmented by increasing the amount of a MVA polypeptide expressed by the cells (Figures 19A and 19B). Exemplary MVA pathways polypeptides include any of the following polypeptides: acetyl-CoA acetyltransferase (AA-CoA thiolase) polypeptides, 3-hydroxy-3-methylglutaryl-CoA synthase (HMG-CoA synthase) polypeptides, 3-hydroxy-3-methylglutaryl-CoA reductase (HMG-CoA reductase) polypeptides, mevalonate kinase (MVK) polypeptides, phosphomevalonate kinase (PMK) polypeptides, diphosphomevalonate decarboxylase (MVD) polypeptides, phosphomevalonate decarboxylase (PMDC) polypeptides, isopentenyl phosphate kinase (IPK) polypeptides, IDI polypeptides, and polypeptides (*e.g.*, fusion polypeptides) having an activity of two or more MVA pathway polypeptides. For example, one or more MVA pathway nucleic acids can be introduced into the cells. In some embodiments, the cells contain the upper MVA pathway, which includes AA-CoA thiolase, HMG-CoA synthase, and HMG-CoA reductase nucleic acids. In some embodiments, the cells contain the lower MVA pathway, which includes MVK, PMK, MVD, and IDI nucleic acids. In some embodiments, the cells contain the entire MVA pathway, which includes AA-CoA thiolase, HMG-CoA synthase, HMG-CoA reductase, MVK, PMK, MVD, and IDI nucleic acids. In some embodiments, the cells contain an entire MVA pathway that includes AA-CoA thiolase, HMG-CoA synthase, HMG-CoA reductase, MVK, PMDC, IPK, and IDI nucleic acids. The MVA pathway nucleic acids may be heterologous nucleic acids or duplicate copies of endogenous nucleic acids. In some embodiments, the amount of one or more MVA pathway polypeptides is increased by replacing the endogenous promoters or regulatory regions for the MVA pathway nucleic acids with other promoters and/or regulatory regions that result in greater transcription of the MVA pathway nucleic acids. In some embodiments, the cells contain both a heterologous

nucleic acid encoding an isoprene synthase polypeptide (*e.g.*, a plant isoprene synthase nucleic acid) and a duplicate copy of an endogenous nucleic acid encoding an isoprene synthase polypeptide.

[0264] For example, *E. coli* cells containing a nucleic acid encoding a kudzu isoprene synthase polypeptide and nucleic acids encoding *Saccharomyces cerevisia* MVK, PMK, MVD, and IDI polypeptides generated isoprene at a rate of 6.67×10^4 nmol/L_{broth}/OD₆₀₀/hr (*see* Example 8). Additionally, a 14 liter fermentation of *E. coli* cells with nucleic acids encoding *Enterococcus faecalis* AA-CoA thiolase, HMG-CoA synthase, and HMG-CoA reductase polypeptides produced 22 grams of mevalonic acid (an intermediate of the MVA pathway). A shake flask of these cells produced 2-4 grams of mevalonic acid per liter. These results indicate that heterologous MVA pathway nucleic acids are active in *E. coli*. *E. coli* cells that contain nucleic acids for both the upper MVA pathway and the lower MVA pathway as well as a kudzu isoprene synthase (strain MCM 127) produced significantly more isoprene (874 µg/L_{broth}/hr/OD) compared to *E. coli* cells with nucleic acids for only the lower MVA pathway and the kudzu isoprene synthase (strain MCM 131) (*see* Table 3 and Example 8, part VIII). *E. coli* cells containing a nucleic acid encoding *P. alba* isoprene synthase polypeptide and a nucleic acid encoding *M. mazei* MVK polypeptide generated 320.6 g (at a peak specific rate of 9.54×10^4 nmol/L_{broth}/OD₆₀₀/hr (*i.e.* 9.5×10^{-5} mol/L_{broth}/OD₆₀₀/hr)) of isoprene during a 67 hour fermentation in the absence of yeast extract feeding or 395.5 g (at a peak specific rate of 8.66×10^4 nmol/L_{broth}/OD₆₀₀/hr) during a 68 hour fermentation in the presence of yeast extract feeding (*see* Example 14).

[0265] In some embodiments, at least a portion of the cells maintain the heterologous isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acid for at least about 5, 10, 20, 50, 75, 100, 200, 300, or more cell divisions in a continuous culture (such as a continuous culture without dilution). In some embodiments of any of the aspects of the invention, the nucleic acid comprising the heterologous or duplicate copy of an endogenous isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acid also comprises a selective marker, such as a kanamycin, ampicillin, carbenicillin, gentamicin, hygromycin, phleomycin, bleomycin, neomycin, or chloramphenicol antibiotic resistance nucleic acid.

[0266] As indicated in Example 7, part VI, the amount of isoprene produced can be further increased by adding yeast extract to the cell culture medium using *E. coli* cells with kudzu

isoprene synthase, *S. cerevisia* IDI, and *E. coli* DXS nucleic acids to produce isoprene. In particular, the amount of isoprene produced was linearly proportional to the amount of yeast extract in the cell medium for the concentrations tested (Figure 48C). Additionally, approximately 0.11 grams of isoprene per liter of broth was produced from a cell medium with yeast extract and glucose (Example 7, part VIII). Increasing the amount of yeast extract in the presence of glucose resulted in more isoprene being produced than increasing the amount of glucose in the presence of yeast extract. Also, increasing the amount of yeast extract allowed the cells to produce a high level of isoprene for a longer length of time and improved the health of the cells.

[0267] Isoprene production was also demonstrated using three types of hydrolyzed biomass (bagasse, corn stover, and soft wood pulp) as the carbon source (Figures 46A-C and Figures 127A and 127B). *E. coli* cells with kudzu isoprene synthase, *S. cerevisia* IDI, and *E. coli* DXS nucleic acids produced as much isoprene from these hydrolyzed biomass carbon sources as from the equivalent amount of glucose (*e.g.*, 1% glucose, w/v). *E. coli* cells expressing *P. alba* isoprene synthase and the MVA pathway produced isoprene at a higher initial growth rate from ammonia fiber expansion (AFEX) pretreated corn stover than from the equivalent amount of glucose. (Figures 127A and 127B). If desired, any other biomass carbon source can be used in the compositions and methods of the invention. Biomass carbon sources are desirable because they are cheaper than many conventional cell mediums, thereby facilitating the economical production of isoprene.

[0268] Additionally, invert sugar was shown to function as a carbon source for the generation of isoprene (Figure 47D). For example, 2.4 g/L of isoprene was produced from cells expressing MVA pathway polypeptides and a Kudzu isoprene synthase (Example 8, part XV). Glycerol was also used as a carbon source for the generation of 2.2 mg/L of isoprene from cells expressing a Kudzu isoprene synthase (Example 8, part XIV). Expressing a DXS nucleic acid, an IDI nucleic acid, and/or one or more MVA pathway nucleic acids (such as nucleic acids encoding the entire MVA pathway) in addition to an isoprene synthase nucleic acid may increase the production of isoprene from glycerol.

[0269] Additionally, xylose, acetate, and glycerol were also shown to function as a carbon source for the generation of isoprene (Figures 127A-127D). For example, *E. coli* cells with *P. alba* isoprene synthase and the MVA pathway grown on acetate as the only carbon source

had a specific productivity of isoprene about twice as high as during growth on glucose (Example 14, Part IV; Figures 127A and 127B).

[0270] In some embodiments, an oil is included in the cell medium. For example, *B. subtilis* cells containing a kudzu isoprene synthase nucleic acid produced isoprene when cultured in a cell medium containing an oil and a source of glucose (Example 4, part III). As another example, *E. coli* fadR atoC mutant cells containing the upper and lower MVA pathway plus kudzu isoprene synthase produced isoprene when cultured in a cell medium containing palm oil and a source of glucose (Example 16, part II). In some embodiments, more than one oil (such as 2, 3, 4, 5, or more oils) is included in the cell medium. While not intending to be bound to any particular theory, it is believed that (i) the oil may increase the amount of carbon in the cells that is available for conversion to isoprene, (ii) the oil may increase the amount of acetyl-CoA in the cells, thereby increasing the carbon flow through the MVA pathway, and/or (ii) the oil may provide extra nutrients to the cells, which is desirable since a lot of the carbon in the cells is converted to isoprene rather than other products. In some embodiments, cells that are cultured in a cell medium containing oil naturally use the MVA pathway to produce isoprene or are genetically modified to contain nucleic acids for the entire MVA pathway. In some embodiments, the oil is partially or completely hydrolyzed before being added to the cell culture medium to facilitate the use of the oil by the host cells.

[0271] One of the major hurdles to commercial production of small molecules such as isoprene in cells (*e.g.*, bacteria) is the decoupling of production of the molecule from growth of the cells. In some embodiments for the commercially viable production of isoprene, a significant amount of the carbon from the feedstock is converted to isoprene, rather than to the growth and maintenance of the cells ("carbon efficiency"). In various embodiments, the cells convert greater than or about 0.0015, 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.12, 0.14, 0.16, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, or 8.0% of the carbon in the cell culture medium into isoprene. In particular embodiments, a significant portion of the carbon from the feedstock that is converted to downstream products is converted to isoprene. As described further in Example 11, *E. coli* cells expressing MVA pathway and kudzu isoprene synthase nucleic acids exhibited decoupling of the production of isoprene or the intermediate mevalonic acid from growth, resulting in high carbon efficiency. In particular, mevalonic acid was formed from cells

expressing the upper MVA pathway from *Enterococcus faecalis*. Isoprene was formed from cells expressing the upper MVA pathway from *Enterococcus faecalis*, the lower MVA pathway from *Saccharomyces cerevisiae*, and the isoprene synthase from *Pueraria montana* (Kudzu). This decoupling of isoprene or mevalonic acid production from growth was demonstrated in four different strains of *E. coli*: BL21(LDE3), BL21(LDE3) Tuner, FM5, and MG1655. The first two *E. coli* strains are B strains, and the latter two are K12 strains. Decoupling of production from growth was also demonstrated in a variant of MG1655 with *ack* and *pta* genes deleted. This variant also demonstrated less production of acetate.

Exemplary Polypeptides and Nucleic Acids

[0272] Various isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids can be used in the compositions and methods of the invention.

[0273] As used herein, “polypeptides” includes polypeptides, proteins, peptides, fragments of polypeptides, and fusion polypeptides that include part or all of a first polypeptide (*e.g.*, an isoprene synthase, DXS, IDI, or MVA pathway polypeptide) and part or all of a second polypeptide (*e.g.*, a peptide that facilitates purification or detection of the fusion polypeptide, such as a His-tag). In some embodiments, the fusion polypeptide has an activity of two or more MVA pathway polypeptides (such as AA-CoA thiolase and HMG-CoA reductase polypeptides). In some embodiments, the polypeptide is a naturally-occurring polypeptide (such as the polypeptide encoded by an *Enterococcus faecalis mvaE* nucleic acid) that has an activity of two or more MVA pathway polypeptides.

[0274] In various embodiments, a polypeptide has at least or about 50, 100, 150, 175, 200, 250, 300, 350, 400, or more amino acids. In some embodiments, the polypeptide fragment contains at least or about 25, 50, 75, 100, 150, 200, 300, or more contiguous amino acids from a full-length polypeptide and has at least or about 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, or 100% of an activity of a corresponding full-length polypeptide. In particular embodiments, the polypeptide includes a segment of or the entire amino acid sequence of any naturally-occurring isoprene synthase, DXS, IDI, or MVA pathway polypeptide. In some embodiments, the polypeptide has one or more mutations compared to the sequence of a wild-type (*i.e.*, a sequence occurring in nature) isoprene synthase, DXS, IDI, or MVA pathway polypeptide.

[0275] In some embodiments, the polypeptide is an isolated polypeptide. As used herein, an “isolated polypeptide” is not part of a library of polypeptides, such as a library of 2, 5, 10, 20, 50 or more different polypeptides and is separated from at least one component with which it occurs in nature. An isolated polypeptide can be obtained, for example, by expression of a recombinant nucleic acid encoding the polypeptide.

[0276] In some embodiments, the polypeptide is a heterologous polypeptide. By “heterologous polypeptide” is meant a polypeptide whose amino acid sequence is not identical to that of another polypeptide naturally expressed in the same host cell. In particular, a heterologous polypeptide is not identical to a wild-type polypeptide that is found in the same host cell in nature.

[0277] As used herein, a “nucleic acid” refers to two or more deoxyribonucleotides and/or ribonucleotides in either single or double-stranded form. In some embodiments, the nucleic acid is a recombinant nucleic acid. By “recombinant nucleic acid” means a nucleic acid of interest that is free of one or more nucleic acids (*e.g.*, genes) which, in the genome occurring in nature of the organism from which the nucleic acid of interest is derived, flank the nucleic acid of interest. The term therefore includes, for example, a recombinant DNA which is incorporated into a vector, into an autonomously replicating plasmid or virus, or into the genomic DNA of a prokaryote or eukaryote, or which exists as a separate molecule (*e.g.*, a cDNA, a genomic DNA fragment, or a cDNA fragment produced by PCR or restriction endonuclease digestion) independent of other sequences. In various embodiments, a nucleic acid is a recombinant nucleic acid. In some embodiments, an isoprene synthase, *eife*, DXS, IDI, or MVA pathway nucleic acid is operably linked to another nucleic acid encoding all or a portion of another polypeptide such that the recombinant nucleic acid encodes a fusion polypeptide that includes an isoprene synthase, *eife*, DXS, IDI, or MVA pathway polypeptide and all or part of another polypeptide (*e.g.*, a peptide that facilitates purification or detection of the fusion polypeptide, such as a His-tag). In some embodiments, part or all of a recombinant nucleic acid is chemically synthesized. It is to be understood that mutations, including single nucleotide mutations, can occur within a nucleic acid as defined herein.

[0278] In some embodiments, the nucleic acid is a heterologous nucleic acid. By “heterologous nucleic acid” is meant a nucleic acid whose nucleic acid sequence is not identical to that of another nucleic acid naturally found in the same host cell.

[0279] In particular embodiments, the nucleic acid includes a segment of or the entire nucleic acid sequence of any naturally-occurring isoprene synthase, DXS, IDI, or MVA pathway nucleic acid. In some embodiments, the nucleic acid includes at least or about 50, 100, 150, 200, 300, 400, 500, 600, 700, 800, or more contiguous nucleotides from a naturally-occurring isoprene synthase nucleic acid DXS, IDI, or MVA pathway nucleic acid. In some embodiments, the nucleic acid has one or more mutations compared to the sequence of a wild-type (*i.e.*, a sequence occurring in nature) isoprene synthase, DXS, IDI, or MVA pathway nucleic acid. In some embodiments, the nucleic acid has one or more mutations (*e.g.*, a silent mutation) that increase the transcription or translation of isoprene synthase, DXS, IDI, or MVA pathway nucleic acid. In some embodiments, the nucleic acid is a degenerate variant of any nucleic acid encoding an isoprene synthase, DXS, IDI, or MVA pathway polypeptide.

[0280] “Codon degeneracy” refers to divergence in the genetic code permitting variation of the nucleotide sequence without affecting the amino acid sequence of an encoded polypeptide. The skilled artisan is well aware of the “codon-bias” exhibited by a specific host cell in usage of nucleotide codons to specify a given amino acid. Therefore, when synthesizing a nucleic acid for improved expression in a host cell, it is desirable in some embodiments to design the nucleic acid such that its frequency of codon usage approaches the frequency of preferred codon usage of the host cell.

[0281] The accession numbers of exemplary isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids are listed in Appendix 1 (the accession numbers of Appendix 1 and their corresponding sequences are herein incorporated by reference in their entirety, particularly with respect to the amino acid and nucleic acid sequences of isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids). The Kegg database also contains the amino acid and nucleic acid sequences of numerous exemplary isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids (*see*, for example, the world-wide web at “genome.jp/kegg/pathway/map/map00100.html” and the sequences therein, which are each hereby incorporated by reference in their entirety, particularly with respect to the amino acid and nucleic acid sequences of isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids). In some embodiments, one or more of the isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and/or nucleic acids have a sequence identical to a sequence publicly available on December 12,

2007 or December 11, 2008, such as any of the sequences that correspond to any of the accession numbers in Appendix 1 or any of the sequences present in the Kegg database. Additional exemplary isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and nucleic acids are described further below.

Exemplary Isoprene Synthase Polypeptides and Nucleic Acids

[0282] As noted above, isoprene synthase polypeptides convert dimethylallyl diphosphate (DMAPP) into isoprene. Exemplary isoprene synthase polypeptides include polypeptides, fragments of polypeptides, peptides, and fusions polypeptides that have at least one activity of an isoprene synthase polypeptide. Standard methods can be used to determine whether a polypeptide has isoprene synthase polypeptide activity by measuring the ability of the polypeptide to convert DMAPP into isoprene *in vitro*, in a cell extract, or *in vivo*. In an exemplary assay, cell extracts are prepared by growing a strain (*e.g.*, the *E. coli*/pTrcKudzu strain described herein) in the shake flask method as described in Example 1. After induction is complete, approximately 10 mLs of cells are pelleted by centrifugation at 7000 x g for 10 minutes and resuspended in 5 ml of PEB without glycerol. The cells are lysed using a French Pressure cell using standard procedures. Alternatively the cells are treated with lysozyme (Ready-Lyse lysozyme solution; EpiCentre) after a freeze/thaw at -80C.

[0283] Isoprene synthase polypeptide activity in the cell extract can be measured, for example, as described in Silver *et al.*, *J. Biol. Chem.* 270:13010-13016, 1995 and references therein, which are each hereby incorporated by reference in their entireties, particularly with respect to assays for isoprene synthase polypeptide activity. DMAPP (Sigma) is evaporated to dryness under a stream of nitrogen and rehydrated to a concentration of 100 mM in 100 mM potassium phosphate buffer pH 8.2 and stored at -20 °C. To perform the assay, a solution of 5 µl of 1M MgCl₂, 1 mM (250 µg/ml) DMAPP, 65 µl of Plant Extract Buffer (PEB) (50 mM Tris-HCl, pH 8.0, 20 mM MgCl₂, 5% glycerol, and 2 mM DTT) is added to 25 µl of cell extract in a 20 ml Headspace vial with a metal screw cap and teflon coated silicon septum (Agilent Technologies) and cultured at 37 °C for 15 minutes with shaking. The reaction is quenched by adding 200 µl of 250 mM EDTA and quantified by GC/MS as described in Example 1, part II.

[0284] Exemplary isoprene synthase nucleic acids include nucleic acids that encode a polypeptide, fragment of a polypeptide, peptide, or fusion polypeptide that has at least one

activity of an isoprene synthase polypeptide. Exemplary isoprene synthase polypeptides and nucleic acids include naturally-occurring polypeptides and nucleic acids from any of the source organisms described herein as well as mutant polypeptides and nucleic acids derived from any of the source organisms described herein.

[0285] In some embodiments, the isoprene synthase polypeptide or nucleic acid is from the family Fabaceae, such as the Faboideae subfamily. In some embodiments, the isoprene synthase polypeptide or nucleic acid is a polypeptide or nucleic acid from *Pueraria montana* (kudzu) (Sharkey *et al.*, Plant Physiology 137: 700-712, 2005), *Pueraria lobata*, poplar (such as *Populus alba*, *Populus nigra*, *Populus trichocarpa*, *Populus alba x tremula* (CAC35696), or *Populus alba*) (Sasaki *et al.*, FEBS Letters 579(11): 2514-2518, 2005; Miller *et al.*, Planta 213: 483-487, 2001), aspen (such as *Populus tremuloides*) (Silver *et al.*, JBC 270(22): 13010-1316, 1995), or English Oak (*Quercus robur*) (Zimmer *et al.*, WO 98/02550), which are each hereby incorporated by reference in their entirety, particularly with respect to isoprene synthase nucleic acids and the expression of isoprene synthase polypeptides. Suitable isoprene synthases include, but are not limited to, those identified by Genbank Accession Nos. AY341431, AY316691, AY279379, AJ457070, and AY182241, which are each hereby incorporated by reference in their entirety, particularly with respect to sequences of isoprene synthase nucleic acids and polypeptides. In some embodiments, the isoprene synthase polypeptide or nucleic acid is not a naturally-occurring polypeptide or nucleic acid from *Quercus robur* (*i.e.*, the isoprene synthase polypeptide or nucleic acid is an isoprene synthase polypeptide or nucleic acid other than a naturally-occurring polypeptide or nucleic acid from *Quercus robur*). In some embodiments, the isoprene synthase nucleic acid or polypeptide is a naturally-occurring polypeptide or nucleic acid from poplar. In some embodiments, the isoprene synthase nucleic acid or polypeptide is not a naturally-occurring polypeptide or nucleic acid from poplar.

Exemplary DXS Polypeptides and Nucleic Acids

[0286] As noted above, 1-deoxy-D-xylulose-5-phosphate synthase (DXS) polypeptides convert pyruvate and D-glyceraldehyde-3-phosphate into 1-deoxy-D-xylulose-5-phosphate. Exemplary DXS polypeptides include polypeptides, fragments of polypeptides, peptides, and fusions polypeptides that have at least one activity of a DXS polypeptide. Standard methods (such as those described herein) can be used to determine whether a polypeptide has DXS

polypeptide activity by measuring the ability of the polypeptide to convert pyruvate and D-glyceraldehyde-3-phosphate into 1-deoxy-D-xylulose-5-phosphate *in vitro*, in a cell extract, or *in vivo*. Exemplary DXS nucleic acids include nucleic acids that encode a polypeptide, fragment of a polypeptide, peptide, or fusion polypeptide that has at least one activity of a DXS polypeptide. Exemplary DXS polypeptides and nucleic acids include naturally-occurring polypeptides and nucleic acids from any of the source organisms described herein as well as mutant polypeptides and nucleic acids derived from any of the source organisms described herein.

Exemplary IDI Polypeptides and Nucleic Acids

[0287] Isopentenyl diphosphate isomerase polypeptides (isopentenyl-diphosphate delta-isomerase or IDI) catalyses the interconversion of isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP) (*e.g.*, converting IPP into DMAPP and/or converting DMAPP into IPP). Exemplary IDI polypeptides include polypeptides, fragments of polypeptides, peptides, and fusions polypeptides that have at least one activity of an IDI polypeptide. Standard methods (such as those described herein) can be used to determine whether a polypeptide has IDI polypeptide activity by measuring the ability of the polypeptide to interconvert IPP and DMAPP *in vitro*, in a cell extract, or *in vivo*. Exemplary IDI nucleic acids include nucleic acids that encode a polypeptide, fragment of a polypeptide, peptide, or fusion polypeptide that has at least one activity of an IDI polypeptide. Exemplary IDI polypeptides and nucleic acids include naturally-occurring polypeptides and nucleic acids from any of the source organisms described herein as well as mutant polypeptides and nucleic acids derived from any of the source organisms described herein.

Exemplary MVA Pathway Polypeptides and Nucleic Acids

[0288] Exemplary MVA pathway polypeptides include acetyl-CoA acetyltransferase (AA-CoA thiolase) polypeptides, 3-hydroxy-3-methylglutaryl-CoA synthase (HMG-CoA synthase) polypeptides, 3-hydroxy-3-methylglutaryl-CoA reductase (HMG-CoA reductase) polypeptides, mevalonate kinase (MVK) polypeptides, phosphomevalonate kinase (PMK) polypeptides, diphosphomevalonate decarboxylase (MVD) polypeptides, phosphomevalonate decarboxylase (PMDC) polypeptides, isopentenyl phosphate kinase (IPK) polypeptides, IDI polypeptides, and polypeptides (*e.g.*, fusion polypeptides) having an activity of two or more MVA pathway polypeptides. In particular, MVA pathway polypeptides include

polypeptides, fragments of polypeptides, peptides, and fusions polypeptides that have at least one activity of an MVA pathway polypeptide. Exemplary MVA pathway nucleic acids include nucleic acids that encode a polypeptide, fragment of a polypeptide, peptide, or fusion polypeptide that has at least one activity of an MVA pathway polypeptide. Exemplary MVA pathway polypeptides and nucleic acids include naturally-occurring polypeptides and nucleic acids from any of the source organisms described herein as well as mutant polypeptides and nucleic acids derived from any of the source organisms described herein.

[0289] In particular, acetyl-CoA acetyltransferase polypeptides (AA-CoA thiolase or AACT) convert two molecules of acetyl-CoA into acetoacetyl-CoA. Standard methods (such as those described herein) can be used to determine whether a polypeptide has AA-CoA thiolase polypeptide activity by measuring the ability of the polypeptide to convert two molecules of acetyl-CoA into acetoacetyl-CoA *in vitro*, in a cell extract, or *in vivo*.

[0290] 3-Hydroxy-3-methylglutaryl-CoA synthase (HMG-CoA synthase or HMGS) polypeptides convert acetoacetyl-CoA into 3-hydroxy-3-methylglutaryl-CoA. Standard methods (such as those described herein) can be used to determine whether a polypeptide has HMG-CoA synthase polypeptide activity by measuring the ability of the polypeptide to convert acetoacetyl-CoA into 3-hydroxy-3-methylglutaryl-CoA *in vitro*, in a cell extract, or *in vivo*.

[0291] 3-Hydroxy-3-methylglutaryl-CoA reductase (HMG-CoA reductase or HMGR) polypeptides convert 3-hydroxy-3-methylglutaryl-CoA into mevalonate. Standard methods (such as those described herein) can be used to determine whether a polypeptide has HMG-CoA reductase polypeptide activity by measuring the ability of the polypeptide to convert 3-hydroxy-3-methylglutaryl-CoA into mevalonate *in vitro*, in a cell extract, or *in vivo*.

[0292] Mevalonate kinase (MVK) polypeptide phosphorylates mevalonate to form mevalonate-5-phosphate. Standard methods (such as those described herein) can be used to determine whether a polypeptide has MVK polypeptide activity by measuring the ability of the polypeptide to convert mevalonate into mevalonate-5-phosphate *in vitro*, in a cell extract, or *in vivo*.

[0293] Phosphomevalonate kinase (PMK) polypeptides phosphorylates mevalonate-5-phosphate to form mevalonate-5-diphosphate. Standard methods (such as those described

herein) can be used to determine whether a polypeptide has PMK polypeptide activity by measuring the ability of the polypeptide to convert mevalonate-5-phosphate into mevalonate-5-diphosphate *in vitro*, in a cell extract, or *in vivo*.

[0294] Diphosphomevalonate decarboxylase (MVD or DPMDC) polypeptides convert mevalonate-5-diphosphate into isopentenyl diphosphate (IPP). Standard methods (such as those described herein) can be used to determine whether a polypeptide has MVD polypeptide activity by measuring the ability of the polypeptide to convert mevalonate-5-diphosphate into IPP *in vitro*, in a cell extract, or *in vivo*.

[0295] Phosphomevalonate decarboxylase (PMDC) polypeptides convert mevalonate-5-phosphate into isopentenyl phosphate (IP). Standard methods (such as those described herein) can be used to determine whether a polypeptide has PMDC polypeptide activity by measuring the ability of the polypeptide to convert mevalonate-5-phosphate into IP *in vitro*, in a cell extract, or *in vivo*.

[0296] Isopentenyl phosphate kinase (IPK) polypeptides phosphorylate isopentenyl phosphate (IP) to form isopentenyl diphosphate (IPP). Standard methods (such as those described herein) can be used to determine whether a polypeptide has IPK polypeptide activity by measuring the ability of the polypeptide to convert IP into IPP *in vitro*, in a cell extract, or *in vivo*.

[0297] Exemplary IDI polypeptides and nucleic acids are described above.

Exemplary Methods for Isolating Nucleic Acids

[0298] Isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids can be isolated using standard methods. Methods of obtaining desired nucleic acids from a source organism of interest (such as a bacterial genome) are common and well known in the art of molecular biology (*see*, for example, WO 2004/033646 and references cited therein, which are each hereby incorporated by reference in their entireties, particularly with respect to the isolation of nucleic acids of interest). For example, if the sequence of the nucleic acid is known (such as any of the known nucleic acids described herein), suitable genomic libraries may be created by restriction endonuclease digestion and may be screened with probes complementary to the desired nucleic acid sequence. Once the sequence is isolated, the DNA may be amplified using standard primer directed amplification methods such as polymerase

chain reaction (PCR) (U.S. Patent No. 4,683,202, which is incorporated by reference in its entirety, particularly with respect to PCR methods) to obtain amounts of DNA suitable for transformation using appropriate vectors.

[0299] Alternatively, isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids (such as any isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids with a known nucleic acid sequence) can be chemically synthesized using standard methods.

[0300] Additional isoprene synthase, DXS, IDI, or MVA pathway polypeptides and nucleic acids which may be suitable for use in the compositions and methods described herein can be identified using standard methods. For example, cosmid libraries of the chromosomal DNA of organisms known to produce isoprene naturally can be constructed in organisms such as *E. coli*, and then screened for isoprene production. In particular, cosmid libraries may be created where large segments of genomic DNA (35-45 kb) are packaged into vectors and used to transform appropriate hosts. Cosmid vectors are unique in being able to accommodate large quantities of DNA. Generally cosmid vectors have at least one copy of the cos DNA sequence which is needed for packaging and subsequent circularization of the heterologous DNA. In addition to the cos sequence, these vectors also contain an origin of replication such as ColEI and drug resistance markers such as a nucleic acid resistant to ampicillin or neomycin. Methods of using cosmid vectors for the transformation of suitable bacterial hosts are well described in Sambrook *et al.*, Molecular Cloning: A Laboratory Manual, 2nd ed., Cold Spring Harbor, 1989, which is hereby incorporated by reference in its entirety, particularly with respect to transformation methods.

[0301] Typically to clone cosmids, heterologous DNA is isolated using the appropriate restriction endonucleases and ligated adjacent to the cos region of the cosmid vector using the appropriate ligases. Cosmid vectors containing the linearized heterologous DNA are then reacted with a DNA packaging vehicle such as bacteriophage. During the packaging process, the cos sites are cleaved and the heterologous DNA is packaged into the head portion of the bacterial viral particle. These particles are then used to transfect suitable host cells such as *E. coli*. Once injected into the cell, the heterologous DNA circularizes under the influence of the cos sticky ends. In this manner, large segments of heterologous DNA can be introduced and expressed in host cells.

[0302] Additional methods for obtaining isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids include screening a metagenomic library by assay (such as the headspace assay described herein) or by PCR using primers directed against nucleotides encoding for a length of conserved amino acids (for example, at least 3 conserved amino acids). Conserved amino acids can be identified by aligning amino acid sequences of known isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides. Conserved amino acids for isoprene synthase polypeptides can be identified based on aligned sequences of known isoprene synthase polypeptides. An organism found to produce isoprene naturally can be subjected to standard protein purification methods (which are well known in the art) and the resulting purified polypeptide can be sequenced using standard methods. Other methods are found in the literature (*see*, for example, Julsing *et al.*, *Applied. Microbiol. Biotechnol.* 75: 1377-84, 2007; Withers *et al.*, *Appl Environ Microbiol.* 73(19):6277-83, 2007, which are each hereby incorporated by reference in their entireties, particularly with respect to identification of nucleic acids involved in the synthesis of isoprene).

[0303] Additionally, standard sequence alignment and/or structure prediction programs can be used to identify additional DXS, IDI, or MVA pathway polypeptides and nucleic acids based on the similarity of their primary and/or predicted polypeptide secondary structure with that of known DXS, IDI, or MVA pathway polypeptides and nucleic acids. Standard databases such as the swissprot-trembl database (world-wide web at “expasy.org”, Swiss Institute of Bioinformatics Swiss-Prot group CMU - 1 rue Michel Servet CH-1211 Geneva 4, Switzerland) can also be used to identify isoprene synthase, DXS, IDI, or MVA pathway polypeptides and nucleic acids. The secondary and/or tertiary structure of an isoprene synthase, DXS, IDI, or MVA pathway polypeptide can be predicted using the default settings of standard structure prediction programs, such as PredictProtein (630 West, 168 Street, BB217, New York, N.Y. 10032, USA). Alternatively, the actual secondary and/or tertiary structure of an isoprene synthase, DXS, IDI, or MVA pathway polypeptide can be determined using standard methods. Additional isoprene synthase, DXS, IDI, or MVA pathway nucleic acids can also be identified by hybridization to probes generated from known isoprene synthase, DXS, IDI, or MVA pathway nucleic acids.

Exemplary Promoters and Vectors

[0304] Any of the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid described herein can be included in one or more vectors. Accordingly, the invention also features vectors with one more nucleic acids encoding any of the isoprene synthase, DXS, IDI, or MVA pathway polypeptides that are described herein. As used herein, a “vector” means a construct that is capable of delivering, and desirably expressing one or more nucleic acids of interest in a host cell. Examples of vectors include, but are not limited to, plasmids, viral vectors, DNA or RNA expression vectors, cosmids, and phage vectors. In some embodiments, the vector contains a nucleic acid under the control of an expression control sequence.

[0305] As used herein, an “expression control sequence” means a nucleic acid sequence that directs transcription of a nucleic acid of interest. An expression control sequence can be a promoter, such as a constitutive or an inducible promoter, or an enhancer. An “inducible promoter” is a promoter that is active under environmental or developmental regulation. The expression control sequence is operably linked to the nucleic acid segment to be transcribed.

[0306] In some embodiments, the vector contains a selective marker. The term “selective marker” refers to a nucleic acid capable of expression in a host cell that allows for ease of selection of those host cells containing an introduced nucleic acid or vector. Examples of selectable markers include, but are not limited to, antibiotic resistance nucleic acids (*e.g.*, kanamycin, ampicillin, carbenicillin, gentamicin, hygromycin, phleomycin, bleomycin, neomycin, or chloramphenicol) and/or nucleic acids that confer a metabolic advantage, such as a nutritional advantage on the host cell. Exemplary nutritional selective markers include those markers known in the art as *amdS*, *argB*, and *pyr4*. Markers useful in vector systems for transformation of *Trichoderma* are known in the art (*see, e.g.*, Finkelstein, Chapter 6 in *Biotechnology of Filamentous Fungi*, Finkelstein *et al.*, Eds. Butterworth-Heinemann, Boston, MA, Chap. 6., 1992; and Kinghorn *et al.*, *Applied Molecular Genetics of Filamentous Fungi*, Blackie Academic and Professional, Chapman and Hall, London, 1992, which are each hereby incorporated by reference in their entireties, particularly with respect to selective markers). In some embodiments, the selective marker is the *amdS* nucleic acid, which encodes the enzyme acetamidase, allowing transformed cells to grow on acetamide as a nitrogen source. The use of an *A. nidulans amdS* nucleic acid as a selective marker is

described in Kelley *et al.*, *EMBO J.* 4:475 – 479, 1985 and Penttila *et al.*, *Gene* 61:155-164, 1987 (which are each hereby incorporated by reference in their entireties, particularly with respect to selective markers). In some embodiments, an isoprene synthase, DXS, IDI, or MVA pathway nucleic acid integrates into a chromosome of the cells without a selective marker.

[0307] Suitable vectors are those which are compatible with the host cell employed. Suitable vectors can be derived, for example, from a bacterium, a virus (such as bacteriophage T7 or a M-13 derived phage), a cosmid, a yeast, or a plant. Protocols for obtaining and using such vectors are known to those in the art (*see*, for example, Sambrook *et al.*, *Molecular Cloning: A Laboratory Manual*, 2nd ed., Cold Spring Harbor, 1989, which is hereby incorporated by reference in its entirety, particularly with respect to the use of vectors).

[0308] Promoters are well known in the art. Any promoter that functions in the host cell can be used for expression of an isoprene synthase, DXS, IDI, or MVA pathway nucleic acid in the host cell. Initiation control regions or promoters, which are useful to drive expression of isoprene synthase, DXS, IDI, or MVA pathway nucleic acids in various host cells are numerous and familiar to those skilled in the art (*see*, for example, WO 2004/033646 and references cited therein, which are each hereby incorporated by reference in their entireties, particularly with respect to vectors for the expression of nucleic acids of interest). Virtually any promoter capable of driving these nucleic acids is suitable for the present invention including, but not limited to, CYC1, HIS3, GAL1, GAL10, ADH1, PGK, PHO5, GAPDH, ADCI, TRP1, URA3, LEU2, ENO, and TPI (useful for expression in *Saccharomyces*); AOX1 (useful for expression in *Pichia*); and lac, trp, λP_L , λP_R , T7, tac, and trc (useful for expression in *E. coli*).

[0309] In some embodiments, a glucose isomerase promoter is used (*see*, for example, U.S. Patent No. 7,132,527 and references cited therein, which are each hereby incorporated by reference in their entireties, particularly with respect promoters and plasmid systems for expressing polypeptides of interest). Reported glucose isomerase promoter mutants can be used to vary the level of expression of the polypeptide encoded by a nucleic acid operably linked to the glucose isomerase promoter (U.S. Patent No. 7,132,527). In various

embodiments, the glucose isomerase promoter is contained in a low, medium, or high copy plasmid (U.S. Patent No. 7,132,527).

[0310] In various embodiments, an isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acid is contained in a low copy plasmid (*e.g.*, a plasmid that is maintained at about 1 to about 4 copies per cell), medium copy plasmid (*e.g.*, a plasmid that is maintained at about 10 to about 15 copies per cell), or high copy plasmid (*e.g.*, a plasmid that is maintained at about 50 or more copies per cell). In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is operably linked to a T7 promoter. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid operably linked to a T7 promoter is contained in a medium or high copy plasmid. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is operably linked to a Trc promoter. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid operably linked to a Trc promoter is contained in a medium or high copy plasmid. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is operably linked to a Lac promoter. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid operably linked to a Lac promoter is contained in a low copy plasmid. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is operably linked to an endogenous promoter, such as an endogenous *Escherichia*, *Pantaea*, *Bacillus*, *Yarrowia*, *Streptomyces*, or *Trichoderma* promoter or an endogenous alkaline serine protease, isoprene synthase, DXS, IDI, or MVA pathway promoter. In some embodiments, the heterologous or extra endogenous isoprene synthase, DXS, IDI, or MVA pathway nucleic acid operably linked to an endogenous promoter is contained in a high copy plasmid. In some embodiments, the vector is a replicating plasmid that does not integrate into a chromosome in the cells. In some embodiments, part or all of the vector integrates into a chromosome in the cells.

[0311] In some embodiments, the vector is any vector which when introduced into a fungal host cell is integrated into the host cell genome and is replicated. Reference is made to the Fungal Genetics Stock Center Catalogue of Strains (FGSC, the world-wide web at “fgsc.net” and the references cited therein, which are each hereby incorporated by reference in their

entireties, particularly with respect to vectors) for a list of vectors. Additional examples of suitable expression and/or integration vectors are provided in Sambrook *et al.*, Molecular Cloning: A Laboratory Manual, 2nd ed., Cold Spring Harbor, 1989, Current Protocols in Molecular Biology (F. M. Ausubel *et al.* (eds) 1987, Supplement 30, section 7.7.18); van den Hondel *et al.* in Bennett and Lasure (Eds.) More Gene Manipulations in Fungi, Academic Press pp. 396-428, 1991; and U.S. Patent No. 5,874,276, which are each hereby incorporated by reference in their entireties, particularly with respect to vectors. Particularly useful vectors include pFB6, pBR322, PUC18, pUC100, and pENTR/D.

[0312] In some embodiments, an isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is operably linked to a suitable promoter that shows transcriptional activity in a fungal host cell. The promoter may be derived from one or more nucleic acids encoding a polypeptide that is either endogenous or heterologous to the host cell. In some embodiments, the promoter is useful in a *Trichoderma* host. Suitable non-limiting examples of promoters include *cbh1*, *cbh2*, *egl1*, *egl2*, *pepA*, *hfb1*, *hfb2*, *xyn1*, and *amy*. In some embodiments, the promoter is one that is native to the host cell. For example, in some embodiments when *T. reesei* is the host, the promoter is a native *T. reesei* promoter. In some embodiments, the promoter is *T. reesei cbh1*, which is an inducible promoter and has been deposited in GenBank under Accession No. D86235, which is incorporated by reference in its entirety, particularly with respect to promoters. In some embodiments, the promoter is one that is heterologous to the fungal host cell. Other examples of useful promoters include promoters from the genes of *A. awamori* and *A. niger* glucoamylase (*glaA*) (Nunberg *et al.*, *Mol. Cell Biol.* 4:2306-2315, 1984 and Boel *et al.*, *EMBO J.* 3:1581-1585, 1984, which are each hereby incorporated by reference in their entireties, particularly with respect to promoters); *Aspergillus niger* alpha amylases, *Aspergillus oryzae* TAKA amylase, *T. reesei xln1*, and the *T. reesei cellobiohydrolase 1* (EP 137280, which is incorporated by reference in its entirety, particularly with respect to promoters).

[0313] In some embodiments, the expression vector also includes a termination sequence. Termination control regions may also be derived from various genes native to the host cell. In some embodiments, the termination sequence and the promoter sequence are derived from the same source. In another embodiment, the termination sequence is endogenous to the host cell. A particularly suitable terminator sequence is *cbh1* derived from a *Trichoderma* strain (such as *T. reesei*). Other useful fungal terminators include the terminator from an *A. niger*

or *A. awamori* glucoamylase nucleic acid (Nunberg *et al.*, *Mol. Cell Biol.* 4:2306-2315, 1984 and Boel *et al.*, *EMBO J.* 3:1581-1585, 1984; which are each hereby incorporated by reference in their entireties, particularly with respect to fungal terminators). Optionally, a termination site may be included. For effective expression of the polypeptides, DNA encoding the polypeptide are linked operably through initiation codons to selected expression control regions such that expression results in the formation of the appropriate messenger RNA.

[0314] In some embodiments, the promoter, coding, region, and terminator all originate from the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid to be expressed. In some embodiments, the coding region for an isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is inserted into a general-purpose expression vector such that it is under the transcriptional control of the expression construct promoter and terminator sequences. In some embodiments, genes or part thereof are inserted downstream of the strong *cbh1* promoter.

[0315] An isoprene synthase, DXS, IDI, or MVA pathway nucleic acid can be incorporated into a vector, such as an expression vector, using standard techniques (Sambrook *et al.*, *Molecular Cloning: A Laboratory Manual*, Cold Spring Harbor, 1982, which is hereby incorporated by reference in its entirety, particularly with respect to the screening of appropriate DNA sequences and the construction of vectors). Methods used to ligate the DNA construct comprising a nucleic acid of interest (such as an isoprene synthase, DXS, IDI, or MVA pathway nucleic acid), a promoter, a terminator, and other sequences and to insert them into a suitable vector are well known in the art. For example, restriction enzymes can be used to cleave the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid and the vector. Then, the compatible ends of the cleaved isoprene synthase, DXS, IDI, or MVA pathway nucleic acid and the cleaved vector can be ligated. Linking is generally accomplished by ligation at convenient restriction sites. If such sites do not exist, the synthetic oligonucleotide linkers are used in accordance with conventional practice (*see*, Sambrook *et al.*, *Molecular Cloning: A Laboratory Manual*, 2nd ed., Cold Spring Harbor, 1989, and Bennett and Lasure, *More Gene Manipulations in Fungi*, Academic Press, San Diego, pp 70–76, 1991, which are each hereby incorporated by reference in their entireties, particularly with respect to oligonucleotide linkers). Additionally, vectors can be constructed

using known recombination techniques (*e.g.*, Invitrogen Life Technologies, Gateway Technology).

[0316] In some embodiments, it may be desirable to over-express isoprene synthase, DXS, IDI, or MVA pathway nucleic acids at levels far higher than currently found in naturally-occurring cells. This result may be accomplished by the selective cloning of the nucleic acids encoding those polypeptides into multicopy plasmids or placing those nucleic acids under a strong inducible or constitutive promoter. Methods for over-expressing desired polypeptides are common and well known in the art of molecular biology and examples may be found in Sambrook *et al.*, *Molecular Cloning: A Laboratory Manual*, 2nd ed., Cold Spring Harbor, 1989, which is hereby incorporated by reference in its entirety, particularly with respect to cloning techniques.

[0317] The following resources include descriptions of additional general methodology useful in accordance with the invention: Kreigler, *Gene Transfer and Expression; A Laboratory Manual*, 1990 and Ausubel *et al.*, Eds. *Current Protocols in Molecular Biology*, 1994, which are each hereby incorporated by reference in their entireties, particularly with respect to molecular biology and cloning techniques.

Exemplary Source Organisms

[0318] Isoprene synthase, DXS, IDI, or MVA pathway nucleic acids (and their encoded polypeptides) can be obtained from any organism that naturally contains isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids. As noted above, isoprene is formed naturally by a variety of organisms, such as bacteria, yeast, plants, and animals. Organisms contain the MVA pathway, DXP pathway, or both the MVA and DXP pathways for producing isoprene (Figure 19). Thus, DXS nucleic acids can be obtained, *e.g.*, from any organism that contains the DXP pathway or contains both the MVA and DXP pathways. IDI and isoprene synthase nucleic acids can be obtained, *e.g.*, from any organism that contains the MVA pathway, DXP pathway, or both the MVA and DXP pathways. MVA pathway nucleic acids can be obtained, *e.g.*, from any organism that contains the MVA pathway or contains both the MVA and DXP pathways.

[0319] In some embodiments, the nucleic acid sequence of the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid is identical to the sequence of a nucleic acid that is produced

by any of the following organisms in nature. In some embodiments, the amino acid sequence of the isoprene synthase, DXS, IDI, or MVA pathway polypeptide is identical to the sequence of a polypeptide that is produced by any of the following organisms in nature. In some embodiments, the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid or polypeptide is a mutant nucleic acid or polypeptide derived from any of the organisms described herein. As used herein, “derived from” refers to the source of the nucleic acid or polypeptide into which one or more mutations is introduced. For example, a polypeptide that is “derived from a plant polypeptide” refers to polypeptide of interest that results from introducing one or more mutations into the sequence of a wild-type (*i.e.*, a sequence occurring in nature) plant polypeptide.

[0320] In some embodiments, the source organism is a fungus, examples of which are species of *Aspergillus* such as *A. oryzae* and *A. niger*, species of *Saccharomyces* such as *S. cerevisiae*, species of *Schizosaccharomyces* such as *S. pombe*, and species of *Trichoderma* such as *T. reesei*. In some embodiments, the source organism is a filamentous fungal cell. The term “filamentous fungi” refers to all filamentous forms of the subdivision Eumycotina (*see*, Alexopoulos, C. J. (1962), *Introductory Mycology*, Wiley, New York). These fungi are characterized by a vegetative mycelium with a cell wall composed of chitin, cellulose, and other complex polysaccharides. The filamentous fungi are morphologically, physiologically, and genetically distinct from yeasts. Vegetative growth by filamentous fungi is by hyphal elongation and carbon catabolism is obligatory aerobic. The filamentous fungal parent cell may be a cell of a species of, but not limited to, *Trichoderma*, (*e.g.*, *Trichoderma reesei*, the asexual morph of *Hypocrea jecorina*, previously classified as *T. longibrachiatum*, *Trichoderma viride*, *Trichoderma koningii*, *Trichoderma harzianum*) (Sheir-Neirs *et al.*, *Appl. Microbiol. Biotechnol* 20: 46-53, 1984; ATCC No. 56765 and ATCC No. 26921); *Penicillium sp.*, *Humicola sp.* (*e.g.*, *H. insolens*, *H. lanuginosa*, or *H. grisea*); *Chrysosporium sp.* (*e.g.*, *C. lucknowense*), *Gliocladium sp.*, *Aspergillus sp.* (*e.g.*, *A. oryzae*, *A. niger*, *A. sojae*, *A. japonicus*, *A. nidulans*, or *A. awamori*) (Ward *et al.*, *Appl. Microbiol. Biotechnol.* 39: 7380743, 1993 and Goedegebuur *et al.*, *Genet* 41: 89-98, 2002), *Fusarium sp.*, (*e.g.*, *F. roseum*, *F. gramineum*, *F. cerealis*, *F. oxysporum*, or *F. venenatum*), *Neurospora sp.*, (*e.g.*, *N. crassa*), *Hypocrea sp.*, *Mucor sp.*, (*e.g.*, *M. miehei*), *Rhizopus sp.* and *Emmericella sp.* (*see also*, Innis *et al.*, *Sci.* 228: 21-26, 1985). The term “*Trichoderma*” or “*Trichoderma sp.*” or “*Trichoderma spp.*” refer to any fungal genus previously or currently classified as *Trichoderma*.

[0321] In some embodiments, the fungus is *A. nidulans*, *A. awamori*, *A. oryzae*, *A. aculeatus*, *A. niger*, *A. japonicus*, *T. reesei*, *T. viride*, *F. oxysporum*, or *F. solani*. *Aspergillus* strains are disclosed in Ward et al., *Appl. Microbiol. Biotechnol.* 39:738-743, 1993 and Goedegebuur et al., *Curr Gene* 41:89-98, 2002, which are each hereby incorporated by reference in their entirety, particularly with respect to fungi. In particular embodiments, the fungus is a strain of *Trichoderma*, such as a strain of *T. reesei*. Strains of *T. reesei* are known and non-limiting examples include ATCC No. 13631, ATCC No. 26921, ATCC No. 56764, ATCC No. 56765, ATCC No. 56767, and NRRL 15709, which are each hereby incorporated by reference in their entirety, particularly with respect to strains of *T. reesei*. In some embodiments, the host strain is a derivative of RL-P37. RL-P37 is disclosed in Sheir-Neiss et al., *Appl. Microbiol. Biotechnology* 20:46-53, 1984, which is hereby incorporated by reference in its entirety, particularly with respect to strains of *T. reesei*.

[0322] In some embodiments, the source organism is a yeast, such as *Saccharomyces sp.*, *Schizosaccharomyces sp.*, *Pichia sp.*, or *Candida sp.*

[0323] In some embodiments, the source organism is a bacterium, such as strains of *Bacillus* such as *B. licheniformis* or *B. subtilis*, strains of *Pantoea* such as *P. citrea*, strains of *Pseudomonas* such as *P. alcaligenes*, strains of *Streptomyces* such as *S. albus*, *S. lividans*, or *S. rubiginosus*, or strains of *Escherichia* such as *E. coli*.

[0324] As used herein, “the genus *Bacillus*” includes all species within the genus “*Bacillus*,” as known to those of skill in the art, including but not limited to *B. subtilis*, *B. licheniformis*, *B. lentus*, *B. brevis*, *B. stearothermophilus*, *B. alkalophilus*, *B. amyloliquefaciens*, *B. clausii*, *B. halodurans*, *B. megaterium*, *B. coagulans*, *B. circulans*, *B. lautus*, and *B. thuringiensis*. It is recognized that the genus *Bacillus* continues to undergo taxonomical reorganization. Thus, it is intended that the genus include species that have been reclassified, including but not limited to such organisms as *B. stearothermophilus*, which is now named “*Geobacillus stearothermophilus*.” The production of resistant endospores in the presence of oxygen is considered the defining feature of the genus *Bacillus*, although this characteristic also applies to the recently named *Alicyclobacillus*, *Amphibacillus*, *Aneurinibacillus*, *Anoxybacillus*, *Brevibacillus*, *Filobacillus*, *Gracilibacillus*, *Halobacillus*, *Paenibacillus*, *Salibacillus*, *Thermobacillus*, *Ureibacillus*, and *Virgibacillus*.

[0325] In some embodiments, the source organism is a gram-positive bacterium. Non-limiting examples include strains of *Streptomyces* (e.g., *S. albus*, *S. lividans*, *S. coelicolor*, or *S. griseus*) and *Bacillus*. In some embodiments, the source organism is a gram-negative bacterium, such as *E. coli* or *Pseudomonas sp.*

[0326] In some embodiments, the source organism is a plant, such as a plant from the family Fabaceae, such as the Faboideae subfamily. In some embodiments, the source organism is kudzu, poplar (such as *Populus alba x tremula* CAC35696 or *Populus alba*) (Sasaki *et al.*, *FEBS Letters* 579(11): 2514-2518, 2005), aspen (such as *Populus tremuloides*), or *Quercus robur*.

[0327] In some embodiments, the source organism is an algae, such as a green algae, red algae, glaucophytes, chlorarachniophytes, euglenids, chromista, or dinoflagellates.

[0328] In some embodiments, the source organism is a cyanobacteria, such as cyanobacteria classified into any of the following groups based on morphology: *Chroococcales*, *Pleurocapsales*, *Oscillatoriales*, *Nostocales*, or *Stigonematales*.

[0329] In some embodiments, the source organism is an anaerobic organism. Anaerobic organisms can include, but are not limited to, obligate anaerobes, facultative anaerobes, and aerotolerant anaerobes. Such organisms can be any of the organisms listed above, bacteria, yeast, etc. In one embodiment, the obligate anaerobes can be any one or combination selected from the group consisting of *Clostridium ljungdahlii*, *Clostridium autoethanogenum*, *Eurobacterium limosum*, *Clostridium carboxydovorans*, *Peptostreptococcus productus*, and *Butyribacterium methylotrophicum*. It is to be understood that any combination of any of the source organisms described herein can be used for other embodiments of the invention.

Exemplary Host Cells

[0330] A variety of host cells can be used to express isoprene synthase, DXS, IDI, and/or MVA pathway polypeptides and to produce isoprene in the methods of the claimed invention. Exemplary host cells include cells from any of the organisms listed in the prior section under the heading “*Exemplary Source Organisms*.” The host cell may be a cell that naturally produces isoprene or a cell that does not naturally produce isoprene. In some embodiments, the host cell naturally produces isoprene using the DXP pathway, and an isoprene synthase, DXS, and/or IDI nucleic acid is added to enhance production of isoprene using this pathway.

In some embodiments, the host cell naturally produces isoprene using the MVA pathway, and an isoprene synthase and/or one or more MVA pathway nucleic acids are added to enhance production of isoprene using this pathway. In some embodiments, the host cell naturally produces isoprene using the DXP pathway and one or more MVA pathway nucleic acids are added to produce isoprene using part or all of the MVA pathway as well as the DXP pathway. In some embodiments, the host cell naturally produces isoprene using both the DXP and MVA pathways and one or more isoprene synthase, DXS, IDI, or MVA pathway nucleic acids are added to enhance production of isoprene by one or both of these pathways. It is to be understood that any combination of any of the host organisms described herein can be used for other embodiments of the invention.

Exemplary Transformation Methods

[0331] Isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acids or vectors containing them can be inserted into a host cell (*e.g.*, a plant cell, a fungal cell, a yeast cell, or a bacterial cell described herein) using standard techniques for expression of the encoded isoprene synthase, DXS, IDI, and/or MVA pathway polypeptide. Introduction of a DNA construct or vector into a host cell can be performed using techniques such as transformation, electroporation, nuclear microinjection, transduction, transfection (*e.g.*, lipofection mediated or DEAE-Dextrin mediated transfection or transfection using a recombinant phage virus), incubation with calcium phosphate DNA precipitate, high velocity bombardment with DNA-coated microprojectiles, and protoplast fusion. General transformation techniques are known in the art (*see, e.g.*, Current Protocols in Molecular Biology (F. M. Ausubel *et al.* (eds) Chapter 9, 1987; Sambrook *et al.*, Molecular Cloning: A Laboratory Manual, 2nd ed., Cold Spring Harbor, 1989; and Campbell *et al.*, *Curr. Genet.* 16:53-56, 1989, which are each hereby incorporated by reference in their entirety, particularly with respect to transformation methods). The expression of heterologous polypeptide in *Trichoderma* is described in United States Patent 6,022,725; United States Patent 6,268,328; United States Patent 7,262,041; WO 2005/001036; Harkki *et al.*; *Enzyme Microb. Technol.* 13:227-233, 1991; Harkki *et al.*, *Bio Technol.* 7:596-603, 1989; EP 244,234; EP 215,594; and Nevalainen *et al.*, “The Molecular Biology of *Trichoderma* and its Application to the Expression of Both Homologous and Heterologous Genes,” in Molecular Industrial Mycology, Eds. Leong and Berka, Marcel Dekker Inc., NY pp. 129 – 148, 1992, which are each hereby incorporated by reference in their entirety, particularly with respect to transformation and expression

methods). Reference is also made to Cao *et al.*, (*Sci.* 9:991–1001, 2000; EP 238023; and Yelton *et al.*, *Proceedings. Natl. Acad. Sci. USA* 81:1470-1474, 1984 (which are each hereby incorporated by reference in their entireties, particularly with respect to transformation methods) for transformation of *Aspergillus* strains. The introduced nucleic acids may be integrated into chromosomal DNA or maintained as extrachromosomal replicating sequences.

[0332] Any method known in the art may be used to select transformants. In one non-limiting example, stable transformants including an *amdS* marker are distinguished from unstable transformants by their faster growth rate and the formation of circular colonies with a smooth, rather than ragged outline on solid culture medium containing acetamide. Additionally, in some cases a further test of stability is conducted by growing the transformants on a solid non-selective medium (*e.g.*, a medium that lacks acetamide), harvesting spores from this culture medium, and determining the percentage of these spores which subsequently germinate and grow on selective medium containing acetamide.

[0333] In some embodiments, fungal cells are transformed by a process involving protoplast formation and transformation of the protoplasts followed by regeneration of the cell wall in a known manner. In one specific embodiment, the preparation of *Trichoderma* *sp.* for transformation involves the preparation of protoplasts from fungal mycelia (*see*, Campbell *et al.*, *Curr. Genet.* 16:53-56, 1989, which is incorporated by reference in its entirety, particularly with respect to transformation methods). In some embodiments, the mycelia are obtained from germinated vegetative spores. The mycelia are treated with an enzyme that digests the cell wall resulting in protoplasts. The protoplasts are then protected by the presence of an osmotic stabilizer in the suspending medium. These stabilizers include sorbitol, mannitol, potassium chloride, magnesium sulfate, and the like. Usually the concentration of these stabilizers varies between 0.8 M and 1.2 M. It is desirable to use about a 1.2 M solution of sorbitol in the suspension medium.

[0334] Uptake of DNA into the host *Trichoderma* *sp.* strain is dependent upon the calcium ion concentration. Generally, between about 10 mM CaCl₂ and 50 mM CaCl₂ is used in an uptake solution. In addition to the calcium ion in the uptake solution, other compounds generally included are a buffering system such as TE buffer (10 Mm Tris, pH 7.4; 1 mM EDTA) or 10 mM MOPS, pH 6.0 buffer (morpholinepropanesulfonic acid) and polyethylene glycol (PEG). While not intending to be bound to any particular theory, it is believed that the

polyethylene glycol acts to fuse the cell membranes, thus permitting the contents of the medium to be delivered into the cytoplasm of the *Trichoderma sp.* strain and the plasmid DNA to be transferred to the nucleus. This fusion frequently leaves multiple copies of the plasmid DNA integrated into the host chromosome.

[0335] Usually a suspension containing the *Trichoderma sp.* protoplasts or cells that have been subjected to a permeability treatment at a density of 10^5 to 10^7 /mL (such as 2×10^6 /mL) are used in the transformation. A volume of 100 μ L of these protoplasts or cells in an appropriate solution (*e.g.*, 1.2 M sorbitol and 50 mM CaCl_2) are mixed with the desired DNA. Generally, a high concentration of PEG is added to the uptake solution. From 0.1 to 1 volume of 25% PEG 4000 can be added to the protoplast suspension. In some embodiments, about 0.25 volumes are added to the protoplast suspension. Additives such as dimethyl sulfoxide, heparin, spermidine, potassium chloride, and the like may also be added to the uptake solution and aid in transformation. Similar procedures are available for other fungal host cells (*see, e.g.*, United States Patent 6,022,725 and United States Patent 6,268,328, which are each hereby incorporated by reference in their entireties, particularly with respect to transformation methods).

[0336] Generally, the mixture is then cultured at approximately 0°C for a period of between 10 to 30 minutes. Additional PEG is then added to the mixture to further enhance the uptake of the desired nucleic acid sequence. The 25% PEG 4000 is generally added in volumes of 5 to 15 times the volume of the transformation mixture; however, greater and lesser volumes may be suitable. The 25% PEG 4000 is desirably about 10 times the volume of the transformation mixture. After the PEG is added, the transformation mixture is then cultured either at room temperature or on ice before the addition of a sorbitol and CaCl_2 solution. The protoplast suspension is then further added to molten aliquots of a growth medium. When the growth medium includes a growth selection (*e.g.*, acetamide or an antibiotic) it permits the growth of transformants only.

[0337] The transformation of bacterial cells may be performed according to conventional methods, *e.g.*, as described in Sambrook *et al.*, Molecular Cloning: A Laboratory Manual, Cold Spring Harbor, 1982, which is hereby incorporated by reference in its entirety, particularly with respect to transformation methods.

Exemplary Cell Culture Media

[0338] The invention also includes a cell or a population of cells in culture that produce isoprene. By “cells in culture” is meant two or more cells in a solution (*e.g.*, a cell medium) that allows the cells to undergo one or more cell divisions. “Cells in culture” do not include plant cells that are part of a living, multicellular plant containing cells that have differentiated into plant tissues. In various embodiments, the cell culture includes at least or about 10, 20, 50, 100, 200, 500, 1,000, 5,000, 10,000 or more cells.

[0339] Any carbon source can be used to cultivate the host cells. The term “carbon source” refers to one or more carbon-containing compounds capable of being metabolized by a host cell or organism. For example, the cell medium used to cultivate the host cells may include any carbon source suitable for maintaining the viability or growing the host cells.

[0340] In some embodiments, the carbon source is a carbohydrate (such as monosaccharide, disaccharide, oligosaccharide, or polysaccharids), invert sugar (*e.g.*, enzymatically treated sucrose syrup), glycerol, glycerine (*e.g.*, a glycerine byproduct of a biodiesel or soap-making process), dihydroxyacetone, one-carbon source, oil (*e.g.*, a plant or vegetable oil such as corn, palm, or soybean oil), acetate, animal fat, animal oil, fatty acid (*e.g.*, a saturated fatty acid, unsaturated fatty acid, or polyunsaturated fatty acid), lipid, phospholipid, glycerolipid, monoglyceride, diglyceride, triglyceride, polypeptide (*e.g.*, a microbial or plant protein or peptide), renewable carbon source (*e.g.*, a biomass carbon source such as a hydrolyzed biomass carbon source), yeast extract, component from a yeast extract, polymer, acid, alcohol, aldehyde, ketone, amino acid, succinate, lactate, acetate, ethanol, or any combination of two or more of the foregoing. In some embodiments, the carbon source is a product of photosynthesis, including, but not limited to, glucose. In some embodiment, the carbohydrate is xylose or glucose.

[0341] Exemplary monosaccharides include glucose and fructose; exemplary oligosaccharides include lactose and sucrose, and exemplary polysaccharides include starch and cellulose. Exemplary carbohydrates include C6 sugars (*e.g.*, fructose, mannose, galactose, or glucose) and C5 sugars (*e.g.*, xylose or arabinose). In some embodiments, the cell medium includes a carbohydrate as well as a carbon source other than a carbohydrate (*e.g.*, glycerol, glycerine, dihydroxyacetone, one-carbon source, oil, animal fat, animal oil, fatty acid, lipid, phospholipid, glycerolipid, monoglyceride, diglyceride, triglyceride,

renewable carbon source, or a component from a yeast extract). In some embodiments, the cell medium includes a carbohydrate as well as a polypeptide (*e.g.*, a microbial or plant protein or peptide). In some embodiments, the microbial polypeptide is a polypeptide from yeast or bacteria. In some embodiments, the plant polypeptide is a polypeptide from soy, corn, canola, jatropha, palm, peanut, sunflower, coconut, mustard, rapeseed, cottonseed, palm kernel, olive, safflower, sesame, or linseed.

[0342] In some embodiments, the concentration of the carbohydrate is at least or about 5 grams per liter of broth (g/L, wherein the volume of broth includes both the volume of the cell medium and the volume of the cells), such as at least or about 10, 15, 20, 30, 40, 50, 60, 80, 100, 150, 200, 300, 400, or more g/L. In some embodiments, the concentration of the carbohydrate is between about 50 and about 400 g/L, such as between about 100 and about 360 g/L, between about 120 and about 360 g/L, or between about 200 and about 300 g/L. In some embodiments, this concentration of carbohydrate includes the total amount of carbohydrate that is added before and/or during the culturing of the host cells.

[0343] In some embodiments, the cells are cultured under limited glucose conditions. By “limited glucose conditions” is meant that the amount of glucose that is added is less than or about 105% (such as about 100%) of the amount of glucose that is consumed by the cells. In particular embodiments, the amount of glucose that is added to the culture medium is approximately the same as the amount of glucose that is consumed by the cells during a specific period of time. In some embodiments, the rate of cell growth is controlled by limiting the amount of added glucose such that the cells grow at the rate that can be supported by the amount of glucose in the cell medium. In some embodiments, glucose does not accumulate during the time the cells are cultured. In various embodiments, the cells are cultured under limited glucose conditions for greater than or about 1, 2, 3, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, or 70 hours. In various embodiments, the cells are cultured under limited glucose conditions for greater than or about 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 95, or 100% of the total length of time the cells are cultured. While not intending to be bound by any particular theory, it is believed that limited glucose conditions may allow more favorable regulation of the cells.

[0344] In some embodiments, the cells are cultured in the presence of an excess of glucose. In particular embodiments, the amount of glucose that is added is greater than about 105%

(such as about or greater than 110, 120, 150, 175, 200, 250, 300, 400, or 500%) or more of the amount of glucose that is consumed by the cells during a specific period of time. In some embodiments, glucose accumulates during the time the cells are cultured.

[0345] Exemplary lipids are any substance containing one or more fatty acids that are C4 and above fatty acids that are saturated, unsaturated, or branched.

[0346] Exemplary oils are lipids that are liquid at room temperature. In some embodiments, the lipid contains one or more C4 or above fatty acids (*e.g.*, contains one or more saturated, unsaturated, or branched fatty acid with four or more carbons). In some embodiments, the oil is obtained from soy, corn, canola, jatropha, palm, peanut, sunflower, coconut, mustard, rapeseed, cottonseed, palm kernel, olive, safflower, sesame, linseed, oleagineous microbial cells, Chinese tallow, or any combination of two or more of the foregoing.

[0347] Exemplary fatty acids include compounds of the formula RCOOH, where “R” is a hydrocarbon. Exemplary unsaturated fatty acids include compounds where “R” includes at least one carbon-carbon double bond. Exemplary unsaturated fatty acids include, but are not limited to, oleic acid, vaccenic acid, linoleic acid, palmitelaidic acid, and arachidonic acid. Exemplary polyunsaturated fatty acids include compounds where “R” includes a plurality of carbon-carbon double bonds. Exemplary saturated fatty acids include compounds where “R” is a saturated aliphatic group. In some embodiments, the carbon source includes one or more C₁₂-C₂₂ fatty acids, such as a C₁₂ saturated fatty acid, a C₁₄ saturated fatty acid, a C₁₆ saturated fatty acid, a C₁₈ saturated fatty acid, a C₂₀ saturated fatty acid, or a C₂₂ saturated fatty acid. In an exemplary embodiment, the fatty acid is palmitic acid. In some embodiments, the carbon source is a salt of a fatty acid (*e.g.*, an unsaturated fatty acid), a derivative of a fatty acid (*e.g.*, an unsaturated fatty acid), or a salt of a derivative of fatty acid (*e.g.*, an unsaturated fatty acid). Suitable salts include, but are not limited to, lithium salts, potassium salts, sodium salts, and the like. Di- and triglycerols are fatty acid esters of glycerol.

[0348] In some embodiments, the concentration of the lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride is at least or about 1 gram per liter of broth (g/L, wherein the volume of broth includes both the volume of the cell medium and the volume of the cells), such as at least or about 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, 150, 200, 300, 400, or more g/L. In some embodiments, the concentration of the lipid, oil, fat, fatty acid,

monoglyceride, diglyceride, or triglyceride is between about 10 and about 400 g/L, such as between about 25 and about 300 g/L, between about 60 and about 180 g/L, or between about 75 and about 150 g/L. In some embodiments, the concentration includes the total amount of the lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride that is added before and/or during the culturing of the host cells. In some embodiments, the carbon source includes both (i) a lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride and (ii) a carbohydrate, such as glucose. In some embodiments, the ratio of the lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride to the carbohydrate is about 1:1 on a carbon basis (*i.e.*, one carbon in the lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride per carbohydrate carbon). In particular embodiments, the amount of the lipid, oil, fat, fatty acid, monoglyceride, diglyceride, or triglyceride is between about 60 and 180 g/L, and the amount of the carbohydrate is between about 120 and 360 g/L.

[0349] Exemplary microbial polypeptide carbon sources include one or more polypeptides from yeast or bacteria. Exemplary plant polypeptide carbon sources include one or more polypeptides from soy, corn, canola, jatropha, palm, peanut, sunflower, coconut, mustard, rapeseed, cottonseed, palm kernel, olive, safflower, sesame, or linseed.

[0350] Exemplary renewable carbon sources include cheese whey permeate, cornsteep liquor, sugar beet molasses, barley malt, and components from any of the foregoing. Exemplary renewable carbon sources also include acetate, glucose, hexose, pentose and xylose present in biomass, such as corn, switchgrass, sugar cane, cell waste of fermentation processes, and protein by-product from the milling of soy, corn, or wheat. In some embodiments, the biomass carbon source is a lignocellulosic, hemicellulosic, or cellulosic material such as, but are not limited to, a grass, wheat, wheat straw, bagasse, sugar cane bagasse, soft wood pulp, corn, corn cob or husk, corn kernel, fiber from corn kernels, corn stover, switch grass, rice hull product, or a by-product from wet or dry milling of grains (*e.g.*, corn, sorghum, rye, triticate, barley, wheat, and/or distillers grains). Exemplary cellulosic materials include wood, paper and pulp waste, herbaceous plants, and fruit pulp. In some embodiments, the carbon source includes any plant part, such as stems, grains, roots, or tubers. In some embodiments, all or part of any of the following plants are used as a carbon source: corn, wheat, rye, sorghum, triticate, rice, millet, barley, cassava, legumes, such as beans and peas, potatoes, sweet potatoes, bananas, sugarcane, and/or tapioca. In some

embodiments, the carbon source is a biomass hydrolysate, such as a biomass hydrolysate that includes both xylose and glucose or that includes both sucrose and glucose.

[0351] In some embodiments, the renewable carbon source (such as biomass) is pretreated before it is added to the cell culture medium. In some embodiments, the pretreatment includes enzymatic pretreatment, chemical pretreatment, or a combination of both enzymatic and chemical pretreatment (*see, for example, Farzaneh et al., Bioresource Technology* 96 (18): 2014-2018, 2005; U.S. Patent No. 6,176,176; U.S. Patent No. 6,106,888; which are each hereby incorporated by reference in their entireties, particularly with respect to the pretreatment of renewable carbon sources). In some embodiments, the renewable carbon source is partially or completely hydrolyzed before it is added to the cell culture medium.

[0352] In some embodiments, the renewable carbon source (such as corn stover) undergoes ammonia fiber expansion (AFEX) pretreatment before it is added to the cell culture medium (*see, for example, Farzaneh et al., Bioresource Technology* 96 (18): 2014-2018, 2005). During AFEX pretreatment, a renewable carbon source is treated with liquid anhydrous ammonia at moderate temperatures (such as about 60 to about 100 °C) and high pressure (such as about 250 to about 300 psi) for about 5 minutes. Then, the pressure is rapidly released. In this process, the combined chemical and physical effects of lignin solubilization, hemicellulose hydrolysis, cellulose decrystallization, and increased surface area enables near complete enzymatic conversion of cellulose and hemicellulose to fermentable sugars. AFEX pretreatment has the advantage that nearly all of the ammonia can be recovered and reused, while the remaining serves as nitrogen source for microbes in downstream processes. Also, a wash stream is not required for AFEX pretreatment. Thus, dry matter recovery following the AFEX treatment is essentially 100%. AFEX is basically a dry to dry process. The treated renewable carbon source is stable for long periods and can be fed at very high solid loadings in enzymatic hydrolysis or fermentation processes. Cellulose and hemicellulose are well preserved in the AFEX process, with little or no degradation. There is no need for neutralization prior to the enzymatic hydrolysis of a renewable carbon source that has undergone AFEX pretreatment. Enzymatic hydrolysis of AFEX-treated carbon sources produces clean sugar streams for subsequent fermentation use.

[0353] In some embodiments, the concentration of the carbon source (*e.g., a renewable carbon source*) is equivalent to at least or about 0.1, 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15, 20, 30, 40, or

50% glucose (w/v). The equivalent amount of glucose can be determined by using standard HPLC methods with glucose as a reference to measure the amount of glucose generated from the carbon source. In some embodiments, the concentration of the carbon source (*e.g.*, a renewable carbon source) is equivalent to between about 0.1 and about 20% glucose, such as between about 0.1 and about 10% glucose, between about 0.5 and about 10% glucose, between about 1 and about 10% glucose, between about 1 and about 5% glucose, or between about 1 and about 2% glucose.

[0354] In some embodiments, the carbon source includes yeast extract or one or more components of yeast extract. In some embodiments, the concentration of yeast extract is at least 1 gram of yeast extract per liter of broth (g/L, wherein the volume of broth includes both the volume of the cell medium and the volume of the cells), such as at least or about 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, 150, 200, 300, or more g/L. In some embodiments, the concentration of yeast extract is between about 1 and about 300 g/L, such as between about 1 and about 200 g/L, between about 5 and about 200 g/L, between about 5 and about 100 g/L, or between about 5 and about 60 g/L. In some embodiments, the concentration includes the total amount of yeast extract that is added before and/or during the culturing of the host cells. In some embodiments, the carbon source includes both yeast extract (or one or more components thereof) and another carbon source, such as glucose. In some embodiments, the ratio of yeast extract to the other carbon source is about 1:5, about 1:10, or about 1:20 (w/w).

[0355] Additionally the carbon source may also be one-carbon substrates such as carbon dioxide, or methanol. Glycerol production from single carbon sources (*e.g.*, methanol, formaldehyde, or formate) has been reported in methylotrophic yeasts (Yamada *et al.*, *Agric. Biol. Chem.*, 53(2) 541-543, 1989, which is hereby incorporated by reference in its entirety, particularly with respect to carbon sources) and in bacteria (Hunter *et. al.*, *Biochemistry*, 24, 4148-4155, 1985, which is hereby incorporated by reference in its entirety, particularly with respect to carbon sources). These organisms can assimilate single carbon compounds, ranging in oxidation state from methane to formate, and produce glycerol. The pathway of carbon assimilation can be through ribulose monophosphate, through serine, or through xylulose-momophosphate (Gottschalk, *Bacterial Metabolism*, Second Edition, Springer-Verlag: New York, 1986, which is hereby incorporated by reference in its entirety, particularly with respect to carbon sources). The ribulose monophosphate pathway involves the condensation of formate with ribulose-5-phosphate to form a six carbon sugar that

becomes fructose and eventually the three carbon product glyceraldehyde-3-phosphate. Likewise, the serine pathway assimilates the one-carbon compound into the glycolytic pathway via methylenetetrahydrofolate.

[0356] In addition to one and two carbon substrates, methylotrophic organisms are also known to utilize a number of other carbon containing compounds such as methylamine, glucosamine and a variety of amino acids for metabolic activity. For example, methylotrophic yeast are known to utilize the carbon from methylamine to form trehalose or glycerol (Bellion *et al.*, *Microb. Growth Cl Compd.*, [Int. Symp.], 7th ed., 415-32. Editors: Murrell *et al.*, Publisher: Intercept, Andover, UK, 1993, which is hereby incorporated by reference in its entirety, particularly with respect to carbon sources). Similarly, various species of *Candida* metabolize alanine or oleic acid (Sulter *et al.*, *Arch. Microbiol.* 153(5), 485-9, 1990, which is hereby incorporated by reference in its entirety, particularly with respect to carbon sources).

[0357] In some embodiments, cells are cultured in a standard medium containing physiological salts and nutrients (*see, e.g.*, Pourquie, J. *et al.*, *Biochemistry and Genetics of Cellulose Degradation*, eds. Aubert *et al.*, Academic Press, pp. 71-86, 1988 and Ilmen *et al.*, *Appl. Environ. Microbiol.* 63:1298-1306, 1997, which are each hereby incorporated by reference in their entireties, particularly with respect to cell media). Exemplary growth media are common commercially prepared media such as Luria Bertani (LB) broth, Sabouraud Dextrose (SD) broth, or Yeast medium (YM) broth. Other defined or synthetic growth media may also be used, and the appropriate medium for growth of particular host cells are known by someone skilled in the art of microbiology or fermentation science.

[0358] In addition to an appropriate carbon source, the cell medium desirably contains suitable minerals, salts, cofactors, buffers, and other components known to those skilled in the art suitable for the growth of the cultures or the enhancement of isoprene production (*see, for example*, WO 2004/033646 and references cited therein and WO 96/35796 and references cited therein, which are each hereby incorporated by reference in their entireties, particularly with respect cell medias and cell culture conditions). In some embodiments where an isoprene synthase, DXS, IDI, and/or MVA pathway nucleic acid is under the control of an inducible promoter, the inducing agent (*e.g.*, a sugar, metal salt or antimicrobial), is desirably added to the medium at a concentration effective to induce expression of an isoprene

synthase, DXS, IDI, and/or MVA pathway polypeptide. In some embodiments, cell medium has an antibiotic (such as kanamycin) that corresponds to the antibiotic resistance nucleic acid (such as a kanamycin resistance nucleic acid) on a vector that has one or more DXS, IDI, or MVA pathway nucleic acids.

Exemplary Cell Culture Conditions

[0359] Materials and methods suitable for the maintenance and growth of bacterial cultures are well known in the art. Exemplary techniques may be found in Manual of Methods for General Bacteriology Gerhardt *et al.*, *eds*), American Society for Microbiology, Washington, D.C. (1994) or Brock in Biotechnology: A Textbook of Industrial Microbiology, Second Edition (1989) Sinauer Associates, Inc., Sunderland, MA, which are each hereby incorporated by reference in their entireties, particularly with respect to cell culture techniques. In some embodiments, the cells are cultured in a culture medium under conditions permitting the expression of one or more isoprene synthase, DXS, IDI, or MVA pathway polypeptides encoded by a nucleic acid inserted into the host cells.

[0360] Standard cell culture conditions can be used to culture the cells (*see*, for example, WO 2004/033646 and references cited therein, which are each hereby incorporated by reference in their entireties, particularly with respect to cell culture and fermentation conditions). Cells are grown and maintained at an appropriate temperature, gas mixture, and pH (such as at about 20 to about 37°C, at about 6% to about 84% CO₂, and at a pH between about 5 to about 9). In some embodiments, cells are grown at 35°C in an appropriate cell medium. In some embodiments, *e.g.*, cultures are cultured at approximately 28°C in appropriate medium in shake cultures or fermentors until desired amount of isoprene production is achieved. In some embodiments, the pH ranges for fermentation are between about pH 5.0 to about pH 9.0 (such as about pH 6.0 to about pH 8.0 or about 6.5 to about 7.0). Reactions may be performed under aerobic, anoxic, or anaerobic conditions based on the requirements of the host cells. Exemplary culture conditions for a given filamentous fungus are known in the art and may be found in the scientific literature and/or from the source of the fungi such as the American Type Culture Collection and Fungal Genetics Stock Center.

[0361] In various embodiments, the cells are grown using any known mode of fermentation, such as batch, fed-batch, or continuous processes. In some embodiments, a batch method of fermentation is used. Classical batch fermentation is a closed system where

the composition of the media is set at the beginning of the fermentation and is not subject to artificial alterations during the fermentation. Thus, at the beginning of the fermentation the cell medium is inoculated with the desired host cells and fermentation is permitted to occur adding nothing to the system. Typically, however, “batch” fermentation is batch with respect to the addition of carbon source and attempts are often made at controlling factors such as pH and oxygen concentration. In batch systems, the metabolite and biomass compositions of the system change constantly until the time the fermentation is stopped. Within batch cultures, cells moderate through a static lag phase to a high growth log phase and finally to a stationary phase where growth rate is diminished or halted. In some embodiments, cells in log phase are responsible for the bulk of the isoprene production. In some embodiments, cells in stationary phase produce isoprene.

[0362] In some embodiments, a variation on the standard batch system is used, such as the Fed-Batch system. Fed-Batch fermentation processes comprise a typical batch system with the exception that the carbon source is added in increments as the fermentation progresses. Fed-Batch systems are useful when catabolite repression is apt to inhibit the metabolism of the cells and where it is desirable to have limited amounts of carbon source in the cell medium. Fed-batch fermentations may be performed with the carbon source (*e.g.*, glucose) in a limited or excess amount. Measurement of the actual carbon source concentration in Fed-Batch systems is difficult and is therefore estimated on the basis of the changes of measurable factors such as pH, dissolved oxygen, and the partial pressure of waste gases such as CO₂. Batch and Fed-Batch fermentations are common and well known in the art and examples may be found in Brock, *Biotechnology: A Textbook of Industrial Microbiology*, Second Edition (1989) Sinauer Associates, Inc., which is hereby incorporated by reference in its entirety, particularly with respect to cell culture and fermentation conditions.

[0363] In some embodiments, continuous fermentation methods are used. Continuous fermentation is an open system where a defined fermentation medium is added continuously to a bioreactor and an equal amount of conditioned medium is removed simultaneously for processing. Continuous fermentation generally maintains the cultures at a constant high density where cells are primarily in log phase growth.

[0364] Continuous fermentation allows for the modulation of one factor or any number of factors that affect cell growth or isoprene production. For example, one method maintains a

limiting nutrient such as the carbon source or nitrogen level at a fixed rate and allows all other parameters to moderate. In other systems, a number of factors affecting growth can be altered continuously while the cell concentration (*e.g.*, the concentration measured by media turbidity) is kept constant. Continuous systems strive to maintain steady state growth conditions. Thus, the cell loss due to media being drawn off is balanced against the cell growth rate in the fermentation. Methods of modulating nutrients and growth factors for continuous fermentation processes as well as techniques for maximizing the rate of product formation are well known in the art of industrial microbiology and a variety of methods are detailed by Brock, *Biotechnology: A Textbook of Industrial Microbiology*, Second Edition (1989) Sinauer Associates, Inc., which is hereby incorporated by reference in its entirety, particularly with respect to cell culture and fermentation conditions.

[0365] In some embodiments, cells are immobilized on a substrate as whole cell catalysts and subjected to fermentation conditions for isoprene production.

[0366] In some embodiments, bottles of liquid culture are placed in shakers in order to introduce oxygen to the liquid and maintain the uniformity of the culture. In some embodiments, an incubator is used to control the temperature, humidity, shake speed, and/or other conditions in which a culture is grown. The simplest incubators are insulated boxes with an adjustable heater, typically going up to ~65 °C. More elaborate incubators can also include the ability to lower the temperature (via refrigeration), or the ability to control humidity or CO₂ levels. Most incubators include a timer; some can also be programmed to cycle through different temperatures, humidity levels, *etc.* Incubators can vary in size from tabletop to units the size of small rooms.

[0367] If desired, a portion or all of the cell medium can be changed to replenish nutrients and/or avoid the build up of potentially harmful metabolic byproducts and dead cells. In the case of suspension cultures, cells can be separated from the media by centrifuging or filtering the suspension culture and then resuspending the cells in fresh media. In the case of adherent cultures, the media can be removed directly by aspiration and replaced. In some embodiments, the cell medium allows at least a portion of the cells to divide for at least or about 5, 10, 20, 40, 50, 60, 65, or more cell divisions in a continuous culture (such as a continuous culture without dilution).

[0368] In some embodiments, a constitutive or leaky promoter (such as a Trc promoter) is used and a compound (such as IPTG) is not added to induce expression of the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid(s) operably linked to the promoter. In some embodiments, a compound (such as IPTG) is added to induce expression of the isoprene synthase, DXS, IDI, or MVA pathway nucleic acid(s) operably linked to the promoter.

Exemplary Methods for Decoupling Isoprene Production from Cell Growth

[0369] Desirably, carbon from the feedstock is converted to isoprene rather than to the growth and maintenance of the cells. In some embodiments, the cells are grown to a low to medium OD₆₀₀, then production of isoprene is started or increased. This strategy permits a large portion of the carbon to be converted to isoprene.

[0370] In some embodiments, cells reach an optical density such that they no longer divide or divide extremely slowly, but continue to make isoprene for several hours (such as about 2, 4, 6, 8, 10, 15, 20, 25, 30, or more hours). For example, Figs. 60A-67C illustrate that cells may continue to produce a substantial amount of mevalonic acid or isoprene after the cells reach an optical density such that they no longer divide or divide extremely slowly. In some cases, the optical density at 550 nm decreases over time (such as a decrease in the optical density after the cells are no longer in an exponential growth phase due to cell lysis), and the cells continue to produce a substantial amount of mevalonic acid or isoprene. In some embodiments, the optical density at 550 nm of the cells increases by less than or about 50% (such as by less than or about 40, 30, 20, 10, 5, or 0%) over a certain time period (such as greater than or about 5, 10, 15, 20, 25, 30, 40, 50 or 60 hours), and the cells produce isoprene at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, or more nmole of isoprene/gram of cells for the wet weight of the cells/hour (nmole/g_{wcm}/hr) during this time period. In some embodiments, the amount of isoprene is between about 2 to about 5,000 nmole/g_{wcm}/hr, such as between about 2 to about 100 nmole/g_{wcm}/hr, about 100 to about 500 nmole/g_{wcm}/hr, about 150 to about 500 nmole/g_{wcm}/hr, about 500 to about 1,000 nmole/g_{wcm}/hr, about 1,000 to about 2,000 nmole/g_{wcm}/hr, or about 2,000 to about 5,000 nmole/g_{wcm}/hr. In some embodiments, the amount of isoprene is between about 20 to about 5,000 nmole/g_{wcm}/hr, about 100 to about 5,000 nmole/g_{wcm}/hr, about 200 to about 2,000

nmole/g_{wcm}/hr, about 200 to about 1,000 nmole/g_{wcm}/hr, about 300 to about 1,000 nmole/g_{wcm}/hr, or about 400 to about 1,000 nmole/g_{wcm}/hr.

[0371] In some embodiments, the optical density at 550 nm of the cells increases by less than or about 50% (such as by less than or about 40, 30, 20, 10, 5, or 0%) over a certain time period (such as greater than or about 5, 10, 15, 20, 25, 30, 40, 50 or 60 hours), and the cells produce a cumulative titer (total amount) of isoprene at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 50,000, 100,000, or more mg of isoprene/L of broth (mg/L_{broth}, wherein the volume of broth includes the volume of the cells and the cell medium) during this time period. In some embodiments, the amount of isoprene is between about 2 to about 5,000 mg/L_{broth}, such as between about 2 to about 100 mg/L_{broth}, about 100 to about 500 mg/L_{broth}, about 500 to about 1,000 mg/L_{broth}, about 1,000 to about 2,000 mg/L_{broth}, or about 2,000 to about 5,000 mg/L_{broth}. In some embodiments, the amount of isoprene is between about 20 to about 5,000 mg/L_{broth}, about 100 to about 5,000 mg/L_{broth}, about 200 to about 2,000 mg/L_{broth}, about 200 to about 1,000 mg/L_{broth}, about 300 to about 1,000 mg/L_{broth}, or about 400 to about 1,000 mg/L_{broth}.

[0372] In some embodiments, the optical density at 550 nm of the cells increases by less than or about 50% (such as by less than or about 40, 30, 20, 10, 5, or 0%) over a certain time period (such as greater than or about 5, 10, 15, 20, 25, 30, 40, 50 or 60 hours), and the cells convert greater than or about 0.0015, 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.12, 0.14, 0.16, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 7.0, or 8.0% of the carbon in the cell culture medium into isoprene during this time period. In some embodiments, the percent conversion of carbon into isoprene is between such as about 0.002 to about 4.0%, about 0.002 to about 3.0%, about 0.002 to about 2.0%, about 0.002 to about 1.6%, about 0.002 to about 0.005%, about 0.005 to about 0.01%, about 0.01 to about 0.05%, about 0.05 to about 0.15%, 0.15 to about 0.2%, about 0.2 to about 0.3%, about 0.3 to about 0.5%, about 0.5 to about 0.8%, about 0.8 to about 1.0%, or about 1.0 to about 1.6%. In some embodiments, the percent conversion of carbon into isoprene is between about 0.002 to about 0.4%, 0.002 to about 0.16%, 0.04 to about 0.16%, about 0.005 to about 0.3%, about 0.01 to about 0.3%, or about 0.05 to about 0.3%.

[0373] In some embodiments, isoprene is only produced in stationary phase. In some embodiments, isoprene is produced in both the growth phase and stationary phase. In various embodiments, the amount of isoprene produced (such as the total amount of isoprene produced or the amount of isoprene produced per liter of broth per hour per OD₆₀₀) during stationary phase is greater than or about 2, 3, 4, 5, 10, 20, 30, 40, 50, or more times the amount of isoprene produced during the growth phase for the same length of time. In various embodiments, greater than or about 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99% or more of the total amount of isoprene that is produced (such as the production of isoprene during a fermentation for a certain amount of time, such as 20 hours) is produced while the cells are in stationary phase. In various embodiments, greater than or about 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99% or more of the total amount of isoprene that is produced (such as the production of isoprene during a fermentation for a certain amount of time, such as 20 hours) is produced while the cells divide slowly or not at all such that the optical density at 550 nm of the cells increases by less than or about 50% (such as by less than or about 40, 30, 20, 10, 5, or 0%). In some embodiments, isoprene is only produced in the growth phase.

[0374] In some embodiments, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids are placed under the control of a promoter or factor that is more active in stationary phase than in the growth phase. For example, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids may be placed under control of a stationary phase sigma factor, such as RpoS. In some embodiments, one or more MVA pathway, IDI, DXP, or isoprene synthase nucleic acids are placed under control of a promoter inducible in stationary phase, such as a promoter inducible by a response regulator active in stationary phase.

Production of Isoprene within Safe Operating Ranges

[0375] The production of isoprene within safe operating levels according to its flammability characteristics simplifies the design and construction of commercial facilities, vastly improves the ability to operate safely, and limits the potential for fires to occur. In particular, the optimal ranges for the production of isoprene are within the safe zone, *i.e.*, the nonflammable range of isoprene concentrations. In one such aspect, the invention features a method for the production of isoprene within the nonflammable range of isoprene concentrations (outside the flammability envelope of isoprene).

[0376] Thus, computer modeling and experimental testing were used to determine the flammability limits of isoprene (such as isoprene in the presence of O₂, N₂, CO₂, or any combination of two or more of the foregoing gases) in order to ensure process safety. The flammability envelope is characterized by the lower flammability limit (LFL), the upper flammability limit (UFL), the limiting oxygen concentration (LOC), and the limiting temperature. For a system to be flammable, a minimum amount of fuel (such as isoprene) must be in the presence of a minimum amount of oxidant, typically oxygen. The LFL is the minimum amount of isoprene that must be present to sustain burning, while the UFL is the maximum amount of isoprene that can be present. Above this limit, the mixture is fuel rich and the fraction of oxygen is too low to have a flammable mixture. The LOC indicates the minimum fraction of oxygen that must also be present to have a flammable mixture. The limiting temperature is based on the flash point of isoprene and is that lowest temperature at which combustion of isoprene can propagate. These limits are specific to the concentration of isoprene, type and concentration of oxidant, inerts present in the system, temperature, and pressure of the system. Compositions that fall within the limits of the flammability envelope propagate combustion and require additional safety precautions in both the design and operation of process equipment.

[0377] The following conditions were tested using computer simulation and mathematical analysis and experimental testing. If desired, other conditions (such as other temperature, pressure, and permanent gas compositions) may be tested using the methods described herein to determine the LFL, UFL, and LOC concentrations.

(1) Computer simulation and mathematical analysis

Test Suite 1:

isoprene: 0 wt% - 14 wt%

O₂: 6 wt% - 21 wt%

N₂: 79 wt% - 94 wt%

Test Suite 2:

isoprene: 0 wt% - 14 wt%

O₂: 6 wt% - 21 wt%

N₂: 79 wt% - 94 wt%

Saturated with H₂O

Test Suite 3:

isoprene: 0 wt% - 14 wt%

O₂: 6 wt% - 21 wt%

N₂: 79 wt% - 94 wt%

CO₂: 5 wt% - 30 wt%

(2) Experimental testing for final determination of flammability limits

Test Suite 1:

isoprene: 0 wt% - 14 wt%

O₂: 6 wt% - 21 wt%

N₂: 79 wt% - 94 wt%

Test Suite 2:

isoprene: 0 wt% - 14 wt%

O₂: 6 wt% - 21 wt%

N₂: 79 wt% - 94 wt%

Saturated with H₂O

[0378] Simulation software was used to give an estimate of the flammability characteristics of the system for several different testing conditions. CO₂ showed no significant affect on the system's flammability limits. Test suites 1 and 2 were confirmed by experimental testing.

The modeling results were in-line with the experimental test results. Only slight variations were found with the addition of water.

[0379] The LOC was determined to be 9.5 vol% for an isoprene, O₂, N₂, and CO₂ mixture at 40°C and 1 atmosphere. The addition of up to 30% CO₂ did not significantly affect the flammability characteristics of an isoprene, O₂, and N₂ mixture. Only slight variations in flammability characteristics were shown between a dry and water saturated isoprene, O₂, and N₂ system. The limiting temperature is about -54 °C. Temperatures below about -54 °C are too low to propagate combustion of isoprene.

[0380] In some embodiments, the LFL of isoprene ranges from about 1.5 vol.% to about 2.0 vol%, and the UFL of isoprene ranges from about 2.0 vol.% to about 12.0 vol.%, depending on the amount of oxygen in the system. In some embodiments, the LOC is about 9.5 vol% oxygen. In some embodiments, the LFL of isoprene is between about 1.5 vol.% to about 2.0 vol%, the UFL of isoprene is between about 2.0 vol.% to about 12.0 vol.%, and the LOC is about 9.5 vol% oxygen when the temperature is between about 25 °C to about 55 °C (such as about 40 °C) and the pressure is between about 1 atmosphere and 3 atmospheres.

[0381] In some embodiments, isoprene is produced in the presence of less than about 9.5 vol% oxygen (that is, below the LOC required to have a flammable mixture of isoprene). In some embodiments in which isoprene is produced in the presence of greater than or about 9.5 vol% oxygen, the isoprene concentration is below the LFL (such as below about 1.5 vol.%). For example, the amount of isoprene can be kept below the LFL by diluting the isoprene composition with an inert gas (*e.g.*, by continuously or periodically adding an inert gas such as nitrogen to keep the isoprene composition below the LFL). In some embodiments in which isoprene is produced in the presence of greater than or about 9.5 vol% oxygen, the isoprene concentration is above the UFL (such as above about 12 vol.%). For example, the amount of isoprene can be kept above the UFL by using a system (such as any of the cell culture systems described herein) that produces isoprene at a concentration above the UFL. If desired, a relatively low level of oxygen can be used so that the UFL is also relatively low. In this case, a lower isoprene concentration is needed to remain above the UFL.

[0382] In some embodiments in which isoprene is produced in the presence of greater than or about 9.5 vol% oxygen, the isoprene concentration is within the flammability envelope (such as between the LFL and the UFL). In some embodiments when the isoprene concentration may fall within the flammability envelope, one or more steps are performed to reduce the probability of a fire or explosion. For example, one or more sources of ignition (such as any materials that may generate a spark) can be avoided. In some embodiments, one or more steps are performed to reduce the amount of time that the concentration of isoprene remains within the flammability envelope. In some embodiments, a sensor is used to detect when the concentration of isoprene is close to or within the flammability envelope. If desired, the concentration of isoprene can be measured at one or more time points during the culturing of cells, and the cell culture conditions and/or the amount of inert gas can be adjusted using standard methods if the concentration of isoprene is close to or within the

flammability envelope. In particular embodiments, the cell culture conditions (such as fermentation conditions) are adjusted to either decrease the concentration of isoprene below the LFL or increase the concentration of isoprene above the UFL. In some embodiments, the amount of isoprene is kept below the LFL by diluting the isoprene composition with an inert gas (such as by continuously or periodically adding an inert gas to keep the isoprene composition below the LFL).

[0383] In some embodiments, the amount of flammable volatiles other than isoprene (such as one or more sugars) is at least about 2, 5, 10, 50, 75, or 100-fold less than the amount of isoprene produced. In some embodiments, the portion of the gas phase other than isoprene gas comprises between about 0% to about 100% (volume) oxygen, such as between about 0% to about 10%, about 10% to about 20%, about 20% to about 30%, about 30% to about 40%, about 40% to about 50%, about 50% to about 60%, about 60% to about 70%, about 70% to about 80%, about 80% to about 90%, or about 90% to about 100% (volume) oxygen. In some embodiments, the portion of the gas phase other than isoprene gas comprises between about 0% to about 99% (volume) nitrogen, such as between about 0% to about 10%, about 10% to about 20%, about 20% to about 30%, about 30% to about 40%, about 40% to about 50%, about 50% to about 60%, about 60% to about 70%, about 70% to about 80%, about 80% to about 90%, or about 90% to about 99% (volume) nitrogen.

[0384] In some embodiments, the portion of the gas phase other than isoprene gas comprises between about 1% to about 50% (volume) CO₂, such as between about 1% to about 10%, about 10% to about 20%, about 20% to about 30%, about 30% to about 40%, or about 40% to about 50% (volume) CO₂.

[0385] In some embodiments, an isoprene composition also contains ethanol. For example, ethanol may be used for extractive distillation of isoprene, resulting in compositions (such as intermediate product streams) that include both ethanol and isoprene. Desirably, the amount of ethanol is outside the flammability envelope for ethanol. The LOC of ethanol is about 8.7 vol%, and the LFL for ethanol is about 3.3 vol% at standard conditions, such as about 1 atmosphere and about 60 °F (NFPA 69 *Standard on Explosion Prevention Systems*, 2008 edition, which is hereby incorporated by reference in its entirety, particularly with respect to LOC, LFL, and UFL values). In some embodiments, compositions that include isoprene and ethanol are produced in the presence of less than the LOC required to have a flammable

mixture of ethanol (such as less than about 8.7% vol%). In some embodiments in which compositions that include isoprene and ethanol are produced in the presence of greater than or about the LOC required to have a flammable mixture of ethanol, the ethanol concentration is below the LFL (such as less than about 3.3 vol.%).

[0386] In various embodiments, the amount of oxidant (such as oxygen) is below the LOC of any fuel in the system (such as isoprene or ethanol). In various embodiments, the amount of oxidant (such as oxygen) is less than about 60, 40, 30, 20, 10, or 5% of the LOC of isoprene or ethanol. In various embodiments, the amount of oxidant (such as oxygen) is less than the LOC of isoprene or ethanol by at least 2, 4, 5, or more absolute percentage points (vol %). In particular embodiments, the amount of oxygen is at least 2 absolute percentage points (vol %) less than the LOC of isoprene or ethanol (such as an oxygen concentration of less than 7.5 vol% when the LOC of isoprene is 9.5 vol%). In various embodiments, the amount of fuel (such as isoprene or ethanol) is less than or about 25, 20, 15, 10, or 5% of the LFL for that fuel.

Exemplary Production of Bioisoprene

[0387] In some embodiments, the cells are cultured in a culture medium under conditions permitting the production of isoprene by the cells. By “peak absolute productivity” is meant the maximum absolute amount of isoprene in the off-gas during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). By “peak absolute productivity time point” is meant the time point during a fermentation run when the absolute amount of isoprene in the off-gas is at a maximum during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). In some embodiments, the isoprene amount is measured at the peak absolute productivity time point. In some embodiments, the peak absolute productivity for the cells is about any of the isoprene amounts disclosed herein.

[0388] By “peak specific productivity” is meant the maximum amount of isoprene produced per cell during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). By “peak specific productivity time point” is meant the time point during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run) when the amount of isoprene produced per cell is at a maximum. The peak specific productivity is determined by dividing

the total productivity by the amount of cells, as determined by optical density at 600nm (OD₆₀₀). In some embodiments, the isoprene amount is measured at the peak specific productivity time point. In some embodiments, the peak specific productivity for the cells is about any of the isoprene amounts per cell disclosed herein.

[0389] By “peak volumetric productivity” is meant the maximum amount of isoprene produced per volume of broth (including the volume of the cells and the cell medium) during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). By “peak specific volumetric productivity time point” is meant the time point during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run) when the amount of isoprene produced per volume of broth is at a maximum. The peak specific volumetric productivity is determined by dividing the total productivity by the volume of broth and amount of time. In some embodiments, the isoprene amount is measured at the peak specific volumetric productivity time point. In some embodiments, the peak specific volumetric productivity for the cells is about any of the isoprene amounts per volume per time disclosed herein.

[0390] By “peak concentration” is meant the maximum amount of isoprene produced during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). By “peak concentration time point” is meant the time point during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run) when the amount of isoprene produced per cell is at a maximum. In some embodiments, the isoprene amount is measured at the peak concentration time point. In some embodiments, the peak concentration for the cells is about any of the isoprene amounts disclosed herein.

[0391] By “average volumetric productivity” is meant the average amount of isoprene produced per volume of broth (including the volume of the cells and the cell medium) during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). The average volumetric productivity is determined by dividing the total productivity by the volume of broth and amount of time. In some embodiments, the average specific volumetric productivity for the cells is about any of the isoprene amounts per volume per time disclosed herein.

[0392] By “cumulative total productivity” is meant the cumulative, total amount of isoprene produced during the culturing of cells for a particular period of time (*e.g.*, the culturing of cells during a particular fermentation run). In some embodiments, the cumulative, total amount of isoprene is measured. In some embodiments, the cumulative total productivity for the cells is about any of the isoprene amounts disclosed herein.

[0393] As used herein, “relative detector response” refers to the ratio between the detector response (such as the GC/MS area) for one compound (such as isoprene) to the detector response (such as the GC/MS area) of one or more compounds (such as all C5 hydrocarbons). The detector response may be measured as described herein, such as the GC/MS analysis performed with an Agilent 6890 GC/MS system fitted with an Agilent HP-5MS GC/MS column (30 m x 250 μm ; 0.25 μm film thickness). If desired, the relative detector response can be converted to a weight percentage using the response factors for each of the compounds. This response factor is a measure of how much signal is generated for a given amount of a particular compound (that is, how sensitive the detector is to a particular compound). This response factor can be used as a correction factor to convert the relative detector response to a weight percentage when the detector has different sensitivities to the compounds being compared. Alternatively, the weight percentage can be approximated by assuming that the response factors are the same for the compounds being compared. Thus, the weight percentage can be assumed to be approximately the same as the relative detector response.

[0394] In some embodiments, the cells in culture produce isoprene at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 12,500, 20,000, 30,000, 40,000, 50,000, 75,000, 100,000, 125,000, 150,000, 188,000, or more nmole of isoprene/gram of cells for the wet weight of the cells/hour (nmole/g_{wcm}/hr). In some embodiments, the amount of isoprene is between about 2 to about 200,000 nmole/g_{wcm}/hr, such as between about 2 to about 100 nmole/g_{wcm}/hr, about 100 to about 500 nmole/g_{wcm}/hr, about 150 to about 500 nmole/g_{wcm}/hr, about 500 to about 1,000 nmole/g_{wcm}/hr, about 1,000 to about 2,000 nmole/g_{wcm}/hr, about 2,000 to about 5,000 nmole/g_{wcm}/hr, about 5,000 to about 10,000 nmole/g_{wcm}/hr, about 10,000 to about 50,000 nmole/g_{wcm}/hr, about 50,000 to about 100,000 nmole/g_{wcm}/hr, about 100,000 to about 150,000 nmole/g_{wcm}/hr, or about 150,000 to about 200,000 nmole/g_{wcm}/hr. In some embodiments, the amount of isoprene is between about 20 to about 200,000 nmole/g_{wcm}/hr,

about 100 to about 5,000 nmole/g_{wcm}/hr, about 200 to about 2,000 nmole/g_{wcm}/hr, about 200 to about 1,000 nmole/g_{wcm}/hr, about 300 to about 1,000 nmole/g_{wcm}/hr, about 400 to about 1,000 nmole/g_{wcm}/hr, about 1,000 to about 5,000 nmole/g_{wcm}/hr, about 2,000 to about 20,000 nmole/g_{wcm}/hr, about 5,000 to about 50,000 nmole/g_{wcm}/hr, about 10,000 to about 100,000 nmole/g_{wcm}/hr, about 20,000 to about 150,000 nmole/g_{wcm}/hr, or about 20,000 to about 200,000 nmole/g_{wcm}/hr.

[0395] The amount of isoprene in units of nmole/g_{wcm}/hr can be measured as disclosed in United States Patent 5,849,970, which is hereby incorporated by reference in its entirety, particularly with respect to the measurement of isoprene production. For example, two mL of headspace (*e.g.*, headspace from a culture such as 2 mL of culture cultured in sealed vials at 32 °C with shaking at 200 rpm for approximately 3 hours) are analyzed for isoprene using a standard gas chromatography system, such as a system operated isothermally (85 °C) with an n-octane/porasil C column (Alltech Associates, Inc., Deerfield, Ill.) and coupled to a RGD2 mercuric oxide reduction gas detector (Trace Analytical, Menlo Park, CA) (*see*, for example, Greenberg et al, *Atmos. Environ.* 27A: 2689-2692, 1993; Silver *et al.*, *Plant Physiol.* 97:1588-1591, 1991, which are each hereby incorporated by reference in their entireties, particularly with respect to the measurement of isoprene production). The gas chromatography area units are converted to nmol isoprene via a standard isoprene concentration calibration curve. In some embodiments, the value for the grams of cells for the wet weight of the cells is calculated by obtaining the A₆₀₀ value for a sample of the cell culture, and then converting the A₆₀₀ value to grams of cells based on a calibration curve of wet weights for cell cultures with a known A₆₀₀ value. In some embodiments, the grams of the cells is estimated by assuming that one liter of broth (including cell medium and cells) with an A₆₀₀ value of 1 has a wet cell weight of 1 gram. The value is also divided by the number of hours the culture has been incubating for, such as three hours.

[0396] In some embodiments, the cells in culture produce isoprene at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 100,000, or more ng of isoprene/gram of cells for the wet weight of the cells/hr (ng/g_{wcm}/h). In some embodiments, the amount of isoprene is between about 2 to about 5,000 ng/g_{wcm}/h, such as between about 2 to about 100 ng/g_{wcm}/h, about 100 to about 500 ng/g_{wcm}/h, about 500 to about 1,000 ng/g_{wcm}/h, about 1,000 to about 2,000 ng/g_{wcm}/h, or about 2,000 to about 5,000 ng/g_{wcm}/h. In some embodiments, the

amount of isoprene is between about 20 to about 5,000 ng/g_{wcm}/h, about 100 to about 5,000 ng/g_{wcm}/h, about 200 to about 2,000 ng/g_{wcm}/h, about 200 to about 1,000 ng/g_{wcm}/h, about 300 to about 1,000 ng/g_{wcm}/h, or about 400 to about 1,000 ng/g_{wcm}/h. The amount of isoprene in ng/g_{wcm}/h can be calculated by multiplying the value for isoprene production in the units of nmole/g_{wcm}/hr discussed above by 68.1 (as described in Equation 5 below).

[0397] In some embodiments, the cells in culture produce a cumulative titer (total amount) of isoprene at greater than or about 1, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,250, 1,500, 1,750, 2,000, 2,500, 3,000, 4,000, 5,000, 10,000, 50,000, 100,000, or more mg of isoprene/L of broth (mg/L_{broth}, wherein the volume of broth includes the volume of the cells and the cell medium). In some embodiments, the amount of isoprene is between about 2 to about 5,000 mg/L_{broth}, such as between about 2 to about 100 mg/L_{broth}, about 100 to about 500 mg/L_{broth}, about 500 to about 1,000 mg/L_{broth}, about 1,000 to about 2,000 mg/L_{broth}, or about 2,000 to about 5,000 mg/L_{broth}. In some embodiments, the amount of isoprene is between about 20 to about 5,000 mg/L_{broth}, about 100 to about 5,000 mg/L_{broth}, about 200 to about 2,000 mg/L_{broth}, about 200 to about 1,000 mg/L_{broth}, about 300 to about 1,000 mg/L_{broth}, or about 400 to about 1,000 mg/L_{broth}.

[0398] The specific productivity of isoprene in mg of isoprene/L of headspace from shake flask or similar cultures can be measured by taking a 1 ml sample from the cell culture at an OD₆₀₀ value of approximately 1.0, putting it in a 20 mL vial, incubating for 30 minutes, and then measuring the amount of isoprene in the headspace (as described, for example, in Example I, part II). If the OD₆₀₀ value is not 1.0, then the measurement can be normalized to an OD₆₀₀ value of 1.0 by dividing by the OD₆₀₀ value. The value of mg isoprene/L headspace can be converted to mg/L_{broth}/hr/OD₆₀₀ of culture broth by multiplying by a factor of 38. The value in units of mg/L_{broth}/hr/OD₆₀₀ can be multiplied by the number of hours and the OD₆₀₀ value to obtain the cumulative titer in units of mg of isoprene/L of broth.

[0399] In some embodiments, the cells in culture have an average volumetric productivity of isoprene at greater than or about 0.1, 1.0, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1,100, 1,200, 1,300, 1,400, 1,500, 1,600, 1,700, 1,800, 1,900, 2,000, 2,100, 2,200, 2,300, 2,400, 2,500, 2,600, 2,700, 2,800, 2,900, 3,000, 3,100, 3,200, 3,300, 3,400, 3,500, or more mg of isoprene/L of broth/hr (mg/L_{broth}/hr, wherein the volume of broth includes the volume of the cells and the cell medium). In some embodiments, the average

volumetric productivity of isoprene is between about 0.1 to about 3,500 mg/L_{broth}/hr, such as between about 0.1 to about 100 mg/L_{broth}/hr, about 100 to about 500 mg/L_{broth}/hr, about 500 to about 1,000 mg/L_{broth}/hr, about 1,000 to about 1,500 mg/L_{broth}/hr, about 1,500 to about 2,000 mg/L_{broth}/hr, about 2,000 to about 2,500 mg/L_{broth}/hr, about 2,500 to about 3,000 mg/L_{broth}/hr, or about 3,000 to about 3,500 mg/L_{broth}/hr. In some embodiments, the average volumetric productivity of isoprene is between about 10 to about 3,500 mg/L_{broth}/hr, about 100 to about 3,500 mg/L_{broth}/hr, about 200 to about 1,000 mg/L_{broth}/hr, about 200 to about 1,500 mg/L_{broth}/hr, about 1,000 to about 3,000 mg/L_{broth}/hr, or about 1,500 to about 3,000 mg/L_{broth}/hr.

[0400] In some embodiments, the cells in culture have a peak volumetric productivity of isoprene at greater than or about 0.5, 1.0, 10, 25, 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, 800, 900, 1,000, 1100, 1200, 1300, 1,400, 1,500, 1,600, 1,700, 1,800, 1,900, 2,000, 2,100, 2,200, 2,300, 2,400, 2,500, 2,600, 2,700, 2,800, 2,900, 3,000, 3,100, 3,200, 3,300, 3,400, 3,500, 3,750, 4,000, 4,250, 4,500, 4,750, 5,000, 5,250, 5,500, 5,750, 6,000, 6,250, 6,500, 6,750, 7,000, 7,250, 7,500, 7,750, 8,000, 8,250, 8,500, 8,750, 9,000, 9,250, 9,500, 9,750, 10,000, 12,500, 15,000, or more mg of isoprene/L of broth/hr (mg/L_{broth}/hr, wherein the volume of broth includes the volume of the cells and the cell medium). In some embodiments, the peak volumetric productivity of isoprene is between about 0.5 to about 15,000 mg/L_{broth}/hr, such as between about 0.5 to about 10 mg/L_{broth}/hr, about 1.0 to about 100 mg/L_{broth}/hr, about 100 to about 500 mg/L_{broth}/hr, about 500 to about 1,000 mg/L_{broth}/hr, about 1,000 to about 1,500 mg/L_{broth}/hr, about 1,500 to about 2,000 mg/L_{broth}/hr, about 2,000 to about 2,500 mg/L_{broth}/hr, about 2,500 to about 3,000 mg/L_{broth}/hr, about 3,000 to about 3,500 mg/L_{broth}/hr, about 3,500 to about 5,000 mg/L_{broth}/hr, about 5,000 to about 7,500 mg/L_{broth}/hr, about 7,500 to about 10,000 mg/L_{broth}/hr, about 10,000 to about 12,500 mg/L_{broth}/h, or about 12,500 to about 15,000 mg/L_{broth}/hr. In some embodiments, the peak volumetric productivity of isoprene is between about 10 to about 15,000 mg/L_{broth}/hr, about 100 to about 2,500 mg/L_{broth}/hr, about 1,000 to about 5,000 mg/L_{broth}/hr, about 2,500 to about 7,500 mg/L_{broth}/hr, about 5,000 to about 10,000 mg/L_{broth}/hr, about 7,500 to about 12,500 mg/L_{broth}/hr, or about 10,000 to about 15,000 mg/L_{broth}/hr.

[0401] The instantaneous isoprene production rate in mg/L_{broth}/hr in a fermentor can be measured by taking a sample of the fermentor off-gas, analyzing it for the amount of isoprene (in units such as mg of isoprene per L_{gas}) as described, for example, in Example I, part II and

multiplying this value by the rate at which off-gas is passed through each liter of broth (*e.g.*, at 1 vvm (volume of air/volume of broth/minute) this is 60 L_{gas} per hour). Thus, an off-gas level of 1 mg/L_{gas} corresponds to an instantaneous production rate of 60 mg/L_{broth}/hr at air flow of 1 vvm. If desired, the value in units of mg/L_{broth}/hr can be divided by the OD₆₀₀ value to obtain the specific rate in units of mg/L_{broth}/hr/OD. The average value of mg isoprene/L_{gas} can be converted to the total product productivity (grams of isoprene per liter of fermentation broth, mg/L_{broth}) by multiplying this average off-gas isoprene concentration by the total amount of off-gas sparged per liter of fermentation broth during the fermentation. Thus, an average off-gas isoprene concentration of 0.5 mg/L_{broth}/hr over 10 hours at 1 vvm corresponds to a total product concentration of 300 mg isoprene/L_{broth}.

[0402] In some embodiments, the cells in culture convert greater than or about 0.0015, 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.12, 0.14, 0.16, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2, 1.4, 1.6, 2.0, 2.2, 2.4, 2.6, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0, 17.0, 18.0, 19.0, 20.0, 21.0, 22.0, 23.0, 23.2, 23.4, 23.6, 23.8, 24.0, 25.0, 30.0, 31.0, 32.0, 33.0, 35.0, 37.5, 40.0, 45.0, 47.5, 50.0, 55.0, 60.0, 65.0, 70.0, 75.0, 80.0, 85.0, or 90.0 molar % of the carbon in the cell culture medium into isoprene. In some embodiments, the percent conversion of carbon into isoprene is between about 0.002 to about 90.0 molar %, such as about 0.002 to about 0.005%, about 0.005 to about 0.01%, about 0.01 to about 0.05%, about 0.05 to about 0.15%, 0.15 to about 0.2%, about 0.2 to about 0.3%, about 0.3 to about 0.5%, about 0.5 to about 0.8%, about 0.8 to about 1.0%, about 1.0 to about 1.6%, about 1.6 to about 3.0%, about 3.0 to about 5.0%, about 5.0 to about 8.0%, about 8.0 to about 10.0%, about 10.0 to about 15.0%, about 15.0 to about 20.0%, about 20.0 to about 25.0%, about 25.0% to 30.0%, about 30.0% to 35.0%, about 35.0% to 40.0%, about 45.0% to 50.0%, about 50.0% to 55.0%, about 55.0% to 60.0%, about 60.0% to 65.0%, about 65.0% to 70.0%, about 75.0% to 80.0%, about 80.0% to 85.0%, or about 85.0% to 90.0%. In some embodiments, the percent conversion of carbon into isoprene is between about 0.002 to about 0.4 molar %, 0.002 to about 0.16 molar %, 0.04 to about 0.16 molar %, about 0.005 to about 0.3 molar %, about 0.01 to about 0.3 molar %, about 0.05 to about 0.3 molar %, about 0.1 to 0.3 molar %, about 0.3 to about 1.0 molar %, about 1.0 to about 5.0 molar %, about 2 to about 5.0 molar %, about 5.0 to about 10.0 molar %, about 7 to about 10.0 molar %, about 10.0 to about 20.0 molar %, about 12 to about 20.0 molar %, about 16 to about 20.0 molar %, about 18 to about 20.0 molar %, about 18 to 23.2 molar %, about 18 to 23.6 molar %, about 18 to about 23.8 molar %, about 18 to about 24.0 molar %, about 18 to about 25.0 molar %, about 20 to about

30.0 molar %, about 30 to about 40.0 molar %, about 30 to about 50.0 molar %, about 30 to about 60.0 molar %, about 30 to about 70.0 molar %, about 30 to about 80.0 molar %, or about 30 to about 90.0 molar %.

[0403] The percent conversion of carbon into isoprene (also referred to as “% carbon yield”) can be measured by dividing the moles carbon in the isoprene produced by the moles carbon in the carbon source (such as the moles of carbon in batched and fed glucose and yeast extract). This number is multiplied by 100% to give a percentage value (as indicated in Equation 1).

Equation 1

$$\text{Carbon Yield} = \frac{\text{moles carbon in isoprene produced}}{(\text{moles carbon in carbon source}) \times 100}$$

[0404] For this calculation, yeast extract can be assumed to contain 50% w/w carbon. As an example, for the 500 liter described in Example 7, part VIII, the percent conversion of carbon into isoprene can be calculated as shown in Equation 2.

Equation 2

$$\begin{aligned} \% \text{ Carbon Yield} &= \frac{39.1 \text{ g isoprene} \times 1/68.1 \text{ mol/g} \times 5 \text{ C/mol}}{[(181,221 \text{ g glucose} \times 1/180 \text{ mol/g} \times 6 \text{ C/mol}) + (17,780 \text{ g yeast extract} \times 0.5 \times 1/12 \text{ mol/g})] \times 100} \\ &= 0.042\% \end{aligned}$$

[0405] For the two 500 liter fermentations described herein (Example 7, parts VII and VIII), the percent conversion of carbon into isoprene was between 0.04-0.06%. A 0.11-0.16% carbon yield has been achieved using 14 liter systems as described herein.

[0406] One skilled in the art can readily convert the rates of isoprene production or amount of isoprene produced into any other units. Exemplary equations are listed below for interconverting between units.

Units for Rate of Isoprene production (total and specific)

Equation 3

$$1 \text{ g isoprene/L}_{\text{broth}}/\text{hr} = 14.7 \text{ mmol isoprene/L}_{\text{broth}}/\text{hr} \text{ (total volumetric rate)}$$

Equation 4

$1 \text{ nmol isoprene} / g_{\text{wcm}}/\text{hr} = 1 \text{ nmol isoprene} / L_{\text{broth}}/\text{hr}/OD_{600}$ (This conversion assumes that one liter of broth with an OD_{600} value of 1 has a wet cell weight of 1 gram.)

Equation 5

$1 \text{ nmol isoprene}/g_{\text{wcm}}/\text{hr} = 68.1 \text{ ng isoprene}/g_{\text{wcm}}/\text{hr}$ (given the molecular weight of isoprene)

Equation 6

$1 \text{ nmol isoprene}/L_{\text{gas}} \text{ O}_2/\text{hr} = 90 \text{ nmol isoprene}/L_{\text{broth}}/\text{hr}$ (at an O_2 flow rate of 90 L/hr per L of culture broth)

Equation 7

$1 \text{ } \mu\text{g isoprene}/L_{\text{gas}} \text{ isoprene in off-gas} = 60 \text{ } \mu\text{g isoprene}/L_{\text{broth}}/\text{hr}$ at a flow rate of 60 L_{gas} per L_{broth} (1 vvm)

Units for Titer (total and specific)**Equation 8**

$1 \text{ nmol isoprene}/\text{mg cell protein} = 150 \text{ nmol isoprene}/L_{\text{broth}}/OD_{600}$ (This conversion assumes that one liter of broth with an OD_{600} value of 1 has a total cell protein of approximately 150 mg) (specific productivity)

Equation 9

$1 \text{ g isoprene}/L_{\text{broth}} = 14.7 \text{ mmol isoprene}/L_{\text{broth}}$ (total titer)

[0407] If desired, Equation 10 can be used to convert any of the units that include the wet weight of the cells into the corresponding units that include the dry weight of the cells.

Equation 10

Dry weight of cells = (wet weight of cells)/3.3

[0408] If desired, Equation 11 can be used to convert between units of ppm and $\mu\text{g}/\text{L}$. In particular, “ppm” means parts per million defined in terms of $\mu\text{g}/\text{g}$ (w/w). Concentrations of

gases can also be expressed on a volumetric basis using “ppmv” (parts per million by volume), defined in terms of $\mu\text{L/L}$ (vol/vol). Conversion of $\mu\text{g/L}$ to ppm (*e.g.*, μg of analyte per g of gas) can be performed by determining the mass per L of off-gas (*i.e.*, the density of the gas). For example, a liter of air at standard temperature and pressure (STP; 101.3 kPa(1bar) and 273.15K) has a density of approximately 1.29 g/L. Thus, a concentration of 1 ppm ($\mu\text{g/g}$) equals 1.29 $\mu\text{g/L}$ at STP (equation 11). The conversion of ppm ($\mu\text{g/g}$) to $\mu\text{g/L}$ is a function of both pressure, temperature, and overall composition of the off-gas.

Equation 11

1 ppm ($\mu\text{g/g}$) equals 1.29 $\mu\text{g/L}$ at standard temperature and pressure (STP; 101.3 kPa (1 bar) and 273.15K).

[0409] Conversion of $\mu\text{g/L}$ to ppmv (*e.g.*, μL of analyte per L of gas) can be performed using the Universal Gas Law (equation 12). For example, an off-gas concentration of 1000 $\mu\text{g/L}_{\text{gas}}$ corresponds to 14.7 $\mu\text{mol/L}_{\text{gas}}$. The universal gas constant is $0.082057 \text{ L}\cdot\text{atm}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$, so using equation 12, the volume occupied by 14.7 μmol of HG at STP is equal to 0.329 mL. Therefore, the concentration of 1000 $\mu\text{g/L}$ HG is equal to 329 ppmv or 0.0329% (v/v) at STP.

Equation 12

$PV = nRT$, where “P” is pressure, “V” is volume, “n” is moles of gas, “R” is the Universal gas constant, and “T” is temperature in Kelvin.

[0410] The amount of impurities in isoprene compositions are typically measured herein on a weight per volume (w/v) basis in units such as $\mu\text{g/L}$. If desired, measurements in units of $\mu\text{g/L}$ can be converted to units of mg/m^3 using equation 13.

Equation 13

$$1 \mu\text{g/L} = 1 \text{ mg/m}^3$$

[0411] In some embodiments encompassed by the invention, a cell comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide produces an amount of isoprene that is at least or about 2-fold, 3-fold, 5-fold, 10-fold, 25-fold, 50-fold, 100-fold, 150-fold, 200-fold, 400-fold, or greater than the amount of isoprene produced from a

corresponding cell grown under essentially the same conditions without the heterologous nucleic acid encoding the isoprene synthase polypeptide.

[0412] In some embodiments encompassed by the invention, a cell comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide and one or more heterologous nucleic acids encoding a DXS, IDI, and/or MVA pathway polypeptide produces an amount of isoprene that is at least or about 2-fold, 3-fold, 5-fold, 10-fold, 25-fold, 50-fold, 100-fold, 150-fold, 200-fold, 400-fold, or greater than the amount of isoprene produced from a corresponding cell grown under essentially the same conditions without the heterologous nucleic acids.

[0413] In some embodiments, the isoprene composition comprises greater than or about 99.90, 99.92, 99.94, 99.96, 99.98, or 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the composition. In some embodiments, the composition has a relative detector response of greater than or about 99.90, 99.91, 99.92, 99.93, 99.94, 99.95, 99.96, 99.97, 99.98, 99.99, or 100% for isoprene compared to the detector response for all C5 hydrocarbons in the composition. In some embodiments, the isoprene composition comprises between about 99.90 to about 99.92, about 99.92 to about 99.94, about 99.94 to about 99.96, about 99.96 to about 99.98, about 99.98 to 100% isoprene by weight compared to the total weight of all C5 hydrocarbons in the composition.

[0414] In some embodiments, the isoprene composition comprises less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% C5 hydrocarbons other than isoprene (such 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the composition. In some embodiments, the composition has a relative detector response of less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for C5 hydrocarbons other than isoprene compared to the detector response for all C5 hydrocarbons in the composition. In some embodiments, the composition has a relative detector response of less than or about 0.12, 0.10, 0.08, 0.06, 0.04, 0.02, 0.01, 0.005, 0.001, 0.0005, 0.0001, 0.00005, or 0.00001% for 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-

ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne compared to the detector response for all C5 hydrocarbons in the composition. In some embodiments, the isoprene composition comprises between about 0.02 to about 0.04%, about 0.04 to about 0.06%, about 0.06 to 0.08%, about 0.08 to 0.10%, or about 0.10 to about 0.12% C5 hydrocarbons other than isoprene (such 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne) by weight compared to the total weight of all C5 hydrocarbons in the composition. .

[0415] In some embodiments, the isoprene composition comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 $\mu\text{g/L}$ of a compound that inhibits the polymerization of isoprene for any compound in the composition that inhibits the polymerization of isoprene. In some embodiments, the isoprene composition comprises between about 0.005 to about 50, such as about 0.01 to about 10, about 0.01 to about 5, about 0.01 to about 1, about 0.01 to about 0.5, or about 0.01 to about 0.005 $\mu\text{g/L}$ of a compound that inhibits the polymerization of isoprene for any compound in the composition that inhibits the polymerization of isoprene. In some embodiments, the isoprene composition comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 $\mu\text{g/L}$ of a hydrocarbon other than isoprene (such 1,3-cyclopentadiene, cis-1,3-pentadiene, trans-1,3-pentadiene, 1,4-pentadiene, 1-pentyne, 2-pentyne, 1-pentene, 2-methyl-1-butene, 3-methyl-1-butyne, pent-4-ene-1-yne, trans-pent-3-ene-1-yne, or cis-pent-3-ene-1-yne). In some embodiments, the isoprene composition comprises between about 0.005 to about 50, such as about 0.01 to about 10, about 0.01 to about 5, about 0.01 to about 1, about 0.01 to about 0.5, or about 0.01 to about 0.005 $\mu\text{g/L}$ of a hydrocarbon other than isoprene. In some embodiments, the isoprene composition comprises less than or about 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 $\mu\text{g/L}$ of a protein or fatty acid (such as a protein or fatty acid that is naturally associated with natural rubber).

[0416] In some embodiments, the isoprene composition comprises less than or about 10, 5, 1, 0.8, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of alpha acetylenes, piperylenes, acetonitrile, or 1,3-cyclopentadiene. In some embodiments, the isoprene composition comprises less than or about 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of sulfur or allenes. In some embodiments, the isoprene composition comprises less than or about 30, 20, 15, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of all acetylenes (such as 1-pentyne, 2-pentyne, 3-methyl-1-butyne, pent-4-ene-1-

yne, trans-pent-3-ene-1-yne, and cis-pent-3-ene-1-yne). In some embodiments, the isoprene composition comprises less than or about 2000, 1000, 500, 200, 100, 50, 40, 30, 20, 10, 5, 1, 0.5, 0.1, 0.05, 0.01, or 0.005 ppm of isoprene dimers, such as cyclic isoprene dimers (*e.g.*, cyclic C10 compounds derived from the dimerization of two isoprene units).

[0417] In some embodiments, the isoprene composition includes ethanol, acetone, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In particular embodiments, the isoprene composition comprises greater than or about 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 60, 80, 100, or 120 µg/L of ethanol, acetone, a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol), or any two or more of the foregoing. In some embodiments, the isoprene composition comprises between about 0.005 to about 120, such as about 0.01 to about 80, about 0.01 to about 60, about 0.01 to about 40, about 0.01 to about 30, about 0.01 to about 20, about 0.01 to about 10, about 0.1 to about 80, about 0.1 to about 60, about 0.1 to about 40, about 5 to about 80, about 5 to about 60, or about 5 to about 40 µg/L of ethanol, acetone, a C5 prenyl alcohol, or any two or more of the foregoing.

[0418] In some embodiments, the isoprene composition includes one or more of the following components: 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, 2,3-cycloheptenolpyridine, or a linear isoprene polymer (such as a linear isoprene dimer or a linear isoprene trimer derived from the polymerization of multiple isoprene units). In various embodiments, the amount of one of these components relative to amount of isoprene in units of percentage by weight (*i.e.*, weight of the component divided by the weight of isoprene times 100) is greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110% (w/w). In some embodiments, the relative detector response for the second compound compared to the detector response for isoprene is greater than or about 0.01, 0.02, 0.05, 0.1, 0.5, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, or 110%. In various embodiments, the amount of one of these components relative to amount of isoprene in units of percentage by weight (*i.e.*, weight of the component divided by the

weight of isoprene times 100) is between about 0.01 to about 105 % (w/w), such as about 0.01 to about 90, about 0.01 to about 80, about 0.01 to about 50, about 0.01 to about 20, about 0.01 to about 10, about 0.02 to about 50, about 0.05 to about 50, about 0.1 to about 50, or 0.1 to about 20% (w/w).

[0419] In some embodiments, the isoprene composition includes one or more of the following: an alcohol, an aldehyde, or a ketone (such as any of the alcohols, aldehydes, or ketones described herein). In some embodiments, the isoprene composition includes (i) an alcohol and an aldehyde, (ii) an alcohol and a ketone, (iii) an aldehyde and a ketone, or (iv) an alcohol, an aldehyde, and a ketone.

[0420] In some embodiments, the isoprene composition contains one or more of the following: methanol, ethanol, methanethiol, 1-butanol, 3-methyl-1-propanol, acetone, acetic acid, 2-butanone, 2-methyl-1-butanol, or indole. In some embodiments, the isoprene composition contains 1 ppm or more of one or more of the following: methanol, acetaldehyde, ethanol, methanethiol, 1-butanol, 3-methyl-1-propanol, acetone, acetic acid, 2-butanone, 2-methyl-1-butanol, or indole. In some embodiments, the concentration of more of one or more of the following: methanol, acetaldehyde, ethanol, methanethiol, 1-butanol, 3-methyl-1-propanol, acetone, acetic acid, 2-butanone, 2-methyl-1-butanol, or indole, is between about 1 to about 10,000 ppm in an isoprene composition (such as off-gas before it is purified). In some embodiments, the isoprene composition (such as off-gas after it has undergone one or more purification steps) includes one or more of the following: methanol, acetaldehyde, ethanol, methanethiol, 1-butanol, 3-methyl-1-propanol, acetone, acetic acid, 2-butanone, 2-methyl-1-butanol, or indole, at a concentration between about 1 to about 100 ppm, such as about 1 to about 10 ppm, about 10 to about 20 ppm, about 20 to about 30 ppm, about 30 to about 40 ppm, about 40 to about 50 ppm, about 50 to about 60 ppm, about 60 to about 70 ppm, about 70 to about 80 ppm, about 80 to about 90 ppm, or about 90 to about 100 ppm. Volatile organic compounds from cell cultures (such as volatile organic compounds in the headspace of cell cultures) can be analyzed using standard methods such as those described herein or other standard methods such as proton transfer reaction-mass spectrometry (*see, for example, Bunge et al., Applied and Environmental Microbiology*, 74(7):2179-2186, 2008 which is hereby incorporated by reference in its entirety, particular with respect to the analysis of volatile organic compounds).

[0421] In some embodiments, the composition comprises greater than about 2 mg of isoprene, such as greater than or about 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 200, 300, 400, 500, 600, 700, 800, 900, or 1000 mg of isoprene. In some embodiments, the composition comprises greater than or about 2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 g of isoprene. In some embodiments, the amount of isoprene in the composition is between about 2 to about 5,000 mg, such as between about 2 to about 100 mg, about 100 to about 500 mg, about 500 to about 1,000 mg, about 1,000 to about 2,000 mg, or about 2,000 to about 5,000 mg. In some embodiments, the amount of isoprene in the composition is between about 20 to about 5,000 mg, about 100 to about 5,000 mg, about 200 to about 2,000 mg, about 200 to about 1,000 mg, about 300 to about 1,000 mg, or about 400 to about 1,000 mg. In some embodiments, greater than or about 20, 25, 30, 40, 50, 60, 70, 80, 90, or 95% by weight of the volatile organic fraction of the composition is isoprene.

[0422] In some embodiments, the composition includes ethanol. In some embodiments, the composition includes between about 75 to about 90% by weight of ethanol, such as between about 75 to about 80%, about 80 to about 85%, or about 85 to about 90% by weight of ethanol. In some embodiments in which the composition includes ethanol, the composition also includes between about 4 to about 15% by weight of isoprene, such as between about 4 to about 8%, about 8 to about 12%, or about 12 to about 15% by weight of isoprene.

[0423] In some embodiments encompassed by the invention, a cell comprising one or more heterologous nucleic acids encoding an isoprene synthase polypeptide, DXS polypeptide, IDI polypeptide, and/or MVA pathway polypeptide produces an amount of an isoprenoid compound (such as a compound with 10 or more carbon atoms that is formed from the reaction of one or more IPP molecules with one or more DMAPP molecules) that is greater than or about 2-fold, 3-fold, 5-fold, 10-fold, 25-fold, 50-fold, 100-fold, 150-fold, 200-fold, 400-fold, or greater than the amount of the isoprenoid compound produced from a corresponding cell grown under essentially the same conditions without the one or more heterologous nucleic acids. In some embodiments encompassed by the invention, a cell comprising one or more heterologous nucleic acids encoding an isoprene synthase polypeptide, DXS polypeptide, IDI polypeptide, and/or MVA pathway polypeptide produces an amount of a C5 prenyl alcohol (such as 3-methyl-3-buten-1-ol or 3-methyl-2-buten-1-ol) that is greater than or about 2-fold, 3-fold, 5-fold, 10-fold, 25-fold, 50-fold, 100-fold, 150-fold, 200-fold, 400-fold, or greater than the amount of the C5 prenyl alcohol produced from a

corresponding cell grown under essentially the same conditions without the one or more heterologous nucleic acids.

Exemplary Isoprene Purification Methods

[0424] In some embodiments, any of the methods described herein further include recovering the isoprene. For example, the isoprene produced using the compositions and methods of the invention can be recovered using standard techniques, such as gas stripping, fractionation, adsorption/desorption, pervaporation, thermal or vacuum desorption of isoprene from a solid phase, or extraction of isoprene immobilized or absorbed to a solid phase with a solvent (see, for example, United States Patent 4,703,007 and United States Patent 4,570,029, which are each hereby incorporated by reference in their entireties, particularly with respect to isoprene recovery and purification methods). In some embodiments, the recovery of isoprene involves the isolation of isoprene in a liquid form (such as a neat solution of isoprene or a solution of isoprene in a solvent). Gas stripping involves the removal of isoprene vapor from the fermentation off-gas stream in a continuous manner. Such removal can be achieved in several different ways including, but not limited to, adsorption to a solid phase, partition into a liquid phase, or direct condensation. In some embodiments, membrane enrichment of a dilute isoprene vapor stream above the dew point of the vapor resulting in the condensation of liquid isoprene.

[0425] The recovery of isoprene may involve one step or multiple steps. In some embodiments, the removal of isoprene vapor from the fermentation off-gas and the conversion of isoprene to a liquid phase are performed simultaneously. For example, isoprene can be directly condensed from the off-gas stream to form a liquid. In some embodiments, the removal of isoprene vapor from the fermentation off-gas and the conversion of isoprene to a liquid phase are performed sequentially. For example, isoprene may be adsorbed to a solid phase and then extracted from the solid phase with a solvent. In one embodiment, the isoprene is recovered by using absorption stripping as described in U.S. Provisional Appl. No. 61/288,142.

[0426] In some embodiments, any of the methods described herein further include purifying the isoprene. For example, the isoprene produced using the compositions and methods of the invention can be purified using standard techniques. Purification refers to a process through which isoprene is separated from one or more components that are present

when the isoprene is produced. In some embodiments, the isoprene is obtained as a substantially pure liquid. Examples of purification methods include (i) distillation from a solution in a liquid extractant and (ii) chromatography. As used herein, “purified isoprene” means isoprene that has been separated from one or more components that are present when the isoprene is produced. In some embodiments, the isoprene is at least about 20%, by weight, free from other components that are present when the isoprene is produced. In various embodiments, the isoprene is at least or about 25%, 30%, 40%, 50%, 60%, 70%, 75%, 80%, 90%, 95%, or 99%, by weight, pure. Purity can be assayed by any appropriate method, *e.g.*, by column chromatography, HPLC analysis, or GC-MS analysis.

[0427] In some embodiments, at least a portion of the gas phase remaining after one or more recovery steps for the removal of isoprene is recycled by introducing the gas phase into a cell culture system (such as a fermentor) for the production of isoprene.

Isoprene Polymerization

[0428] The biosoprene compositions described herein can be subjected to chemical reactions to polymerize it to various products, such as copolymers or polymers of specific molecular weight. As described above, “copolymers” refers to a polymer that is made from polymerizing isoprene with another non-isoprene molecules, including but not limited to, 1,3-butadiene, styrene, α -methyl styrene. Isoprene can be purified from the bioisoprene compositions prior to any polymerization reactions. In one embodiment, the isoprene used is an isoprene monomer. In another embodiment, the isoprene used is polyisoprene in which isoprene monomers have been polymerized to form a polymer of isoprene units. In one embodiment, the polyisoprene is not a linear polyisoprene (*i.e.*, non-linear polyisoprene). In another embodiment, the polyisoprene is a linear polyisoprene.

[0429] Polymers, either polyisoprene or copolymer, can also be either soluble polymer or gel polymer or a combination thereof. In one embodiment, a polymer is at least about 30% soluble polymer, at least about 40% soluble polymer, at least about 50% soluble polymer, at least about 60% soluble polymer, at least about 70% soluble polymer, at least about 80% soluble polymer, at least about 90% soluble polymer, at least about 95% soluble polymer, or at least about 100% soluble polymer, with the remainder being gel polymer.

[0430] In some embodiments, the polymer is a soluble polymer. The soluble polymer can have a molecular weight ranging from 300,000 to 800,000. The soluble polymer can have a molecular weight of at least about 300,000; 400,000; 500,000; 600,000; 700,000; 800,000; 900,000; or 1,000,000. The soluble polymer can have a molecular weight of at most about 300,000; 400,000; 500,000; 600,000; 700,000; 800,000; 900,000; or 1,000,000. The soluble polymer can be two dimensional.

[0431] In other embodiments, the polymer is a gel polymer. In one embodiment, the gel polymer has a molecular weight ranging from at least about 1 million to at least about 50 million. In some embodiments, the gel polymer is at least about 1 million, at least about 2 millions, at least about 3 millions, at least about 4 millions, at least about 5 millions, at least about 6 millions, at least about 7 millions, at least about 8 millions, at least about 9 millions, at least about 10 millions, at least about 15 millions, at least about 20 millions, at least about 25 millions, at least about 30 millions, at least about 35 millions, at least about 40 millions, at least about 45 millions, or at least about 50 millions. In yet other embodiments, the gel polymer is at most about 1 million, at most about 2 millions, at most about 3 millions, at most about 4 millions, at most about 5 millions, at most about 6 millions, at most about 7 millions, at most about 8 millions, at most about 9 millions, at most about 10 millions, at most about 15 millions, at most about 20 millions, at most about 25 millions, at most about 30 millions, at most about 35 millions, at most about 40 millions, at most about 45 millions, or at least about 50 millions. The gel component can be three-dimensional.

[0432] In some aspects, polyisoprene polymers and methods of making polyisoprene polymers are provided. The polyisoprene may comprise one or more of the embodiments described herein (*e.g.*, an indicated $d^{13}C$ value). In some embodiments, any of the methods described herein (*e.g.*, methods of making and/or purifying isoprene) further include polymerizing the isoprene (*e.g.*, any isoprene described herein). For example, standard methods can be used to polymerize the purified isoprene to form *cis*-polyisoprene or other downstream products using standard methods. Accordingly, as described herein, in one aspect is provided a tire comprising polyisoprene, such as *cis*-1,4- polyisoprene and/or *trans*-1,4- polyisoprene made from any of the isoprene compositions disclosed herein and/or using any of the methods of polymerization disclosed herein. In some of these embodiments, the polyisoprene (*e.g.*, any polyisoprene polymer described herein) is made from any isoprene or isoprene composition described herein.

[0433] In some aspects, the invention provides for systems for producing a polymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with other isoprene molecules to produce a polymer of isoprene with a molecular weight of about 5,000 to about 100,000. As used herein, “at least a portion of the isoprene starting composition” can refer to at least about 1%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, 99.5%, 99.6%, 99.7%, 99.8%, 99.9%, or 100% of the isoprene starting composition undergoing polymerization.

[0434] In other aspects, polyisoprene polymers and copolymers and methods of making these types of polymers of various molecular weights are provided. In one embodiment, the polymers have a molecular weight of about 5,000 to about 100,000. In other embodiments, the the polymers have a molecular weight of at least about 6,000; 7,000; 8,000; 9,000; 10,000; 12,000; 15,000; 20,000; 25,000; 30,000; 35,000; 40,000; 45,000; 50,000; 55,000; 60,000; 70,000; 80,000; 90,000 or 100,000. In other embodiments, the the polymers have a molecular weight of at most about 6,000; 7,000; 8,000; 9,000; 10,000; 12,000; 15,000; 20,000; 25,000; 30,000; 35,000; 40,000; 45,000; 50,000; 55,000; 60,000; 70,000; 80,000, 90,000 or 100,000.

[0435] Additional methods and compositions are described in United States Provisional patent application No. 61/097,186, filed on September 15, 2008, WO 2010/031062, United States Provisional patent application No. 61/097,189, filed on September 15, 2008, WO 2010/031077, United States Provisional patent application No. 61/097,163, filed on September 15, 2008, WO 2010/031079, and United States Patent Application Serial No. 12/335,071 (US 2009/0203102 A1) all of which are incorporated by reference in their entireties, particularly with respect to compositions and methods for producing isoprene.

[0436] In one aspect, provided is a method for producing a polymer of isoprene derived from renewable resources comprising: (a) obtaining isoprene from renewable resources; (b) polymerizing isoprene derived from renewable resources; and (c) recovering the polymer produced. In some embodiments, the isoprene from renewable resources is obtained by a method which comprises the steps of (i) culturing cells comprising a heterologous nucleic

acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene, (ii) producing the isoprene, and (iii) recovering the isoprene from the culture. A polymer of isoprene derived from renewable resources, such as a polyisoprene homopolymer, a liquid polyisoprene polymer or a co-polymer of isoprene and one or more additional monomers, produced by any of the methods described herein is intended by the invention.

[0437] In some embodiments, the invention provide for a system for producing a copolymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with another non-isoprene molecule to produce a copolymer. As used herein, “at least a portion of the isoprene starting composition” can refer to at least about 1%, 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, 99.5%, 99.6%, 99.7%, 99.8%, 99.9%, or 100% of the isoprene starting composition undergoing polymerization.

[0438] In some embodiments, the isoprene of this invention can be polymerized into useful polymers, including synthetic rubber, utilizing the same techniques that are applicable to isoprene that is derived from petrochemical sources. The polymerization and recovery of such isoprene containing polymers are suitably carried out according to various methods suitable for diene monomer polymerization processes. This includes batchwise, semi-continuous, or continuous operations under conditions that exclude air and other atmospheric impurities, particularly oxygen and moisture. The polymerization of the isoprene monomer may also be carried out in a number of different polymerization reactor systems, including but not limited to bulk polymerization, vapor phase polymerization, solution polymerization, suspension polymerization, emulsion polymerization, and precipitation polymerization systems. The commercially preferred methods of polymerization are typically solution polymerization and emulsion polymerization.

[0439] In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises a catalyst for polymerizing isoprene. In some embodiments, the system and compositions further comprises a polymerization initiator. The polymerization reaction can also be

initiated using a vast array of different polymerization initiators or catalyst systems. The initiator or catalyst system used will be dependent upon the desired characteristics of the isoprene containing polymer being synthesized. For instance, in cases where cis-1,4-polyisoprene rubber is being made a Ziegler Natta catalyst system which is comprised of titanium tetrachloride and triethyl aluminum can be utilized. In synthesizing other types of isoprene containing polymers other types of initiator systems may be needed. For instance, isoprene containing polymers can be made using agree radical initiator, a redox initiator, an anionic initiator, or a cationic initiator. The preferred initiation or catalyst system will depend upon the polymer microstructure, molecular weight, molecular weight distribution, and chain branching desired. The preferred initiators will also depend upon whether the isoprene is being homopolymerized or copolymerized with additional monomers. In the case of copolymers the initiator used will also depend upon whether it is desirable for the polymer being made to have a random, non-random, or tapered distribution of repeat units that are derived of the particular monomers. For instance, anionic initiators or controlled free radical initiators are typically used in synthesizing block copolymers having isoprene blocks.

[0440] It is important for the initiator or catalyst system employed to be compatible with the type of polymerization system used. For instance, in emulsion polymerizations free radical initiators are typically utilized. In solution polymerizations anionic initiators, such as alkyl lithium compounds, are typically employed to initiate the polymerization. An advantage of free radical polymerization is that reactions can typically be carried out under less rigorous conditions than ionic polymerizations. Free radical initiation systems also exhibit a greater tolerance of trace impurities.

[0441] Conventional emulsion recipes may also be employed in polymerizing isoprene in accordance with the present invention; however, some restrictions and modifications may arise either from the inclusion of additional comonomers, or the restrictions on polymerization parameters. In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises an ionic surfactant. Ionic surfactants, known in the art, including sulfonate detergents and carboxylate, sulfate, and phosphate soaps are useful in this invention. The level of ionic surfactant is computed based upon the total weight of the organic components and may range from about 2 to 30 parts by weight of ionic surfactant per 100 parts by weight of organic components.

[0442] Examples of free radical initiators that are useful in the practice of the present invention are those known as "redox" initiators, such as combinations of chelated iron salts, sodium formaldehyde sulfoxylate, and organic hydroperoxides. Representative of organic hydroperoxides are cumene hydroperoxide, paramenthane hydroperoxide, and tertiary butyl hydroperoxide. Tertiary butyl hydroperoxide (t-BHP), tertiary butyl peracetate (t-BPA) and "azo" initiators, such as azobisisobutyronitrile (AIBN), are preferred.

[0443] The reaction temperature utilized in free radical polymerizations is typically maintained in the range of 0°C to 150°C. Temperatures between about 20°C and 120°C are generally preferred and temperatures within the range of 60°C to 100°C are normally most preferred. The reaction pressure is not critical. It is typically only sufficiently high to maintain liquid phase reaction conditions; it may be autogenic pressure, which will vary depending upon the components of the reaction mixture and the temperature, or it may be higher, e.g., up to 1000 psi.

[0444] In some embodiments, the method for producing a polymer of isoprene derived from renewable resources comprises polymerizing isoprene derived from renewable resources in a batch process. In batch operations, the polymerization time can be varied as desired from as little as a few minutes to as long as several days. Polymerization in batch processes may be terminated when monomer is no longer absorbed, or earlier, if desired, e.g., if the reaction mixture becomes too viscous. In continuous operations, the polymerization mixture may be passed through a reactor or series of reactors of any suitable design. The polymerization reactions in such cases are suitably adjusted by varying the residence time in the reactor system. Residence times vary with the type of reactor system and range from 10 to 15 minutes to 24 or more hours. The concentration of monomer in the reaction mixture may vary upwards from 5 percent by weight of the reaction mixture, depending on the conditions employed; the range from 20 to 80 percent by weight is preferred.

[0445] In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises a suitable organic solvent. In some embodiments, the polymerization of isoprene is carried out in a suitable organic solvent that is liquid under the conditions of reaction and which is relatively inert. The solvent may have the same number of carbon atoms per molecule as the diene reactant or it may be in a different boiling range. Preferred organic solvents are

normally alkanes and cycloalkanes. The solvents can be comprised of one or more aromatic, paraffinic or cycloparaffinic compounds. These solvents will normally contain from about 4 carbon atoms per mole to about 10 carbon atoms per molecule and will be liquid under the conditions of the polymerization. Some representative examples of suitable organic solvents include pentane, isooctane, cyclohexane, methylcyclohexane, isohexane, n-heptane, n-octane, n-hexane, benzene, toluene, xylene, ethylbenzene, diethylbenzene, isobutylbenzene, petroleum ether, kerosene, petroleum spirits, petroleum naphtha, and the like, alone or in admixture. Aromatic hydrocarbons, such as benzene, toluene, isopropylbenzene, xylene, or halogenated aromatic compounds, such as chlorobenzene, bromobenzene, or orthodichlorobenzene, may also be employed, but are not preferred in most cases. Other useful solvents include tetrahydrofuran and dioxane.

[0446] In the solution polymerization, there will normally be from 5 to 30 weight percent monomers in the polymerization medium. Such polymerization media are, of course, comprised of the organic solvent and monomers. In most cases, it will be preferred for the polymerization medium to contain from 10 to 25 weight percent monomers. It is generally more preferred for the polymerization medium to contain 15 to 20 weight percent monomers.

[0447] The polymerization is typically carried out to attain an essentially complete conversion of monomers into polymer. Incremental monomer addition, or a chain transfer agent, may be used in order to avoid excessive gel formation. Such minor modifications are within the skill of the artisan. After the polymerization is complete, the polymer is recovered from a slurry or solution of the polymer. A simple filtration may be adequate to separate polymer from diluent. Other means for separating polymer from diluent may be employed. The polymer may be treated, separately or while slurried in the reaction mixture, in order to separate residues. Such treatment may be with alcohols such as methanol, ethanol, or isopropanol, with acidified alcohols, or with other similar polar liquids. In many cases the polymers are obtained in hydrocarbon solutions and the polymer can be recovered by coagulation with acidified alcohol, e.g., rapidly stirred methanol or isopropanol containing 2% hydrochloric acid. Following this initial coagulation, the polymers may be washed with an appropriate liquid, such as methanol.

[0448] In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises one

or more additional monomers. As has been previously noted, the isoprene can also be copolymerized with one or more additional comonomers to make useful copolymers. Some adjustments in the polymerization recipe or reaction conditions may be necessary to obtain a satisfactory rate of polymer formation, depending on the relative amount of isoprene included and the other monomers involved. Examples of comonomers that are useful in the practice of this invention include other diene monomers, such as 1,3-butadiene and hexadienes. Vinyl aromatic monomers can also be copolymerizable with isoprene to make useful polymers. Such vinyl aromatic monomers include styrene, *a*-methylstyrene, divinylbenzene, vinyl chloride, vinyl acetate, vinylidene chloride, methyl methacrylate, ethyl acrylate, vinylpyridine, acrylonitrile, methacrylonitrile, methacrylic acid, itaconic acid and acrylic acid. Mixtures of different comonomers can also be employed at differing levels.

[0449] In some embodiments, the isoprene monomer is copolymerized with one or more additional conjugated diolefin monomers. Those containing from 4 to 8 carbon atoms are generally preferred for commercial purposes. Some specific representative examples of conjugated diolefin monomers that can be copolymerized with isoprene include 1,3-butadiene, 2,3-dimethyl-1,3-butadiene, piperylene, 3-butyl-1,3-octadiene, 2-phenyl-1,3-butadiene, and the like, alone or in admixture.

[0450] In some embodiments, the isoprene monomer is copolymerized with one or more additional ethylenically unsaturated monomers. Some representative examples of ethylenically unsaturated monomers that can copolymerized with isoprene include alkyl acrylates, such as methyl acrylate, ethyl acrylate, butyl acrylate, methyl methacrylate and the like; vinylidene monomers having one or more terminal $\text{CH}_2=\text{CH}-$ groups; vinyl aromatics such as styrene, *a*-methylstyrene, bromostyrene, chlorostyrene, fluorostyrene and the like; α -olefins such as ethylene, propylene, 1-butene and the like; vinyl halides, such as vinylbromide, chloroethene (vinylchloride), vinylfluoride, vinyliodide, 1,2-dibromoethene, 1,1-dichloroethene (vinylidene chloride), 1,2-dichloroethene and the like; vinyl esters, such as vinyl acetate; α , β -olefinically unsaturated nitriles, such as acrylonitrile and methacrylonitrile; α , β -olefinically unsaturated amides, such as acrylamide, *N*-methylacrylamide, *N,N*-dimethylacrylamide, methacrylamide and the like. Functionalized monomers can also optionally be copolymerized with the isoprene in making useful rubbery polymers. Functionalized monomers of this type and methods by which they can be incorporated into rubbery polymers are described in United States Patent 6,627,721 and

United States Patent 6,936,669. The teachings of United States Patent 6,627,721 and United States Patent 6,936,669 are incorporated herein by reference for the purpose of describing such functionalized monomers and their incorporation into isoprene containing polymers.

[0451] Rubbery polymers which are copolymers of one or more diene monomers with one or more other ethylenically unsaturated monomers will normally contain from about 50 weight percent to about 99 weight percent conjugated diolefin monomers (including isoprene) and from about 1 weight percent to about 50 weight percent of the other ethylenically unsaturated monomers in addition to the conjugated diolefin monomers. For example, rubbery copolymers of isoprene monomer with vinylaromatic monomers, such as styrene-isoprene rubbers will normally which contain from 50 to 95 weight percent isoprene and from 5 to 50 weight percent vinylaromatic monomers.

[0452] Vinyl aromatic monomers are probably the most important group of ethylenically unsaturated monomers which are commonly incorporated into isoprene containing rubbers. Such vinyl aromatic monomers typically contain from 8 to 20 carbon atoms. Usually, the vinyl aromatic monomer will contain from 8 to 14 carbon atoms. The most widely used vinyl aromatic monomer is styrene. Some examples of vinyl aromatic monomers that can be utilized include styrene, 1-vinylnaphthalene, 2-vinylnaphthalene, α -methylstyrene, 4-phenylstyrene, 3-methylstyrene and the like.

[0453] Some representative examples of isoprene containing rubbery polymers include cis-1,3-polyisoprene homopolymer rubber, 3,4-polyisoprene rubber, styrene-isoprene rubber (SIR), β -methylstyrene-isoprene rubber, styrene-isoprene-butadiene rubber (SIBR), styrene-isoprene rubber (SIR), isoprene-butadiene rubber (IBR), α -methylstyrene-isoprene-butadiene rubber and α -methylstyrene-styrene-isoprene-butadiene rubber. In cases where the rubbery polymer is comprised of repeat units that are derived from two or more monomers, the repeat units which are derived from the different monomers, including the isoprene, will normally be distributed in an essentially random manner. The repeat units that are derived from the monomers differ from the monomer in that a double bond is normally consumed in by the polymerization reaction.

[0454] In some embodiments, the method for producing a polymer of isoprene derived from renewable resources comprises polymerizing isoprene derived from renewable resources in a continuous process. The rubbery polymer can be made by solution

polymerization in a batch process or in a continuous process by continuously charging the isoprene monomer and optionally additional monomers into a polymerization zone. The polymerization zone will typically be a polymerization reactor or a series of polymerization reactors. The polymerization zone will normally provide agitation to keep the monomers, polymer, initiator, and modifier well dispersed throughout the organic solvent the polymerization zone. Such continuous polymerizations are typically conducted in a multiple reactor system. The rubbery polymer synthesized is continuously withdrawn from the polymerization zone. The monomer conversion attained in the polymerization zone will normally be at least about 85 percent. It is preferred for the monomer conversion to be at least about 90 percent.

[0455] In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises a polymerization initiator and a polar modifier. The polymerization can be initiated with an anionic initiator, such as an alkyl lithium compound. The alkyl lithium compounds that can be used will typically contain from 1 to about 8 carbon atoms, such as n-butyl lithium. The amount of the lithium initiator utilized will vary with the monomers being polymerized and with the molecular weight that is desired for the polymer being synthesized. However, as a general rule, from 0.01 to 1 phm (parts per 100 parts by weight of monomer) of the lithium initiator will be utilized. In most cases, from 0.01 to 0.1 phm of the lithium initiator will be utilized with it being preferred to utilize 0.025 to 0.07 phm of the lithium initiator.

[0456] Such anionic polymerizations are optionally conducted in the presence of polar modifiers, such as alkyltetrahydrofurfuryl ethers. Some representative examples of specific polar modifiers that can be used include methyltetrahydrofurfuryl ether, ethyltetrahydrofurfuryl ether, propyltetrahydrofurfuryl ether, butyltetrahydrofurfuryl ether, hexyltetrahydrofurfuryl ether, octyltetrahydrofurfuryl ether, dodecyltetrahydrofurfuryl ether, diethyl ether, di-n-propyl ether, diisopropyl ether, di-n-butyl ether, tetrahydrofuran, dioxane, ethylene glycol dimethyl ether, ethylene glycol diethyl ether, diethylene glycol dimethyl ether, diethylene glycol diethyl ether, triethylene glycol dimethyl ether, trimethylamine, triethylamine, N,N,N',N'-tetramethylethylenediamine, N-methylmorpholine, N-ethylmorpholine, or N-phenylmorpholine.

[0457] The polar modifier will typically be employed at a level wherein the molar ratio of the polar modifier to the lithium initiator is within the range of about 0.01:1 to about 5:1. The molar ratio of the polar modifier to the lithium initiator will more typically be within the range of about 0.1:1 to about 4:1. It is generally preferred for the molar ratio of polar modifier to the lithium initiator to be within the range of about 0.25:1 to about 3:1. It is generally most preferred for the molar ratio of polar modifier to the lithium initiator to be within the range of about 0.5:1 to about 3:2.

[0458] The polymerization temperature utilized in such anionic polymerizations can vary over a broad range of from about -20°C to about 180°C. In most cases, a polymerization temperature within the range of about 30°C to about 125°C will be utilized. It is typically preferred for the polymerization temperature to be within the range of about 45°C to about 100°C. It is typically most preferred for the polymerization temperature to be within the range of about 60°C to about 90°C. The pressure used will normally be sufficient to maintain a substantially liquid phase under the conditions of the polymerization reaction.

[0459] In some embodiments, the system and compositions for producing a polymer of isoprene by polymerizing isoprene derived from renewable resources further comprises a polymerization chain terminator such as an alcohol, a terminating agent, or a coupling agent. Such anionic polymerizations of isoprene are normally conducted for a length of time sufficient to permit substantially complete polymerization of the isoprene and any additional monomers that are present. In other words, the polymerization is normally carried out until high conversions of at least about 85 percent are attained. The polymerization is then normally terminated by the addition of an agent, such as an alcohol, a terminating agent, or a coupling agent. For example, a tin halide and/or silicon halide can be used as a coupling agent. The tin halide and/or the silicon halide are continuously added in cases where asymmetrical coupling is desired. This continuous addition of tin coupling agent and/or the silicon coupling agent is normally done in a reaction zone separate from the zone where the bulk of the polymerization is occurring. The coupling agents will normally be added in a separate reaction vessel after the desired degree of conversion has been attained. The coupling agents can be added in a hydrocarbon solution, e.g., in cyclohexane, to the polymerization admixture with suitable mixing for distribution and reaction. In other words, the coupling will typically be added only after a high degree of conversion has already been attained. For instance, the coupling agent will normally be added only after a monomer

conversion of greater than about 85 percent has been realized. It will typically be preferred for the monomer conversion to reach at least about 90 percent before the coupling agent is added.

[0460] The tin halides used as coupling agents will normally be tin tetrahalides, such as tin tetrachloride, tin tetrabromide, tin tetrafluoride or tin tetraiodide. However, tin trihalides can also optionally be used. Polymers coupled with tin trihalides having a maximum of three arms. This is, of course, in contrast to polymers coupled with tin tetrahalides which have a maximum of four arms. To induce a higher level of branching, tin tetrahalides are normally preferred. As a general rule, tin tetrachloride is most preferred.

[0461] The silicon coupling agents that can be used will normally be silicon tetrahalides, such as silicon tetrachloride, silicon tetrabromide, silicon tetrafluoride or silicon tetraiodide. However, silicon trihalides can also optionally be used. Polymers coupled with silicon trihalides having a maximum of three arms. This is, of course, in contrast to polymers coupled with silicon tetrahalides which have a maximum of four arms. To induce a higher level of branching, silicon tetrahalides are normally preferred. As a general rule, silicon tetrachloride is most preferred of the silicon coupling agents.

[0462] A combination of a tin halide and a silicon halide can optionally be used to couple the rubbery polymer. By using such a combination of tin and silicon coupling agents improved properties for tire rubbers, such as lower hysteresis, can be attained. It is particularly desirable to utilize a combination of tin and silicon coupling agents in tire tread compounds that contain both silica and carbon black. In such cases, the molar ratio of the tin halide to the silicon halide employed in coupling the rubbery polymer will normally be within the range, of 20:80 to 95:5. The molar ratio of the tin halide to the silicon halide employed in coupling the rubbery polymer will more typically be within the range of 40:60 to 90:10. The molar ratio of the tin halide to the silicon halide employed in coupling the rubbery polymer will preferably be within the range of 60:40 to 85:15. The molar ratio of the tin halide to the silicon halide employed in coupling the rubbery polymer will most preferably be within the range of 65:35 to 80:20.

[0463] Broadly, and exemplary, a range of about 0.01 to 4.5 milliequivalents of tin coupling agent (tin halide and silicon halide) is employed per 100 grams of the rubbery polymer. It is normally preferred to utilize about 0.01 to about 1.5 milliequivalents of the

coupling agent per 100 grams of polymer to obtain the desired Mooney viscosity. The larger quantities tend to result in production of polymers containing terminally reactive groups or insufficient coupling. One equivalent of tin coupling agent per equivalent of lithium is considered an optimum amount for maximum branching. For instance, if a mixture tin tetrahalide and silicon tetrahalide is used as the coupling agent, one mole of the coupling agent would be utilized per four moles of live lithium ends. In cases where a mixture of tin trihalide and silicon trihalide is used as the coupling agent, one mole of the coupling agent will optimally be utilized for every three moles of live lithium ends. The coupling agent can be added in a hydrocarbon solution, e.g., in cyclohexane, to the polymerization admixture in the reactor with suitable mixing for distribution and reaction.

[0464] After the coupling has been completed, a tertiary chelating alkyl 1,2-ethylenediamine or a metal salt of a cyclic alcohol can optionally be added to the polymer cement to stabilize the coupled rubbery polymer. In most cases, from about 0.01 phr (parts by weight per 100 parts by weight of dry rubber) to about 2 phr of the chelating alkyl 1,2-ethylenediamine or metal salt of the cyclic alcohol will be added to the polymer cement to stabilize the rubbery polymer. Typically, from about 0.05 phr to about 1 phr of the chelating alkyl 1,2-ethylenediamine or metal salt of the cyclic alcohol will be added. More typically, from about 0.1 phr to about 0.6 phr of the chelating alkyl 1,2-ethylenediamine or the metal salt of the cyclic alcohol will be added to the polymer cement to stabilize the rubbery polymer.

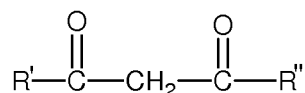
[0465] The terminating agents that can be used to stop the polymerization and to "terminate" the living rubbery polymer include tin monohalides, silicon monohalides, N,N,N',N'-tetradialkyldiamino-benzophenones (such as tetramethyldiaminobenzophenone and the like), N,N-dialkylamino-benzaldehydes (such as dimethylaminobenzaldehyde and the like), 1,3-dialkyl-2-imidazolidinones (such as 1,3-dimethyl-2-imidazolidinone and the like), 1-alkyl substituted pyrrolidinones; 1-aryl substituted pyrrolidinones, dialkyl-dicycloalkyl-carbodiimides containing from about 5 to about 20 carbon atoms, and dicycloalkyl-carbodiimides containing from about 5 to about 20 carbon atoms.

[0466] After the termination step, and optionally the stabilization step, has been completed, the rubbery polymer can be recovered from the organic solvent. The coupled rubbery polymer can be recovered from the organic solvent and residue by means such as chemical

(alcohol) coagulation, thermal desolventization, or other suitable method. For instance, it is often desirable to precipitate the rubbery polymer from the organic solvent by the addition of lower alcohols containing from about 1 to about 4 carbon atoms to the polymer solution. Suitable lower alcohols for precipitation of the rubber from the polymer cement include methanol, ethanol, isopropyl alcohol, normal-propyl alcohol and t-butyl alcohol. The utilization of lower alcohols to precipitate the rubbery polymer from the polymer cement also "terminates" any remaining living polymer by inactivating lithium end groups. After the coupled rubbery polymer is recovered from the solution, steam-stripping can be employed to reduce the level of volatile organic compounds in the coupled rubbery polymer. Additionally, the organic solvent can be removed from the rubbery polymer by drum drying, extruder drying, vacuum drying, and the like.

[0467] As has previously been explained, synthetic cis-1,3-polyisoprene rubber that is similar enough to allow for free substitution with natural rubber can be produced by the solution polymerization of isoprene with a Ziegler Natta catalyst system that is comprised of titanium tetrachloride (TiCl_4) and an organoaluminum compound, such as triethyl aluminum, $\text{Al}(\text{CH}_2\text{-CH}_3)_3$. The polyisoprene rubber that is made with this Ziegler Natta catalyst system has a high cis-microstructure contain of up to 98 percent that closely assimilates that of natural rubber from *Hevea Brasiliensis* (the common rubber tree) which has a cis-microstructure content of virtually 100 percent. However, this slight difference in polymer microstructure results of physical properties that are inferior to those of natural rubber in certain respects. For instance, natural rubber typically exhibits green strength that is superior to that of synthetic cis-1,4-polyisoprene rubber. On the other hand, in certain other respects synthetic cis-1,4-polyisoprene rubber is superior to natural rubber from the *Hevea Brasiliensis*, guayule, and *Taraxacum kok-Saghyz* (Russian dandelion). For instance, natural rubber contains residual proteins, soaps, resins, and sugars since it comes from plants. The presence of these residual impurities can be extremely detrimental in some applications. For instance, the presence of residual proteins in rubber products can cause serious allergic reactions in some people and are a major concern for manufacturers of some rubber-containing products, such as rubber gloves, condoms, syringe plungers, and the like. In any case, the synthetic polyisoprene homopolymer rubbers of this invention that are free from proteins, soaps, resins, and sugars present in natural rubber, including natural rubber from the *Hevea Brasiliensis*.

[0468] United States Patent 3,931,136 discloses a process for producing high molecular weight cis-1,4-polyisoprene. The catalyst used in this process is a three-component mixture of (A) a titanium tetrachloride, (B) an organoaluminum compound of the formula AlR_3 , where each R represents an alkyl group, preferably an alkyl group containing 1 to 8 carbon atoms, an aryl group, preferably a phenyl group, or a cycloalkyl group, preferably a cyclohexyl group, and (C) a beta-diketone of the formula:



where R' and R'' can be the same or different and represent an alkyl group or a aryl group. R' and R'' will preferably represent an alkyl group containing from 1 to 5 carbon atoms or a phenyl group. The teachings of United States Patent 3,931,136 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene.

[0469] A solution polymerization technique for synthesizing cis-1,4-polyisoprene with a catalyst system that is comprised of a mixture of titanium tetrachloride and a trialkylaluminum compound is disclosed by United States Patent 4,430,487. In this process the polymerization is shortstopped with 4,7-diaza-decane-1,10-diamine. The teachings of United States Patent 4,430,487 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene.

[0470] The synthesis of cis-1,4-polyisoprene by polymerizing isoprene with a catalyst system which is comprised of a titanium tetrahalide, a trialkylaluminum compound and diphenylether can result in the formation of unwanted gel. United States Patent 5,919,876 discloses that gel formation can be reduced by conducting such polymerizations in the presence of a diarylamine, such as para-styrenated diphenylamine. United States Patent 5,919,876 more specifically discloses a process for synthesizing cis-1,4-polyisoprene having a low gel content which comprises polymerizing isoprene in an inert organic solvent with a preformed catalyst system which is made by reacting an organoaluminum compound with titanium tetrahalide, such as titanium tetrachloride, in the presence of at least one ether, wherein said polymerization is conducted at a temperature which is within the range of about

0°C to about 100°C, and wherein said polymerization is conducted in the presence of a diarylamine. The teachings of United States Patent 5,919,867 are incorporated herein by reference for the purpose of teaching catalyst systems and solution polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene rubber.

[0471] Cis-1,4-polyisoprene can be made by vapor phase polymerization utilizing a preformed catalyst that is made by reacting an organoaluminum compound with titanium tetrachloride. United States Patent 6,066,705 discloses a method for vapor phase polymerizing isoprene into cis-1,4-polyisoprene in a process comprising the steps of: (1) charging into a reaction zone said isoprene and a preformed catalyst system which is made by reacting an organoaluminum compound with titanium tetrachloride, preferably in the presence of at least one ether; wherein the isoprene is maintained in the vapor phase in said reaction zone by a suitable combination of temperature and pressure; (2) allowing said isoprene to polymerize into cis-1,4-polyisoprene at a temperature within the range of about 35°C to about 70°C; and (3) withdrawing said cis-1,4-polyisoprene from said reaction zone. It has been determined that gel formation can be reduced in such vapor phase polymerizations by conducting the polymerization of the isoprene monomer in the presence of a diarylamine, such as para-styrenated diphenylamine. The teachings of United States Patent 6,066,705 are incorporated herein by reference for the purpose of teaching catalyst systems and vapor phase polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene rubber.

[0472] Polyisoprene rubber that is clear (transparent) and of high purity can be synthesized utilizing a neodymium catalyst system. United States Patent 6,780,948 relates to such a process for the synthesis of polyisoprene rubber which comprises polymerizing isoprene monomer in the presence of a neodymium catalyst system, wherein the neodymium catalyst system is prepared by (1) reacting a neodymium carboxylate with an organoaluminum compound in the presence of isoprene for a period of about 10 minutes to about 30 minutes to produce neodymium-aluminum catalyst component, and (2) subsequently reacting the neodymium-aluminum catalyst component with a dialkyl aluminum chloride for a period of at least 30 minutes to produce the neodymium catalyst system. The teachings of United States Patent 5,919,867 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene rubber that is of high purity.

[0473] United States Patent 7,091,150 and United States Patent 7,199,201 disclose the use of a neodymium catalyst system to polymerize isoprene monomer into synthetic polyisoprene rubber having an extremely high cis-microstructure content and high stereo regularity. This polyisoprene rubber will crystallize under strain and can be compounded into rubber formulations in a manner similar to natural rubber. This technique more specifically discloses a process for the synthesis of polyisoprene rubber which comprises polymerizing isoprene monomer in the presence of a neodymium catalyst system, wherein the neodymium catalyst system is prepared by a process that comprises (1) reacting a neodymium carboxylate with an organoaluminum compound in an organic solvent to produce neodymium-aluminum catalyst component, and (2) subsequently reacting the neodymium-aluminum catalyst component with an elemental halogen to produce the neodymium catalyst system. In practicing this process, the neodymium catalyst system is typically void of nickel-containing compounds.

[0474] The synthetic polyisoprene rubber made by this process is comprised of repeat units that are derived from isoprene, wherein the synthetic polyisoprene rubber has a cis-microstructure content which is within the range of 98.0% to 99.5%, a 3,4-microstructure content which is within the range of 0.5% to 2.0%, and a trans-microstructure content which is within the range of 0.0% to 0.5%. The teachings of United States Patent 7,091,150 and United States Patent 7,199,201 are incorporated herein by reference for the purpose of teaching neodymium catalyst systems and polymerization techniques that can be used in synthesizing cis-1,4-polyisoprene rubber of extremely high cis-microstructure content and high stereo regularity.

[0475] Single component lanthanide catalysts, such as lanthanide diiodides, can also be used in the synthesis of polyisoprene having extremely high cis-microstructure contents. For instance, thulium diiodide, dysprosium diiodide, and neodymium diiodide can initiate the polymerization of isoprene into high cis-1,4-polyisoprene rubber without the need for any additional catalyst components. Lanthanide diiodides can accordingly be used to initiate the polymerization of isoprene monomer into high cis-1,4-polyisoprene under solution polymerization conditions.

[0476] United States Patent 4,894,425 reveals a process for synthesizing polyisoprene that may possess functional groups and that contains more than 70 percent 1,2- and 3,4-structural

units. This process involves the anionic polymerization of isoprene in an inert hydrocarbon solvent in the presence of an organolithium compound as the catalyst and an ether as the cocatalyst, wherein the cocatalyst used is an ethylene glycol dialkyl ether of the formula $R^1-O-CH_2-CH_2-O-R^2$ wherein R^1 and R^2 are alkyl groups having different numbers of carbon atoms, selected from the group consisting of methyl, ethyl, n-propyl, iso-propyl, n-butyl, iso-butyl, sec-butyl, and tert-butyl, and wherein the sum of the carbon atoms in the two alkyl groups R^1 and R^2 is within the range of 5 to 7. The teachings of United States Patent 4,894,425 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing polyisoprene having a high 1,2- and 3,4-microstructure content.

[0477] Crystallizable 3,4-polyisoprene can be synthesized in organic solvents to quantitative yields after short polymerization times by utilizing the catalyst systems described by United States Patent 5,082,906. The 3,4-polyisoprene made utilizing this catalyst system is strain crystallizable and can be employed in tire treads which provide improved traction and improved cut growth resistance. United States Patent 5,082,906 specifically discloses a process for the synthesis of 3,4-polyisoprene which comprises polymerizing isoprene monomer in an organic solvent at a temperature which is within the range of about -10°C to about 100°C in the presence of a catalyst system which is composed of (a) an organoiron compound, (b) an organoaluminum compound, (c) a chelating aromatic amine, and (d) a protonic compound; wherein the molar ratio of the chelating amine to the organoiron compound is within the range of about 0.1:1 to about 1:1, wherein the molar ratio of the organoaluminum compound to the organoiron compound is within the range of about 5:1 to about 200:1, and wherein the molar ratio of the protonic compound to the organoaluminum compound is within the range of about 0.001:1 to about 0.2:1. The teachings of United States Patent 5,082,906 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing polyisoprene having a high 3,4-microstructure content and which is strain crystallizable.

[0478] United States Patent 5,356,997 also relates to a process for the synthesis of strain crystallizable 3,4-polyisoprene. This 3,4-polyisoprene has a 3,4-microstructure content which is within the range of about 65% to about 85%, a cis-1,4-microstructure content which is within the range of about 15% to about 35%, and essentially no trans-1,4-microstructure or 1,2-microstructure. It can be synthesized in organic solvents to quantitative yields after short

polymerization times. United States Patent 5,356,997 specifically discloses a process for the synthesis of 3,4-polyisoprene which comprises polymerizing isoprene monomer in an organic solvent at a temperature which is within the range of about -10°C to about 100°C in the presence of a catalyst system which is comprised of (a) an organoiron compound which is soluble in the organic solvent, wherein the iron in the organoiron compound is in the +3 oxidation state, (b) a partially hydrolyzed organoaluminum compound which was prepared by adding a protonic compound selected from the group consisting of water, alcohols and carboxylic acids to the organoaluminum compound, and (c) a chelating aromatic amine; wherein the molar ratio of the chelating amine to the organoiron compound is within the range of about 0.1:1 to about 1:1, wherein the molar ratio of the organoaluminum compound to the organoiron compound is within the range of about 5:1 to about 200:1, and wherein the molar ratio of the protonic compound to the organoaluminum compound is within the range of about 0,001:1 to about 0.2:1. The teachings of United States Patent 5,356,997 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing polyisoprene having a high 3,4-microstructure content and which is strain crystallizable.

[0479] United States Patent 5,677,402 reveals a process for preparing 3,4-polyisoprene rubber which comprises polymerizing isoprene monomer with an organolithium initiator at a temperature which is within the range of about 30°C to about 100°C in the presence of a sodium alkoxide and a polar modifier, wherein the molar ratio of the sodium alkoxide to the organolithium initiator is within the range of about 0.05:1 to about 3:1; and wherein the molar ratio of the polar modifier to the organolithium initiator is within the range of about 0.25: 1 to about 5:1. The teachings of United States Patent 5,677,402 are incorporated herein by reference for the purpose of teaching catalyst systems and polymerization techniques that can be used in synthesizing 3,4-polyisoprene.

[0480] United States Patent 7,351,768 discloses the synthesis of liquid polyisoprene having a weight average molecular weight which is within the range of 5,000 to 100,000 and preferable within the range of 20,000 to 80,000. The teachings of United States Patent 5,677,402 are incorporated herein by reference for the purpose illustrating the synthesis of liquid polyisoprene.

[0481] United States Patent 6,576,728 discloses a process for the copolymerization of styrene and isoprene to produce low vinyl styrene-isoprene rubber having a random distribution of repeat units that are derived from styrene. The initiator systems employed in these polymerizations are comprised of (a) a lithium initiator and (b) a member selected from the group consisting of (1) a sodium alkoxide, (2) a sodium salt of a sulfonic acid, and (3) a sodium salt of a glycol ether. It is important for the initiator system used in these polymerizations to be free of polar modifiers, such as Lewis bases. The teachings of United States Patent 6,576,728 are incorporated herein by reference for the purpose illustrating the synthesis of styrene-isoprene rubber.

[0482] United States Patent 6,313,216 discloses a process for synthesizing random styrene-isoprene rubber comprising: (1) continuously charging isoprene, styrene, an initiator, and a solvent into a first polymerization zone, (2) allowing the isoprene and styrene to copolymerize in the first polymerization zone to total conversion of 60 to 95 percent to produce a polymer cement containing living styrene-isoprene chains, (3) continuously charging the polymer cement containing living styrene-isoprene chains and additional isoprene monomer into a second polymerization zone, wherein from 5 to 40 percent of the total amount of isoprene charged is charged into the second polymerization zone, (4) allowing the copolymerization to continue in the second polymerization zone to a conversion of the isoprene monomer of at least 90 percent wherein the total conversion of styrene and isoprene in the second polymerization zone is limited to a maximum of 98 percent, (5) withdrawing a polymer cement of random styrene-isoprene rubber having living chain ends from the second reaction zone, (6) killing the living chain ends on the random styrene-isoprene rubber, and (7) recovering the random styrene-isoprene rubber from the polymer cement, wherein the copolymerizations in the first polymerization zone and the second polymerization zone are carried out at a temperature which is within the range of 70°C to 100°C, and wherein the amount of styrene charged into the first polymerization zone is at least 2 percent more than the total amount of styrene bound into the rubber. The teachings of United States Patent 6,313,216 are incorporated herein by reference for the purpose illustrating the synthesis of styrene-isoprene rubber.

[0483] Isoprene-butadiene copolymers having high vinyl contents can be synthesized in organic solvents to high yields after short polymerization times by utilizing the process disclosed in United States Patent 5,061,765. The isoprene-butadiene copolymers made

utilizing this process have a glass transition temperature which is within the range of about 0°C to about -60°C and can be employed in tire treads which provide improved traction and improved cut growth resistance. United States Patent 5,061,765 more specifically discloses a process for the synthesis of isoprene-butadiene copolymers having a high vinyl content which comprises copolymerizing isoprene monomer and butadiene monomer in an organic solvent at a temperature which is within the range of about -10°C to about 100°C in the presence of a catalyst system which is comprised of (a) an organoiron compound, (b) an organoaluminum compound, (c) a chelating aromatic amine, and (d) a protonic compound; wherein the molar ratio of the chelating amine to the organoiron compound is within the range of about 0.1:1 to about 1:1, wherein the molar ratio of the organoaluminum compound to the organoiron compound is within the range of about 5:1 to about 200:1, and wherein the molar ratio of the protonic compound to the organoaluminum compound is within the range of about 0.001:1 to about 0.2:1. The teachings of United States Patent 5,061,765 are incorporated herein by reference for the purpose illustrating the synthesis of isoprene-butadiene rubber.

[0484] A technique for synthesizing rubbery terpolymers of styrene, isoprene and butadiene is disclosed in United States Patent 5,137,998. These rubbery terpolymers exhibit an excellent combination of properties for utilization in tire tread rubber compounds. By utilizing such terpolymers in tire treads, tires having improved wet skid resistance can be built without sacrificing rolling resistance or tread wear characteristics. United States Patent 5,137,998 more specifically discloses a process for preparing a rubbery terpolymer of styrene, isoprene, and butadiene having multiple glass transition temperatures and having an excellent combination of properties for use in making tire treads which comprises: terpolymerizing styrene, isoprene and 1,3-butadiene in an organic solvent at a temperature of no more than about 40°C in the presence of (a) at least one member selected from the group consisting of tripiperidino phosphine oxide and alkali metal alkoxides and (b) an organolithium compound. The teachings of United States Patent 5,137,998 are incorporated herein by reference for the purpose illustrating the synthesis of styrene-isoprene-butadiene rubber.

[0485] A liquid isoprene-butadiene rubber (IBR) which is particularly valuable for use in making treads for high performance automobile tires, including race tires, that exhibit superior dry traction characteristics and durability, can be made by the process disclosed in United States Patent 6,562,895. This isoprene-butadiene rubber is a liquid at room

temperature and is comprised of repeat units which are derived from about 5 weight percent to about 95 weight percent isoprene and from about 5 weight percent to about 95 weight percent 1,3-butadiene, wherein the repeat units derived from isoprene and 1,3-butadiene are in essentially random order. This IBR also has a low number average molecular weight which is within the range of about 3,000 to about 50,000 and has a glass transition temperature which is within the range of about -50°C to about 20°C.

[0486] These isoprene-butadiene copolymers are synthesized utilizing an organolithium initiator and a polar modifier. The level of organolithium initiator employed will be dependent upon the molecular weight which is desired for the liquid isoprene-butadiene polymer being synthesized. As a general rule, in all anionic polymerizations the molecular weight of the polymer produced is inversely proportional to the amount of initiator utilized. Since liquid isoprene-butadiene polymer having a relatively low molecular weight is being synthesized, the amount of initiator employed will be relatively large. As a general rule, from about 0.1 to about 2 phm (parts per hundred parts of monomer by weight) of the organolithium compound will be employed. In most cases, it will be preferred to utilize from about 0.2 to about 1 phm of the organolithium compound with it being most preferred to utilize from about 0.4 phm to 0.6 phm of the organolithium compound. In any case, an amount of organolithium initiator will be selected to result in the production of liquid isoprene-butadiene polymer having a number average molecular weight which is within the range of about 3,000 to about 50,000.

[0487] The amount of organolithium initiator will preferably be selected to result in the production of liquid isoprene-butadiene polymer having a number average molecular weight which is within the range of about 5,000 to about 30,000. The amount of organolithium initiator will most preferably be selected to result in the production of liquid isoprene-butadiene polymer having a number average molecular weight that is within the range of about 8,000 to about 18,000. In any case, it is critical to carry out the copolymerization of the 1,3-butadiene and the styrene in the presence of a polar modifier, such as N,N,N',N'-tetramethylethylenediamine (TMEDA), to attain a high glass transition temperature which is within the range of about -50°C to 20°C. The teachings of United States Patent 6,562,895 are incorporated herein by reference for the purpose illustrating the synthesis of liquid isoprene-butadiene polymers.

[0488] Block copolymers containing a block of polyisoprene can be made by the process described in United States Patent 5,242,984. For instance, linear diblock polymers of styrene and isoprene (S-I block copolymers) and linear triblock polymers of styrene and isoprene (S-I-S triblock polymers) can be made by this process. In this technique, the monomers are polymerized sequentially by anionic polymerization in an inert organic solvent. Normally an organoalkali metal compound, such as an alkyl lithium compound, is used to initiate the polymerization which can be conducted over a broad temperature range.

[0489] Methods of controlling the molecular weights of the blocks and the overall polymer are described in United States Patent 3,149,182 and United States Patent 3,231,635 which state that the amount of monomer can be kept constant and different molecular weights can be achieved by changing the amount of catalyst or that the amount of catalyst can be kept constant and different molecular weights can be achieved by varying the amount of the monomer. Following the sequential polymerization, the product is terminated such as by the addition of a protic terminating agent, e.g. water, alcohol or other reagents or with hydrogen, for the purpose of removing the lithium radical forming the nucleus for the condensed polymer product. The block polymer product is then recovered such as by coagulation utilizing hot water or steam or both. The teachings of United States Patent 5,242,984, United States Patent 3,149,182, and United States Patent 3,231,635 are incorporated herein by reference for the purpose of teaching methods for synthesizing S-I block copolymers and S-I-S triblock polymers.

Carbon fingerprinting

[0490] All types of polymers made with the isoprene of this invention are verifiable as being made with isoprene that did not originate from a petrochemical source. Additionally, the isoprene containing polymers of this invention can also be distinguished from isoprene containing polymers that come from natural sources, such as natural rubber. Accordingly, the isoprene containing polymers of this invention are analytically verifiable as coming from the bio-renewable, environmentally friendly, sources delineated herein.

[0491] Polymers derived from bioisoprene can be distinguished from polymers derived from petrochemical carbon on the basis of dual carbon-isotopic fingerprinting. Additionally, the specific source of biosourced carbon (e.g. glucose vs. glycerol) can be determined by

dual carbon-isotopic fingerprinting (see, US Patent Number 7,169,588, which is herein incorporated by reference).

[0492] This method usefully distinguishes chemically-identical materials, and apportions carbon in products by source (and possibly year) of growth of the biospheric (plant) component. The isotopes, ^{14}C and ^{13}C , bring complementary information to this problem. The radiocarbon dating isotope (^{14}C), with its nuclear half life of 5730 years, clearly allows one to apportion specimen carbon between fossil ("dead") and biospheric ("alive") feedstocks [Currie, L. A. "Source Apportionment of Atmospheric Particles," Characterization of Environmental Particles, J. Buffle and H. P. van Leeuwen, Eds., 1 of Vol. I of the IUPAC Environmental Analytical Chemistry Series (Lewis Publishers, Inc) (1992) 3 74]. The basic assumption in radiocarbon dating is that the constancy of ^{14}C concentration in the atmosphere leads to the constancy of ^{14}C in living organisms. When dealing with an isolated sample, the age of a sample can be deduced approximately by the relationship: $t = (-5730/0.693)\ln(A/A_0)$, where t = age, 5730 years is the half-life of radiocarbon, and A and A_0 are the specific ^{14}C activity of the sample and of the modern standard, respectively [Hsieh, Y., Soil Sci. Soc. Am J., 56, 460, (1992)]. However, because of atmospheric nuclear testing since 1950 and the burning of fossil fuel since 1850, ^{14}C has acquired a second, geochemical time characteristic. Its concentration in atmospheric CO_2 – and hence in the living biosphere – approximately doubled at the peak of nuclear testing, in the mid-1960s. It has since been gradually returning to the steady-state cosmogenic (atmospheric) baseline isotope rate ($^{14}\text{C}/^{12}\text{C}$) of ca. 1.2×10^{-12} , with an approximate relaxation "half-life" of 7-10 years. (This latter half-life must not be taken literally; rather, one must use the detailed atmospheric nuclear input/decay function to trace the variation of atmospheric and biospheric ^{14}C since the onset of the nuclear age.) It is this latter biospheric ^{14}C time characteristic that holds out the promise of annual dating of recent biospheric carbon. ^{14}C can be measured by accelerator mass spectrometry (AMS), with results given in units of "fraction of modern carbon" (f_M). f_M is defined by National Institute of Standards and Technology (NIST) Standard Reference Materials (SRMs) 4990B and 4990C, known as oxalic acids standards HOxI and HOxII, respectively. The fundamental definition relates to 0.95 times the $^{14}\text{C}/^{12}\text{C}$ isotope ratio HOxI (referenced to AD 1950). This is roughly equivalent to decay-corrected pre-Industrial Revolution wood. For the current living biosphere (plant material), $f_M \sim 1.1$.

[0493] The stable carbon isotope ratio ($^{13}\text{C}/^{12}\text{C}$) provides a complementary route to source discrimination and apportionment. The ratio of carbon isotopes ^{13}C and ^{12}C can be used to identify or rule out potential origins for many carbon-containing samples. This method works well because: (1) both isotopes are stable on geological time frames; (2) the ratio of ^{13}C to ^{12}C can be measured with great precision using combinations of combustion analysis, gas chromatography, and isotope ratio mass spectrometry; (3) $^{13}\text{C}/^{12}\text{C}$ ratios for many naturally occurring materials occur within narrow ranges characteristic of those materials; and (4) $^{13}\text{C}/^{12}\text{C}$ ratios for many materials change in predictable ways as these materials undergo chemical reactions.

[0494] Studies involving $^{13}\text{C}/^{12}\text{C}$ ratios at or near natural abundance levels usually report isotopic data as “delta values”, which are represented by the symbol $\delta^{13}\text{C}$ and given in parts per thousand (‰) relative to a standard reference sample. For carbon, the reference sample typically is Pee Dee Belemite, which has a ^{13}C natural abundance of 1.112328‰ and is assigned $\delta^{13}\text{C}$ 0.00‰. The formula relating $^{13}\text{C}/^{12}\text{C}$ ratios to delta values is:

$\delta^{13}\text{C}$ (in ‰) versus standard = $[(R_{\text{sample}} - R_{\text{standard}})/R_{\text{standard}}](1000)$, where R_{sample} is the $^{13}\text{C}/^{12}\text{C}$ ratio for the sample and R_{standard} is the ratio for Pee Dee Belemite.

[0495] Although isotopes of carbon (i.e., ^{13}C and ^{12}C) take part in the same physical processes and same chemical reactions, the slight mass difference between ^{13}C and ^{12}C can be manifested in very slight differences in rates for many reactions and processes. This leads to small differences between $^{13}\text{C}/^{12}\text{C}$ ratios for samples subjected to chemical reactions or physical processes. For example, physical processes such as evaporation or diffusion discriminate against heavier isotopes and typically lead to slight enrichment of the heavier isotope in the original sample as the lighter isotope evaporates or diffuses away more rapidly. The $^{13}\text{C}/^{12}\text{C}$ ratio therefore increases slightly as evaporation or diffusion occurs. For chemical reactions, including enzymatic reactions, the situation is more complex, but there often is a slight discrimination of one isotope over another, which can be detected by measuring $^{13}\text{C}/^{12}\text{C}$ ratios or $\delta^{13}\text{C}$ values. For example, atmospheric CO_2 can be converted into plant matter via two very different mechanisms for photosynthesis: the Calvin-Benson pathway, which occurs in C_3 plants, and the Hatch-Slack pathway, which occurs in C_4 plants. These two mechanisms are sufficiently different to produce a measurable difference in $\delta^{13}\text{C}$ from the same CO_2 . For C_4 plants, $\delta^{13}\text{C}$ typically ranges from -9‰ to -17‰ with a mean

near -13‰. For C₃ plants, $\delta^{13}\text{C}$ typically ranges from -20‰ to -32‰ with a mean near -27‰. Because these ranges are so different and $\delta^{13}\text{C}$ values can be routinely measured within 0.02‰, it is relatively easy to distinguish between plant residues derived from C₃ versus C₄ plants. This has myriad applications in archeology and other fields where analysis of carbon-containing residues from cooking or skeletal remains can be used to track the evolution, activities and diets of humans and other animals.

[0496] More recently, $\delta^{13}\text{C}$ values have been utilized to detect economic fraud, especially the adulteration of foodstuffs by other materials – including potentially harmful synthetics derived from petrochemicals. For example, maize (corn) oil is considered to be a premium vegetable oil and there is a temptation for unscrupulous producers to dilute maize oil with cheaper oils. Fortunately, maize oil is derived from a C₄ plant while most of the cheaper alternatives are derived from C₃ plants or animals. The $\delta^{13}\text{C}$ for authentic maize oil is therefore -13.7‰ to -16.4‰ compared to -25‰ to -32‰ for the alternatives. Any significant dilution of maize oil by a cheaper alternative can be detected by measuring $\delta^{13}\text{C}$. Similarly, the addition of cane sugar (a product of C₄ photosynthesis) to fruit juices, wines, spirits, and honey (all products of C₃ photosynthesis) can be detected by measuring $\delta^{13}\text{C}$ values. It is even possible to detect the adulteration of natural flavors by synthetic analogs and the use of illegal synthetic hormone supplements via $\delta^{13}\text{C}$ values.

[0497] The current invention utilizes the ability to accurately measure $\delta^{13}\text{C}$ values in order to produce new, isotopically unique isoprenic polymers that can be readily distinguished from polymers derived from petroleum-based feedstocks. The current invention also utilizes the ability to accurately measure $\delta^{13}\text{C}$ values in order to produce new, isotopically unique isoprenic polymers that can be readily distinguished from natural rubber. A salient feature of the current invention is that it provides new polymers with a broad range of $\delta^{13}\text{C}$ values that can be tailored and subsequently verified for authenticity. As described earlier, these new polymers satisfy an increasing need from customers for verifiable products that contain neither potential proteinaceous allergens nor feedstocks derived from petroleum.

[0498] The polymers represented by the current invention contain isoprene units that are isotopically unique compared to both natural rubber and synthetic polymers containing petroleum-derived isoprene. In the case of natural rubber derived from *Hevea brasiliensis* (i.e., the common natural rubber tree), $\delta^{13}\text{C}$ values typically range from about -27‰ to about

-28‰. Guayule rubber, which is derived from a desert shrub, has $\delta^{13}\text{C}$ of about -31‰. Both rubbers exhibit $\delta^{13}\text{C}$ values expected for products of C_3 photosynthesis, and both rubbers are known to contain polymer-bound proteins.

[0499] Traditional synthetic polyisoprene can have different $\delta^{13}\text{C}$ values depending on the source of isoprene. For isoprene derived from extractive distillation of C_5 streams from petroleum refineries, $\delta^{13}\text{C}$ is about -22‰ to about -24‰. This range is typical for light, unsaturated hydrocarbons derived from petroleum, and polymers containing petroleum-based isoprene typically contain isoprenic units with the same $\delta^{13}\text{C}$. For polymers containing isoprene derived from the reaction of isobutylene with formaldehyde, $\delta^{13}\text{C}$ values can be about -34.4‰ because formaldehyde is often derived from feedstocks with much more negative $\delta^{13}\text{C}$ values.

[0500] The current invention provides isoprene-containing polymers with very different $\delta^{13}\text{C}$ values. For example, fermentation of corn-derived glucose ($\delta^{13}\text{C}$ -10.73‰) with minimal amounts of other carbon-containing nutrients (e.g., yeast extract) produces isoprene which can be polymerized into polyisoprene with $\delta^{13}\text{C}$ -14.66‰ to -14.85‰. The $\delta^{13}\text{C}$ for this polymer clearly is in a new range that is well outside the normal ranges for natural rubber and all previously known synthetic polyisoprene, and it is within the range normally associated with products derived from C_4 plants. The unique $\delta^{13}\text{C}$ value for this polymer is a direct consequence of the fact that the isoprene in the polymer is derived from corn-based glucose, which indeed is a product derived from C_4 plants.

[0501] It is recognized by those with ordinary skill in the art that similar results can be obtained using other sugars or fermentable derived from C_4 plants. For example, sucrose from sugar cane ($\delta^{13}\text{C}$ -10.4‰), invert sugar from sugar cane ($\delta^{13}\text{C}$ -15.3‰), glucose from cornstarch ($\delta^{13}\text{C}$ -11.1‰), and glucose from hydrolytic degradation of either corn stover ($\delta^{13}\text{C}$ -11.3‰) or sugar cane bagasse ($\delta^{13}\text{C}$ -13.0‰) should all produce isoprene that can be used to produce isoprene polymers with $\delta^{13}\text{C}$ values that are less negative than either natural rubber or synthetic polymers containing petroleum-based isoprene. Those with ordinary skill in the art also will recognize that it should be possible to produce isoprene and isoprene polymers with $\delta^{13}\text{C}$ less negative than about -22‰ from fermentable feedstocks with $\delta^{13}\text{C}$

approximately greater (i.e., less negative) than about -18‰, including mixtures of fermentable feedstocks with an average $\delta^{13}\text{C}$ approximately greater than about -18‰.

[0502] In addition to producing isoprene-containing polymers with $\delta^{13}\text{C}$ values characteristic of products derived from C_4 plants, those skilled in the art will recognize that uniquely isotopically labeled isoprene-containing polymers can be made from fermentable non- C_4 feedstocks. For example, glucose from hydrolyzed softwood pulp ($\delta^{13}\text{C}$ -23‰) should yield isoprene and polyisoprene with $\delta^{13}\text{C}$ near -27‰, which is in a unique range between the normal ranges observed for isoprene derived from extractive distillation of C_5 fractions and isoprene derived from the reaction of isobutylene with formaldehyde. Those skilled in the art also will recognize that fermentation of other sugars with $\delta^{13}\text{C}$ ranges of approximately -20‰ to about -28‰ should produce isoprene and isoprenic polymers with $\delta^{13}\text{C}$ ranging from about -24‰ to about -32‰. These other sugars might include (but are not limited to) glucose from hydrolyzed cellulose ($\delta^{13}\text{C}$ -25 ± 2‰), invert sugar from beet sugar ($\delta^{13}\text{C}$ -26 ‰ to -27 ‰), and lactose ($\delta^{13}\text{C}$ -27 ‰ to -28‰). Fermentation of plant oils ($\delta^{13}\text{C}$ -26 ‰ to -32‰), including palm oil ($\delta^{13}\text{C}$ -30‰) could provide access to isoprene polymers with $\delta^{13}\text{C}$ more negative than -30‰.

[0503] Those skilled in the art will recognize that cofermentation of two or more feedstocks can be used to produce isoprene and therefore isoprene-containing polymers with intermediate $\delta^{13}\text{C}$ values. For example, a 1:1 mixture of sucrose from sugar cane ($\delta^{13}\text{C}$ -10.4‰) and sucrose from beet sugar ($\delta^{13}\text{C}$ -26 ‰ to -27 ‰) should produce isoprene and therefore isoprene-containing polymers with approximately the same $\delta^{13}\text{C}$ value as polymer produced from sucrose derived from a single source with the average $\delta^{13}\text{C}$ value (i.e., approx -18.5‰). The same should be true for invert sugars derived from sugar and beets. In both cases, it should be obvious that the same polymers could be synthesized by mixing and then (co)polymerizing equal amounts of isoprene separately prepared from sucrose or invert sugar derived from sugar cane and beets. It also should be obvious that cofermentation of sugars with other fermentable feedstocks - such as yeast extract and plant oils – can be used to produce isoprene and therefore isoprene-containing polymers with intermediate $\delta^{13}\text{C}$ values. For example, cofermentation of glucose ($\delta^{13}\text{C}$ -10.73‰) and yeast extract ($\delta^{13}\text{C}$ -26 ‰ to -27‰) in a ratio of 181.2 : 17.6 produces isoprene which can be polymerized to polyisoprene with $\delta^{13}\text{C}$ values of -18 ‰ to -20 ‰. In contrast, fermentation of glucose with a minimal

amount of yeast extract and subsequent polymerization of the isoprene produces polyisoprene with $\delta^{13}\text{C}$ values of -14‰ to -15‰.

[0504] For copolymers of isoprene with other monomers, those skilled in the art recognize that there is a finite amount of isoprene that is incorporated into the polymer background as “blocks” of polyisoprene. The tendency of isoprene to form blocks of two or more isoprenic units – even in “random copolymers” - depends on many factors, including the amount of isoprene relative to other monomers, the type of catalyst used for polymerization, and the specific reaction conditions for polymerization. The presence of these blocks along the polymer backbone can usually be detected by NMR spectroscopy. By using a combination of chemical degradation (e.g., ozonolysis) and chromatography, it is possible to isolate fragments of these blocks for chemical analysis, including measurement of $\delta^{13}\text{C}$ values for the blocks derived from isoprene. This provides a way for determining whether copolymers of isoprene with other monomers contain isoprene derived from renewable/sustainable feedstocks, especially feedstocks derived from C_4 plants.

[0505] The polyisoprene polymers of this invention which are made with isoprene monomer from the cells cultures that utilize bio-renewable carbon sources can be identified as such by virtue of their d^{13}C value and other polymer characteristics. For instance, the following isoprene containing polymers are verifiable as containing isoprene monomer that was produced utilizing the method of this invention:

(1) Polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has d^{13}C value of greater than -22‰. Such polyisoprene polymers can have a d^{13}C value which is greater than -21‰, and can also have a d^{13}C value which is greater than -20‰. In some cases, the polyisoprene polymer will have a d^{13}C value which is within the range of -22‰ to -10‰, and in other cases it will have a d^{13}C value which is within the range of -21‰ to -12‰. In still other cases the polyisoprene polymer will have a d^{13}C value which is within the range of -20‰ to -14‰. In many cases, the polyisoprene polymer will be polyisoprene homopolymer rubber.

(2) A polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has d^{13}C value which is within the range of -30‰ to -28.5‰. Such polyisoprene polymers can have a d^{13}C value which is within the range of -30‰ to -29‰. In some cases, the polyisoprene polymer will have a d^{13}C

value which is within the range of -30‰ to -29‰, and in other cases the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -30‰ to -29.5‰. In still other cases the polyisoprene polymer can have a $d^{13}C$ value which is within the range of -29.5‰ to -28.5‰ and in still further cases the polyisoprene polymer can have a $d^{13}C$ value which is within the range of -29.0‰ to -28.5‰. In many cases, the polyisoprene polymer will be polyisoprene homopolymer rubber.

(3) A polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene is free of protein, and wherein the polyisoprene polymer has $d^{13}C$ value which is within the range of -34‰ to -24‰. In some cases this polyisoprene polymer has $d^{13}C$ value which is within the range of -32‰ to -25‰. In some cases this polyisoprene polymer has $d^{13}C$ value which is within the range of -34‰ to -25‰. In other cases the polyisoprene polymer has a $d^{13}C$ value which is within the range of -33‰ to -25‰, and in still other cases the polyisoprene polymer has a $d^{13}C$ value which is within the range of -32‰ to -25‰. In many cases, the polyisoprene polymer will be polyisoprene homopolymer rubber.

(4) A polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a cis-1,4-microstructure content of less than 99.9%, wherein the polyisoprene polymer has a trans-1,4-microstructure content of less than 99.9%, and wherein the polyisoprene polymer has $d^{13}C$ value of which is within the range of -34‰ to -24‰. Such polyisoprene can have a $d^{13}C$ value which is within the range of -34‰ to -25‰. In some cases the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -33‰ to -25‰. In other cases the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -25‰. In other cases the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -24‰. The polyisoprene polymer can have a cis-1,4-microstructure content of less than 99.8%. In other cases the polyisoprene polymer will have a cis-1,4-microstructure content of less than 99.7%. In still other cases the polyisoprene polymer will have a cis-1,4-microstructure content of less than 99.5% or even less than 99%. In many cases the polyisoprene polymer will have a cis-1,4-microstructure content of less than 98.5% or even less than 98%. This polyisoprene polymer can also have a polydispersity of less than 2.0 or even less than 1.8. In some cases the polyisoprene polymer has a polydispersity of less than 1.6 or even less than 1.5. In still other

cases the polyisoprene polymer can have a polydispersity of less than 1.4 or even less than 1.2. In many cases the polyisoprene polymer will have a polydispersity of less than 1.1.

(5) A polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a 3,4-microstructure content of greater than 2%, and wherein the polyisoprene polymer has $d^{13}C$ value of which is within the range of -34‰ to -24‰. Such polyisoprene polymers can have a $d^{13}C$ value which is within the range of -34‰ to -25‰. In some cases the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -33‰ to -25‰. In other cases polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -25‰. In other cases polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -24‰. The polyisoprene polymer can have a 3,4-microstructure content of greater than 5%. In some cases the polyisoprene polymer will have a 3,4-microstructure content of greater than 10%. In other cases the polyisoprene polymer will have a 3,4-microstructure content of greater than 15%. In still other the polyisoprene polymer will have a 3,4-microstructure content of greater than 20%. In many cases the polyisoprene polymer will have a 3,4-microstructure content of greater than 25%. This polyisoprene polymer can have a polydispersity of less than 2.0. In some cases the polyisoprene polymer will have a polydispersity of less than 1.8. In other cases the polyisoprene polymer will have a polydispersity of less than 1.6. In still other cases the polyisoprene polymer will have a polydispersity of less than 1.5 or even than 1.4. In many cases the polyisoprene polymer will have a polydispersity of less than 1.2 or even less than 1.1.

(6) A polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has a 1,2-microstructure content of greater than 2%, and wherein the polyisoprene polymer has $d^{13}C$ value of which is within the range of -34‰ to -24‰. Polyisoprene polymers of this type can have a $d^{13}C$ value which is within the range of -34‰ to -25‰. In some cases, the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -33‰ to -25‰. In other cases, the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -25‰. In other cases, the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -24‰. The polyisoprene polymer can have a 1,2-microstructure content of greater than 5%. In some cases, the polyisoprene polymer will have a 1,2-microstructure content of greater than 10%. In other cases, the polyisoprene polymer will have a 1,2-microstructure content of

greater than 15%. In still other cases, the polyisoprene polymer will have a 1,2-microstructure content of greater than 20%. In many cases, the polyisoprene polymer will have a 1,2-microstructure content of greater than 25%. The polyisoprene polymer can have a polydispersity of less than 2.0. In some cases, the polyisoprene polymer will have a polydispersity of less than 1.8. In other cases, the polyisoprene polymer will have a polydispersity of less than 1.6. In still other cases, the polyisoprene polymer will have a polydispersity of less than 1.5. In many cases, the polyisoprene polymer will have a polydispersity of less than 1.4 or even less than 1.2. It is possible for the polyisoprene polymer to have a polydispersity of less than 1.1.

(7) A polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}C$ value of greater than -22‰ . Such polyisoprene polymers can have a $d^{13}C$ value which is greater than -21‰ . In some cases, the polyisoprene polymer will have a $d^{13}C$ value which is greater than -20‰ . In other cases, the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -22‰ to -10‰ . In still other cases, the polyisoprene polymer will have a $d^{13}C$ value which is within the range of -21‰ to -12‰ . In many cases, the polyisoprene polymer will have a $d^{13}C$ value that is within the range of -20‰ to -14‰ .

(8) A polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}C$ value which is within the range of -34‰ to -24‰ . Such copolymers can have a $d^{13}C$ value is within the range of -34‰ to -25‰ . In some cases, copolymer of this type will have a $d^{13}C$ value which is within the range of -33‰ to -25‰ . In other cases, copolymers of this type will have a $d^{13}C$ value is within the range of -32‰ to -25‰ . In other cases, copolymers of this type will have a $d^{13}C$ value is within the range of -32‰ to -24‰ . Copolymers of this type can be rubbery copolymers of isoprene and 1,3-butadiene, rubbery copolymer of isoprene and styrene, rubbery copolymers of isoprene and α -methyl styrene, and the like.

(9) A liquid polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has weight average molecular weight which is within the range of 5,000 to 100,000, and wherein the liquid polyisoprene polymer has $d^{13}C$ value of which is within the range of -34‰ to -24‰. Such liquid polyisoprene polymers can have a $d^{13}C$ value which is within the range of -34‰ to -25‰. In some cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -33‰ to -25‰. In other cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -25‰. In other cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -24‰. Such liquid polyisoprene polymers can have a weight average molecular weight that is within the range of 20,000 to 80,000. In some cases, the liquid polyisoprene polymer will have a weight average molecular weight which is within the range of 30,000 to 50,000. In other cases, the polyisoprene polymer will have a polydispersity of less than 2.0 or even less than 1.8. In still other cases, the liquid polyisoprene polymer will have a polydispersity of less than 1.6 or even less than 1.5. In many cases, the liquid polyisoprene polymer will have a polydispersity of less than 1.4 or even less than 1.2. It is possible for the liquid polyisoprene polymer to have a polydispersity of less than 1.1.

(10) A liquid polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the liquid polyisoprene polymer has a weight average molecular weight which is within the range of 5,000 to 100,000, and wherein the liquid polyisoprene polymer has $d^{13}C$ value of which is within the range of -34‰ to -24‰. Such liquid polyisoprene polymers can have a $d^{13}C$ value which is within the range of -34‰ to -25‰. In some cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -33‰ to -25‰. In still other cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -25‰. In other cases, the liquid polyisoprene polymer will have a $d^{13}C$ value which is within the range of -32‰ to -24‰. Such liquid polyisoprene can have a weight average molecular weight that is within the range of 20,000 to 80,000. The liquid polyisoprene will typically have a weight average molecular weight which is within the range of 30,000 to 50,000. Such liquid polyisoprene can have a polydispersity of less than 2.0. In some cases, the liquid polyisoprene polymer will have a polydispersity of less than 1.8. In other cases, the liquid polyisoprene polymer has a polydispersity of less than 1.6. In still other cases, the liquid polyisoprene polymer will have

a polydispersity of less than 1.5 or even less than 1.4. In many cases, the liquid polyisoprene polymer will have a polydispersity of less than 1.2 or even less than 1.1.

[0506] The polyisoprene homopolymer, liquid polyisoprene polymer or polyisoprene copolymer, or any variations described herein, produced by chemical polymerization of isoprene derived from renewable resources can be distinguished from products derived from petrochemical resources by its ^{14}C content. In some embodiments, a polymer derived from bioisoprene comprises radioactive carbon-14. In some embodiments, the $^{14}\text{C}/^{12}\text{C}$ ratio is greater than or about 1.0×10^{-12} , 1.05×10^{-12} , 1.1×10^{-12} , 1.15×10^{-12} , or 1.2×10^{-12} . In some embodiments, the polymer derived from bioisoprene has an f_M value of greater than or about 0.9, 0.95, 1.0, 1.05 or 1.1. In some embodiments, the polymer derived from bioisoprene has an f_M value of greater than or about 0.9, 0.95, 1.0, 1.05 or 1.1 and $\delta^{13}\text{C}$ values of greater (less negative) than -22‰ . In some embodiments, the polymer derived from bioisoprene has an f_M value of greater than or about 0.9, 0.95, 1.0, 1.05 or 1.1 and a $\delta^{13}\text{C}$ value which is within the range of -22 to -10 , -21 to -12 , or -20 to -14‰ . In some embodiments, the polymer derived from bioisoprene has an f_M value of greater than or about 0.9, 0.95, 1.0, 1.05 or 1.1 and a $\delta^{13}\text{C}$ value which is within the range of -34 to -24 , -32 to -24 , -34 to -25 , -33 to -25 , -32 to -25 , -30 to -29 , -30.0 to -29.5 , -29.5 to -28.5 , or -29.0 to -28.5‰ .

[0507] This invention is illustrated by the following examples that are merely for the purpose of illustration and are not to be regarded as limiting the scope of the invention or the manner in which it can be practiced. Unless specifically indicated otherwise, parts and percentages are given by weight.

EXAMPLES

[0508] The examples, which are intended to be purely exemplary of the invention and should therefore not be considered to limit the invention in any way, also describe and detail aspects and embodiments of the invention discussed above. Unless indicated otherwise, temperature is in degrees Centigrade and pressure is at or near atmospheric pressure. The foregoing examples and detailed description are offered by way of illustration and not by way of limitation. All publications, patent applications, and patents cited in this specification are herein incorporated by reference as if each individual publication, patent application, or patent were specifically and individually indicated to be incorporated by reference. In particular, all publications cited herein are expressly incorporated herein by reference for the

purpose of describing and disclosing compositions and methodologies which might be used in connection with the invention. Although the foregoing invention has been described in some detail by way of illustration and example for purposes of clarity of understanding, it will be readily apparent to those of ordinary skill in the art in light of the teachings of this invention that certain changes and modifications may be made thereto without departing from the spirit or scope of the appended claims.

[0509] In the practice of this invention ^{13}C analysis can be done by loading 0.5 to 1.0 mg samples into tin cups for carbon isotopic analysis using a Costech ECS4010 Elemental Analyzer as an inlet for a ThermoFinnigan Delta Plus XP isotope ratio mass spectrometer. Samples are dropped into a cobaltous/cobaltic oxide combustion reactor at 1020°C with combustion gases being passed in a helium stream at 85mL/min through a copper reactor (650°C) to convert NO_x to N_2 . CO_2 and N_2 are separated using a 3-m 5Å molecular sieve column. Then, $^{13}\text{C}/^{12}\text{C}$ ratios are calibrated to the VPDB scale using two laboratory standards (Acetanilide B, $-29.52 \pm 0.02\text{‰}$ and cornstarch A, $-11.01 \pm 0.02\text{‰}$) which have been carefully calibrated to the VPDB scale by off-line combustion and dual-inlet analysis using the 2-standard approach of T. B. Coplen et al, New Guidelines for d^{13}C Measurements, Anal. Chem., 78, 2439-2441 (2006). The teachings of Coplen are incorporated herein by reference for the purpose of teaching the technique for determining d^{13}C values.

Example 1: Production of isoprene in *E. coli* expressing recombinant kudzu isoprene synthase

I. Construction of vectors for expression of the kudzu isoprene synthase in *E. coli*

[0510] The protein sequence for the kudzu (*Pueraria montana*) isoprene synthase gene (IspS) was obtained from GenBank (AAQ84170). A kudzu isoprene synthase gene, optimized for *E. coli* codon usage, was purchased from DNA2.0 (SEQ ID NO:1). The isoprene synthase gene was removed from the supplied plasmid by restriction endonuclease digestion with *Bsp*LU11I/*Pst*I, gel-purified, and ligated into pTrcHis2B (Invitrogen) that had been digested with *Nco*I/*Pst*I. The construct was designed such that the stop codon in the isoprene synthase gene 5' to the *Pst*I site. As a result, when the construct was expressed the His-Tag is not attached to the isoprene synthase protein. The resulting plasmid, pTrcKudzu, was verified by sequencing (Figures 2 and 3).

[0511] The isoprene synthase gene was also cloned into pET16b (Novagen). In this case, the isoprene synthase gene was inserted into pET16b such that the recombinant isoprene synthase protein contained the N-terminal His tag. The isoprene synthase gene was amplified from pTrcKudzu by PCR using the primer set pET-His-Kudzu-2F: 5'-CGTGAGATCATATGTGTGCGACCTCTTCTCAATTTAC (SEQ ID NO:3) and pET-His-Kudzu-R: 5'-CGGTCGACGGATCCCTGCAGTTAGACATACATCAGCTG (SEQ ID NO:4). These primers added an *NdeI* site at the 5'-end and a *BamHI* site at the 3' end of the gene respectively. The plasmid pTrcKudzu, described above, was used as template DNA, Herculanase polymerase (Stratagene) was used according to manufacture's directions, and primers were added at a concentration of 10 pMols. The PCR was carried out in a total volume of 25 μ l. The PCR product was digested with *NdeI/BamHI* and cloned into pET16b digested with the same enzymes. The ligation mix was transformed into *E. coli* Top10 (Invitrogen) and the correct clone selected by sequencing. The resulting plasmid, in which the kudzu isoprene synthase gene was expressed from the T7 promoter, was designated pETNHisKudzu (Figures 4 and 5).

[0512] The kudzu isoprene synthase gene was also cloned into the low copy number plasmid pCL1920. Primers were used to amplify the kudzu isoprene synthase gene from pTrcKudzu described above. The forward primer added a *HindIII* site and an *E. coli* consensus RBS to the 5' end. The *PstI* cloning site was already present in pTrcKudzu just 3' of the stop codon so the reverse primer was constructed such that the final PCR product includes the *PstI* site. The sequences of the primers were: *HindIII*-rbs-Kudzu F: 5'-CATATGAAAGCTTGTATCGATTAAATAAGGAGGAATAAACC (SEQ ID NO:6) and *BamHI*-Kudzu R:

[0513] 5'-CGGTCGACGGATCCCTGCAGTTAGACATACATCAGCTG (SEQ ID NO:4). The PCR product was amplified using Herculanase polymerase with primers at a concentration of 10 pmol and with 1 ng of template DNA (pTrcKudzu). The amplification protocol included 30 cycles of (95° C for 1 minute, 60° C for 1 minute, 72° C for 2 minutes). The product was digested with *HindIII* and *PstI* and ligated into pCL1920 which had also been digested with *HindIII* and *PstI*. The ligation mix was transformed into *E. coli* Top10. Several transformants were checked by sequencing. The resulting plasmid was designated pCL-lac-Kudzu (Figures 6 and 7).

II. Determination of isoprene production

[0514] For the shake flask cultures, one ml of a culture was transferred from shake flasks to 20 ml CTC headspace vials (Agilent vial cat# 5188 2753; cap cat# 5188 2759). The cap was screwed on tightly and the vials incubated at the equivalent temperature with shaking at 250 rpm. After 30 minutes the vials were removed from the incubator and analyzed as described below (*see* Table 1 for some experimental values from this assay).

[0515] In cases where isoprene production in fermentors was determined, samples were taken from the off-gas of the fermentor and analyzed directly as described below (*see* Table 2 for some experimental values from this assay).

[0516] The analysis was performed using an Agilent 6890 GC/MS system interfaced with a CTC Analytics (Switzerland) CombiPAL autosampler operating in headspace mode. An Agilent HP-5MS GC/MS column (30 m x 0.25 mm; 0.25 μ m film thickness) was used for separation of analytes. The sampler was set up to inject 500 μ L of headspace gas. The GC/MS method utilized helium as the carrier gas at a flow of 1 ml/minutes. The injection port was held at 250° C with a split ratio of 50:1. The oven temperature was held at 37°C for the 2 minute duration of the analysis. The Agilent 5793N mass selective detector was run in single ion monitoring (SIM) mode on m/z 67. The detector was switched off from 1.4 to 1.7 minutes to allow the elution of permanent gases. Under these conditions isoprene (2-methyl-1,3-butadiene) was observed to elute at 1.78 minutes. A calibration table was used to quantify the absolute amount of isoprene and was found to be linear from 1 μ g/L to 200 μ g/L. The limit of detection was estimated to be 50 to 100 ng/L using this method.

III. Production of isoprene in shake flasks containing *E. coli* cells expressing recombinant isoprene synthase

[0517] The vectors described above were introduced to *E. coli* strain BL21 (Novagen) to produce strains BL21/ptrcKudzu, BL21/pCL-lac-Kudzu and BL21/pETHisKudzu. The strains were spread for isolation onto LA (Luria agar) and carbenicillin (50 μ g/ml) and incubated overnight at 37° C. Single colonies were inoculated into 250 ml baffled shake flasks containing 20 ml Luria Bertani broth (LB) and carbenicillin (100 μ g/ml). Cultures were grown overnight at 20° C with shaking at 200 rpm. The OD₆₀₀ of the overnight cultures were measured and the cultures were diluted into a 250 ml baffled shake flask containing 30

ml MagicMedia (Invitrogen) and carbenicillin (100 µg/ml) to an OD₆₀₀ ~ 0.05. The culture was incubated at 30° C with shaking at 200 rpm. When the OD₆₀₀ ~ 0.5 - 0.8, 400 µM IPTG was added and the cells were incubated for a further 6 hours at 30° C with shaking at 200 rpm. At 0, 2, 4 and 6 hours after induction with IPTG, 1 ml aliquots of the cultures were collected, the OD₆₀₀ was determined and the amount of isoprene produced was measured as described above. Results are shown in Figure 8.

IV. Production of Isoprene from BL21/ptrcKudzu in 14 liter fermentation

[0518] Large scale production of isoprene from *E. coli* containing the recombinant kudzu isoprene synthase gene was determined from a fed-batch culture. The recipe for the fermentation media (TM2) per liter of fermentation medium was as follows: K₂HPO₄ 13.6 g, KH₂PO₄ 13.6 g, MgSO₄ * 7H₂O 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, (NH₄)₂SO₄ 3.2 g, yeast extract 5 g, 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in diH₂O. The pH was adjusted to 6.8 with potassium hydroxide (KOH) and q.s. to volume. The final product was filter sterilized with 0.22 µ filter (only, not autoclaved). The recipe for 1000X Modified Trace Metal Solution was as follows: Citric Acids * H₂O 40 g, MnSO₄ * H₂O 30 g, NaCl 10 g, FeSO₄ * 7H₂O 1 g, CoCl₂ * 6H₂O 1 g, ZnSO * 7H₂O 1 g, CuSO₄ * 5H₂O 100 mg, H₃BO₃ 100 mg, NaMoO₄ * 2H₂O 100 mg. Each component was dissolved one at a time in diH₂O, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with a 0.22 µ filter.

[0519] This experiment was carried out in 14 L bioreactor to monitor isoprene formation from glucose at the desired fermentation, pH 6.7 and temperature 34° C. An inoculum of *E. coli* strain BL21/ptrcKudzu taken from a frozen vial was prepared in soytone-yeast extract-glucose medium. After the inoculum grew to OD₅₅₀ = 0.6, two 600 ml flasks were centrifuged and the contents resuspended in 70 ml supernatant to transfer the cell pellet (70 ml of OD 3.1 material) to the bioreactor. At various times after inoculation, samples were removed and the amount of isoprene produced was determined as described above. Results are shown in Figure 9.

Example 2: Production of isoprene in *E. coli* expressing recombinant poplar isoprene synthase

[0520] The protein sequence for the poplar (*Populus alba* x *Populus tremula*) isoprene synthase (Schnitzler, J-P, *et al.* (2005) *Planta* 222:777-786) was obtained from GenBank (CAC35696). A gene, codon optimized for *E. coli*, was purchased from DNA2.0 (p9796-poplar, Figures 30 and 31). The isoprene synthase gene was removed from the supplied plasmid by restriction endonuclease digestion with *Bsp*LU11I /*Pst*I, gel-purified, and ligated into pTrcHis2B that had been digested with *Nco*I/*Pst*I. The construct is cloned such that the stop codon in the insert is before the *Pst*I site, which results in a construct in which the His-Tag is not attached to the isoprene synthase protein. The resulting plasmid pTrcPoplar (Figures 32 and 33), was verified by sequencing.

Example 3: Production of isoprene in *Pantoea citrea* expressing recombinant kudzu isoprene synthase

[0521] The pTrcKudzu and pCL-lac Kudzu plasmids described in Example 1 were electroporated into *P. citrea* (U.S. Pat. No. 7,241,587). Transformants were selected on LA containing carbenicillin (200 µg/ml) or spectinomycin (50 µg/ml) respectively. Production of isoprene from shake flasks and determination of the amount of isoprene produced was performed as described in Example 1 for *E. coli* strains expressing recombinant kudzu isoprene synthase. Results are shown in Figure 10.

Example 4: Production of isoprene in *Bacillus subtilis* expressing recombinant kudzu isoprene synthase

I. Construction of a *B. subtilis* replicating plasmid for the expression of kudzu isoprene synthase

[0522] The kudzu isoprene synthase gene was expressed in *Bacillus subtilis aprEnprE Pxyl-comK* strain (BG3594comK) using a replicating plasmid (pBS19 with a chloramphenicol resistance cassette) under control of the *aprE* promoter. The isoprene synthase gene, the *aprE* promoter and the transcription terminator were amplified separately and fused using PCR. The construct was then cloned into pBS19 and transformed into *B. subtilis*.

a) Amplification of the *aprE* promoter

[0523] The *aprE* promoter was amplified from chromosomal DNA from *Bacillus subtilis* using the following primers:

CF 797 (+) Start *aprE* promoter MfeI

5'- GACATCAATTGCTCCATTTTCTTCTGCTATC (SEQ ID NO:58)

CF 07-43 (-) Fuse *aprE* promoter to Kudzu *ispS*

5'- ATTGAGAAGAGGTCGCACACACTCTTTACCCTCTCCTTTTA (SEQ ID NO:59)

b) Amplification of the isoprene synthase gene

[0524] The kudzu isoprene synthase gene was amplified from plasmid pTrcKudzu (SEQ ID NO:2). The gene had been codon optimized for *E. coli* and synthesized by DNA 2.0. The following primers were used:

CF 07-42 (+) Fuse the *aprE* promoter to kudzu isoprene synthase gene (GTG start codon)

5'- TAAAAGGAGAGGGTAAAGAGTGTGTGCGACCTCTTCTCAAT (SEQ ID NO:60)

CF 07-45 (-) Fuse the 3' end of kudzu isoprene synthase gene to the terminator

5'- CCAAGGCCGTTTTTTTTTAGACATACATCAGCTGGTTAATC (SEQ ID NO:61)

c) Amplification of the transcription terminator

[0525] The terminator from the alkaline serine protease of *Bacillus amyliquefaciens* was amplified from a previously sequenced plasmid pJHPms382 using the following primers:

CF 07-44 (+) Fuse the 3' end of kudzu isoprene synthase to the terminator

5'- GATTAACCAGCTGATGTATGTCTAAAAAAACCGGCCTTGG (SEQ ID NO:62)

CF 07-46 (-) End of *B. amyliquefaciens* terminator (BamHI)

5'- GACATGACGGATCCGATTACGAATGCCGTCTC (SEQ ID NO:63)

[0526] The kudzu fragment was fused to the terminator fragment using PCR with the following primers:

CF 07-42 (+) Fuse the *aprE* promoter to kudzu isoprene synthase gene (GTG start codon)

5'- TAAAAGGAGAGGGTAAAGAGTGTGTGCGACCTCTTCTCAAT (SEQ ID NO:61)

CF 07-46 (-) End of *B. amyliquefaciens* terminator (BamHI)

5'- GACATGACGGATCCGATTACGAATGCCGTCTC (SEQ ID NO:63)

[0527] The kudzu-terminator fragment was fused to the promoter fragment using PCR with the following primers:

CF 797 (+) Start *aprE* promoter MfeI

5'- GACATCAATTGCTCCATTTTCTTCTGCTATC (SEQ ID NO:64)

CF 07-46 (-) End of *B. amyliquefaciens* terminator (BamHI)

5'- GACATGACGGATCCGATTACGAATGCCGTCTC (SEQ ID NO:63)

[0528] The fusion PCR fragment was purified using a Qiagen kit and digested with the restriction enzymes *MfeI* and *BamHI*. This digested DNA fragment was gel purified using a Qiagen kit and ligated to a vector known as pBS19, which had been digested with *EcoRI* and *BamHI* and gel purified.

[0529] The ligation mix was transformed into *E. coli* Top 10 cells and colonies were selected on LA and 50 carbenicillin plates. A total of six colonies were chosen and grown overnight in LB and 50 carbenicillin and then plasmids were isolated using a Qiagen kit. The plasmids were digested with *EcoRI* and *BamHI* to check for inserts and three of the correct plasmids were sent in for sequencing with the following primers:

CF 149 (+) *EcoRI* start of *aprE* promoter

5'- GACATGAATTCCTCCATTTTCTTCTGC (SEQ ID NO:65)

CF 847 (+) Sequence in pXX 049 (end of *aprE* promoter)

5'- AGGAGAGGGTAAAGAGTGAG (SEQ ID NO:66)

CF 07-45 (-) Fuse the 3' end of kudzu isoprene synthase to the terminator

5'- CCAAGGCCGGTTTTTTTTTAGACATACATCAGCTGGTTAATC (SEQ ID NO:61)

CF 07-48 (+) Sequencing primer for kudzu isoprene synthase

5'- CTTTTCCATCACCCACCTGAAG (SEQ ID NO:67)

CF 07-49 (+) Sequencing in kudzu isoprene synthase

5'- GGCGAAATGGTCCAACAACAAAATTATC (SEQ ID NO:68)

[0530] The plasmid designated pBS Kudzu #2 (Figures 52 and 12) was correct by sequencing and was transformed into BG 3594 comK, a *Bacillus subtilis* host strain. Selection was done on LA and 5 chloramphenicol plates. A transformant was chosen and struck to single colonies on LA and 5 chloramphenicol, then grown in LB and 5 chloramphenicol until it reached an OD₆₀₀ of 1.5. It was stored frozen in a vial at -80° C in the presence of glycerol. The resulting strain was designated CF 443.

II. Production of isoprene in shake flasks containing *B. subtilis* cells expressing recombinant isoprene synthase.

[0531] Overnight cultures were inoculated with a single colony of CF 443 from a LA and Chloramphenicol (Cm, 25 µg/ml). Cultures were grown in LB and Cm at 37° C with shaking at 200 rpm. These overnight cultures (1 ml) were used to inoculate 250 ml baffled shake flasks containing 25 ml Grants II media and chloramphenicol at a final concentration of 25 µg/ml. Grants II Media recipe was 10 g soytone, 3 ml 1M K₂HPO₄, 75 g glucose, 3.6 g urea, 100 ml 10X MOPS, q.s. to 1 L with H₂O, pH 7.2; 10X MOPS recipe was 83.72 g MOPS, 7.17 g tricine, 12 g KOH pellets, 10 ml 0.276M K₂SO₄ solution, 10 ml 0.528M MgCl₂ solution, 29.22 g NaCl, 100 ml 100X micronutrients, q.s. to 1 L with H₂O; and 100X micronutrients recipe was 1.47 g CaCl₂*2H₂O, 0.4 g FeSO₄*7H₂O, 0.1 g MnSO₄*H₂O, 0.1 g ZnSO₄*H₂O, 0.05 g CuCl₂*2H₂O, 0.1 g CoCl₂*6H₂O, 0.1 g Na₂MoO₄*2H₂O, q.s. to 1 L with H₂O. Shake flasks were incubated at 37°C and samples were taken at 18, 24, and 44 hours. At 18 hours the headspaces of CF443 and the control strain were sampled. This represented 18 hours of accumulation of isoprene. The amount of isoprene was determined by gas chromatography as described in Example 1. Production of isoprene was enhanced significantly by expressing recombinant isoprene synthase (Figure 11).

III. Production of isoprene by CF443 in 14 L fermentation

[0532] Large scale production of isoprene from *B. subtilis* containing the recombinant kudzu isoprene synthase gene on a replication plasmid was determined from a fed-batch culture. *Bacillus* strain CF 443, expressing a kudzu isoprene synthase gene, or control strain which does not express a kudzu isoprene synthase gene were cultivated by conventional fed-batch fermentation in a nutrient medium containing soy meal (Cargill), sodium and potassium phosphate, magnesium sulfate and a solution of citric acid, ferric chloride and manganese chloride. Prior to fermentation the media is macerated for 90 minutes using a mixture of

enzymes including cellulases, hemicellulases and pectinases (see, WO95/04134). 14-L batch fermentations are fed with 60% wt/wt glucose (Cargill DE99 dextrose, ADM Versadex greens or Danisco invert sugar) and 99% wt/wt oil (Western Family soy oil, where the 99% wt/wt is the concentration of oil before it was added to the cell culture medium). Feed was started when glucose in the batch was non-detectable. The feed rate was ramped over several hours and was adjusted to add oil on an equal carbon basis. The pH was controlled at 6.8 – 7.4 using 28% w/v ammonium hydroxide. In case of foaming, antifoam agent was added to the media. The fermentation temperature was controlled at 37°C and the fermentation culture was agitated at 750 rpm. Various other parameters such as pH, DO%, airflow, and pressure were monitored throughout the entire process. The DO% is maintained above 20. Samples were taken over the time course of 36 hours and analyzed for cell growth (OD₅₅₀) and isoprene production. Results of these experiments are presented in Figures 53A and 53B.

IV. Integration of the kudzu isoprene synthase (ispS) in *B. subtilis*.

[0533] The kudzu isoprene synthase gene was cloned in an integrating plasmid (pJH101-cmpR) under the control of the *aprE* promoter. Under the conditions tested, no isoprene was detected.

Example 5: Production of isoprene in *Trichoderma*

I. Construction of vectors for expression of the kudzu isoprene synthase in *Trichoderma reesei*

[0534] The *Yarrowia lipolytica* codon-optimized kudzu IS gene was synthesized by DNA 2.0 (SEQ ID NO:8) (Figure 13). This plasmid served as the template for the following PCR amplification reaction: 1 µl plasmid template (20 ng/ul), 1 µl Primer EL-945 (10 µM) 5'-GCTTATGGATCCTCTAGACTATTACACGTACATCAATTGG (SEQ ID NO:9), 1 µl Primer EL-965 (10µM) 5'-CACCATGTGTGCAACCTCCTCCCAGTTTAC (SEQ ID NO:10), 1 µl dNTP (10mM), 5 µl 10x PfuUltra II Fusion HS DNA Polymerase Buffer, 1 µl PfuUltra II Fusion HS DNA Polymerase, 40 µl water in a total reaction volume of 50 µl. The forward primer contained an additional 4 nucleotides at the 5'-end that did not correspond to the *Y. lipolytica* codon-optimized kudzu isoprene synthase gene, but was required for cloning into the pENTR/D-TOPO vector. The reverse primer contained an additional 21 nucleotides at the 5'-end that did not correspond to the *Y. lipolytica* codon-

optimized kudzu isoprene synthase gene, but were inserted for cloning into other vector backbones. Using the MJ Research PTC-200 Thermocycler, the PCR reaction was performed as follows: 95° C for 2 minutes (first cycle only), 95° C for 30 seconds, 55° C for 30 seconds, 72° C for 30 seconds (repeat for 27 cycles), 72° C for 1 minute after the last cycle. The PCR product was analyzed on a 1.2% E-gel to confirm successful amplification of the *Y. lipolytica* codon-optimized kudzu isoprene synthase gene.

[0535] The PCR product was then cloned using the TOPO pENTR/D-TOPO Cloning Kit following manufacturer's protocol: 1 µl PCR reaction, 1 µl Salt solution, 1 µl TOPO pENTR/D-TOPO vector and 3 µl water in a total reaction volume of 6 µl. The reaction was incubated at room temperature for 5 minutes. One microliter of TOPO reaction was transformed into TOP10 chemically competent *E. coli* cells. The transformants were selected on LA and 50 µg/ml kanamycin plates. Several colonies were picked and each was inoculated into a 5 ml tube containing LB and 50 µg/ml kanamycin and the cultures grown overnight at 37° C with shaking at 200 rpm. Plasmids were isolated from the overnight culture tubes using QIAprep Spin Miniprep Kit, following manufacturer's protocol. Several plasmids were sequenced to verify that the DNA sequence was correct.

[0536] A single pENTR/D-TOPO plasmid, encoding a *Y. lipolytica* codon-optimized kudzu isoprene synthase gene, was used for Gateway Cloning into a custom-made pTrex3g vector. Construction of pTrex3g is described in WO 2005/001036 A2. The reaction was performed following manufacturer's protocol for the Gateway LR Clonase II Enzyme Mix Kit (Invitrogen): 1 µl *Y. lipolytica* codon-optimized kudzu isoprene synthase gene pENTR/D-TOPO donor vector, 1 µl pTrex3g destination vector, 6 µl TE buffer, pH 8.0 in a total reaction volume of 8 µl. The reaction was incubated at room temperature for 1 hour and then 1 µl proteinase K solution was added and the incubation continued at 37° C for 10 minutes. Then 1 µl of reaction was transformed into TOP10 chemically competent *E. coli* cells. The transformants were selected on LA and 50 µg/ml carbenicillin plates. Several colonies were picked and each was inoculated into a 5 ml tube containing LB and 50 µg/ml carbenicillin and the cultures were grown overnight at 37° C with shaking at 200 rpm. Plasmids were isolated from the overnight culture tubes using QIAprep Spin Miniprep Kit (Qiagen, Inc.), following manufacturer's protocol. Several plasmids were sequenced to verify that the DNA sequence was correct.

[0537] Biolistic transformation of *Y. lipolytica* codon-optimized kudzu isoprene synthase pTrex3g plasmid (Figure 14) into a quad delete *Trichoderma reesei* strain was performed using the Biolistic PDS-1000/HE Particle Delivery System (see WO 2005/001036 A2). Isolation of stable transformants and shake flask evaluation was performed using protocol listed in Example 11 of patent publication WO 2005/001036 A2.

II. Production of isoprene in recombinant strains of *T. reesei*

[0538] One ml of 15 and 36 hour old cultures of isoprene synthase transformants described above were transferred to head space vials. The vials were sealed and incubated for 5 hours at 30° C. Head space gas was measured and isoprene was identified by the method described in Example 1. Two of the transformants showed traces of isoprene. The amount of isoprene could be increased by a 14 hour incubation. The two positive samples showed isoprene at levels of about 0.5 µg/L for the 14 hour incubation. The untransformed control showed no detectable levels of isoprene. This experiment shows that *T. reesei* is capable of producing isoprene from endogenous precursor when supplied with an exogenous isoprene synthase.

Example 6: Production of isoprene in *Yarrowia*

I. Construction of vectors for expression of the kudzu isoprene synthase in *Yarrowia lipolytica*.

[0539] The starting point for the construction of vectors for the expression of the kudzu isoprene synthase gene in *Yarrowia lipolytica* was the vector pSPZ1(MAP29S_{pb}). The complete sequence of this vector (SEQ ID No:11) is shown in Figure 15.

[0540] The following fragments were amplified by PCR using chromosomal DNA of a *Y. lipolytica* strain GICC 120285 as the template: a promotorless form of the URA3 gene, a fragment of 18S ribosomal RNA gene, a transcription terminator of the *Y. lipolytica* XPR2 gene and two DNA fragments containing the promoters of XPR2 and ICL1 genes. The following PCR primers were used:

ICL1 3

5'- GGTGAATTCAGTCTACTGGGGATTCCCAAATCTATATATACTGCAGGTGAC
(SEQ ID NO:69)

ICL1 5

5'- GCAGGTGGGAAACTATGCACTCC (SEQ ID NO:70)

XPR 3

5'- CCTGAATTCTGTTGGATTGGAGGATTGGATAGTGGG (SEQ ID NO:71)

XPR 5

5'- GGTGTCGACGTACGGTCGAGCTTATTGACC (SEQ ID NO:72)

XPRT3

5'- GGTGGGCCCCGCATTTTGCCACCTACAAGCCAG (SEQ ID NO:73)

XPRT 5

5'- GGTGAATTCTAGAGGATCCCAACGCTGTTGCCTACAACGG (SEQ ID NO:74)

Y18S3

5'- GGTGCGGCCGCTGTCTGGACCTGGTGAGTTTCCCCG (SEQ ID NO:75)

Y18S 5

5'- GGTGGGCCCATTAAATCAGTTATCGTTTATTTGATAG (SEQ ID NO:76)

YURA3

5'- GGTGACCAGCAAGTCCATGGGTGGTTTGATCATGG (SEQ ID NO:77)

YURA 50

5'- GGTGCGGCCGCTTTGGAGTACGACTCCAACCTATG (SEQ ID NO:78)

YURA 51

5'- GCGGCCGCAGACTAAATTTATTTAGTCTCC (SEQ ID NO:79)

[0541] For PCR amplification the PfuUltraII polymerase (Stratagene), supplier-provided buffer and dNTPs, 2.5 μ M primers and the indicated template DNA were used in accordance with the manufacturer's instructions. The amplification was done using the following cycle: 95° C for 1 min; 34x (95° C for 30 sec; 55° C for 30 sec; 72° C for 3 min) and 10 min at 72° C followed by a 4° C incubation.

[0542] Synthetic DNA molecules encoding the kudzu isoprene synthase gene, codon-optimized for expression in *Yarrowia*, was obtained from DNA 2.0 (Figure 16; SEQ ID

NO:12). Full detail of the construction scheme of the plasmids pYLA(KZ1) and pYLI(KZ1) carrying the synthetic kudzu isoprene synthase gene under control of XPR2 and ICL1 promoters respectively is presented in Figure 18. Control plasmids in which a mating factor gene (MAP29) is inserted in place of an isoprene synthase gene were also constructed (Figure 18E and 18F).

[0543] A similar cloning procedure can be used to express a poplar (*Populus alba* x *Populus tremula*) isoprene synthase gene. The sequence of the poplar isoprene is described in Miller B. *et al.* (2001) *Planta* 213, 483-487 and shown in Figure 17 (SEQ ID NO:13). A construction scheme for the generation the plasmids pYLA(POP1) and pYLI(POP1) carrying synthetic poplar isoprene synthase gene under control of XPR2 and ICL1 promoters respectively is presented in Figure 18A and B.

II. Production of isoprene by recombinant strains of *Y. lipolytica*.

[0544] Vectors pYLA(KZ1), pYLI(KZ1), pYLA(MAP29) and pYLI(MAP29) were digested with *Sac*II and used to transform the strain *Y. lipolytica* CLIB 122 by a standard lithium acetate/polyethylene glycol procedure to uridine prototrophy. Briefly, the yeast cells grown in YEPD (1% yeast extract, 2% peptone, 2% glucose) overnight, were collected by centrifugation (4000 rpm, 10 min), washed once with sterile water and suspended in 0.1 M lithium acetate, pH 6.0. Two hundred μ l aliquots of the cell suspension were mixed with linearized plasmid DNA solution (10-20 μ g), incubated for 10 minutes at room temperature and mixed with 1 ml of 50% PEG 4000 in the same buffer. The suspensions were further incubated for 1 hour at room temperature followed by a 2 minutes heat shock at 42° C. Cells were then plated on SC his leu plates (0.67% yeast nitrogen base, 2% glucose, 100 mg/L each of leucine and histidine). Transformants appeared after 3-4 days of incubation at 30° C.

[0545] Three isolates from the pYLA(KZ1) transformation, three isolates from the pYLI(KZ1) transformation, two isolates from the pYLA(MAP29) transformation and two isolates from the pYLI(MAP29) transformation were grown for 24 hours in YEP7 medium (1% yeast extract, 2% peptone, pH 7.0) at 30° C with shaking. Cells from 10 ml of culture were collected by centrifugation, resuspended in 3 ml of fresh YEP7 and placed into 15 ml screw cap vials. The vials were incubated overnight at room temperature with gentle (60 rpm) shaking. Isoprene content in the headspace of these vials was analyzed by gas chromatography using mass-spectrometric detector as described in Example 1. All

transformants obtained with pYLA(KZ1) and pYLI(KZ1) produced readily detectable amounts of isoprene (0.5 µg/L to 1 µg/L, Figure 20). No isoprene was detected in the headspace of the control strains carrying phytase gene instead of an isoprene synthase gene.

Example 7: Production of isoprene in *E. coli* expressing kudzu isoprene synthase and *idi*, or *dxs*, or *idi* and *dxs*

I. Construction of vectors encoding kudzu isoprene synthase and *idi*, or *dxs*, or *idi* and *dxs* for the production of isoprene in *E. coli*

i) Construction of pTrcKudzuKan

[0546] The *bla* gene of pTrcKudzu (described in Example 1) was replaced with the gene conferring kanamycin resistance. To remove the *bla* gene, pTrcKudzu was digested with *Bsp*HI, treated with Shrimp Alkaline Phosphatase (SAP), heat killed at 65°C, then end-filled with Klenow fragment and dNTPs. The 5 kbp large fragment was purified from an agarose gel and ligated to the *kan*^r gene which had been PCR amplified from pCR-Blunt-II-TOPO using primers MCM22 5'- GATCAAGCTTAACCGGAATTGCCAGCTG (SEQ ID NO:14) and MCM23 5'- GATCCGATCGTCAGAAGAACTCGTCAAGAAGGC (SEQ ID NO:15), digested with *Hind*III and *Pvu*I, and end-filled. A transformant carrying a plasmid conferring kanamycin resistance (pTrcKudzuKan) was selected on LA containing kanamycin 50 µg/ml.

ii) Construction of pTrcKudzu yIDI Kan

[0547] pTrcKudzuKan was digested with *Pst*I, treated with SAP, heat killed and gel purified. It was ligated to a PCR product encoding *idi* from *S. cerevisiae* with a synthetic RBS. The primers for PCR were *Nsi*I-YIDI 1 F 5'- CATCAATGCATCGCCCTTAGGAGGTAAAAAAAATGAC (SEQ ID NO:16) and *Pst*I-YIDI 1 R 5'- CCTTCTGCAGGACGCGTTGTTATAGC (SEQ ID NO:17); and the template was *S. cerevisiae* genomic DNA. The PCR product was digested with *Nsi*I and *Pst*I and gel purified prior to ligation. The ligation mixture was transformed into chemically competent TOP10 cells and selected on LA containing 50 µg/ml kanamycin. Several transformants were isolated and sequenced and the resulting plasmid was called pTrcKudzu-yIDI(kan) (Figures 34 and 35).

iii) Construction of pTrcKudzu DXS Kan

[0548] Plasmid pTrcKudzuKan was digested with *Pst*I, treated with SAP, heat killed and gel purified. It was ligated to a PCR product encoding *dxs* from *E. coli* with a synthetic RBS. The primers for PCR were MCM13 5'-

GATCATGCATTCGCCCTTAGGAGGTAAAAAACATGAGTTTTGATATTGCCAAAT
ACCCG (SEQ ID NO:18) and MCM14 5'-

CATGCTGCAGTTATGCCAGCCAGGCCTTGAT (SEQ ID NO:19); and the template was *E. coli* genomic DNA. The PCR product was digested with *Nsi*I and *Pst*I and gel purified prior to ligation. The resulting transformation reaction was transformed into TOP10 cells and selected on LA with kanamycin 50 µg/ml. Several transformants were isolated and sequenced and the resulting plasmid was called pTrcKudzu-DXS(kan) (Figures 36 and 37).

iv) Construction of pTrcKudzu-yIDI-dxs (kan)

[0549] pTrcKudzu-yIDI(kan) was digested with *Pst*I, treated with SAP, heat killed and gel purified. It was ligated to a PCR product encoding *E. coli dxs* with a synthetic RBS (primers MCM13 5'-

GATCATGCATTCGCCCTTAGGAGGTAAAAAACATGAGTTTTGATATTGCCAAAT
ACCCG (SEQ ID NO:18) and MCM14 5'-

CATGCTGCAGTTATGCCAGCCAGGCCTTGAT (SEQ ID NO:19); template TOP10 cells) which had been digested with *Nsi*I and *Pst*I and gel purified. The final plasmid was called pTrcKudzu-yIDI-dxs (kan) (Figures 21 and 22).

v) Construction of pCL PtrcKudzu

[0550] A fragment of DNA containing the promoter, structural gene and terminator from Example 1 above was digested from pTrcKudzu using *Ssp*I and gel purified. It was ligated to pCL1920 which had been digested with *Pvu*II, treated with SAP and heat killed. The resulting ligation mixture was transformed into TOP10 cells and selected in LA containing spectinomycin 50 µg/ml. Several clones were isolated and sequenced and two were selected. pCL PtrcKudzu and pCL PtrcKudzu (A3) have the insert in opposite orientations (Figures 38-41).

vi) Construction of pCL PtrcKudzu yIDI

[0551] The *NsiI*-*PstI* digested, gel purified, IDI PCR amplicon from (ii) above was ligated into pCL PtrcKudzu which had been digested with *PstI*, treated with SAP, and heat killed. The ligation mixture was transformed into TOP10 cells and selected in LA containing spectinomycin 50 µg/ml. Several clones were isolated and sequenced and the resulting plasmid is called pCL PtrcKudzu yIDI (Figures 42 and 43).

vii) Construction of pCL PtrcKudzu DXS

[0552] The *NsiI*-*PstI* digested, gel purified, DXS PCR amplicon from (iii) above was ligated into pCL PtrcKudzu (A3) which had been digested with *PstI*, treated with SAP, and heat killed. The ligation mixture was transformed into TOP10 cells and selected in LA containing spectinomycin 50 µg/ml. Several clones were isolated and sequenced and the resulting plasmid is called pCL PtrcKudzu DXS (Figures 44 and 45).

II. Measurement of isoprene in headspace from cultures expressing kudzu isoprene synthase, *idi*, and/or *dxs* at different copy numbers.

[0553] Cultures of *E. coli* BL21(λDE3) previously transformed with plasmids pTrcKudzu(kan) (A), pTrcKudzu-yIDI kan (B), pTrcKudzu-DXS kan (C), pTrcKudzu-yIDI-DXS kan (D) were grown in LB kanamycin 50 µg/mL. Cultures of pCL PtrcKudzu (E), pCL PtrcKudzu, pCL PtrcKudzu-yIDI (F) and pCL PtrcKudzu-DXS (G) were grown in LB spectinomycin 50 µg/mL. Cultures were induced with 400 µM IPTG at time 0 (OD₆₀₀ approximately 0.5) and samples taken for isoprene headspace measurement (see Example 1). Results are shown in Figure 23A-23G.

[0554] Plasmid pTrcKudzu-yIDI-dxs (kan) was introduced into *E. coli* strain BL21 by transformation. The resulting strain BL21/pTrc Kudzu IDI DXS was grown overnight in LB containing kanamycin (50 µg/ml) at 20°C and used to inoculate shake flasks of TM3 (13.6 g K₂PO₄, 13.6 g KH₂PO₄, 2.0 g MgSO₄*7H₂O), 2.0 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 3.2 g (NH₄)₂SO₄, 0.2 g yeast extract, 1.0 ml 1000x Modified Trace Metal Solution, adjusted to pH 6.8 and q.s. to H₂O, and filter sterilized) containing 1% glucose. Flasks were incubated at 30°C until an OD₆₀₀ of 0.8 was reached, and then induced with 400 µM IPTG. Samples were taken at various times after induction and the amount of isoprene in the head space was measured as described in Example 1. Results are shown in Figure 23H.

III. Production of isoprene from biomass in *E. coli*/pTrcKudzu yIDI DXS

[0555] The strain BL21 pTrcKudzuIDIDXS was tested for the ability to generate isoprene from three types of biomass; bagasse, corn stover and soft wood pulp with glucose as a control. Hydrolysates of the biomass were prepared by enzymatic hydrolysis (Brown, L and Torget, R., 1996, NREL standard assay method Lap-009 “Enzymatic Saccharification of Lignocellulosic Biomass”) and used at a dilution based upon glucose equivalents. In this example, glucose equivalents were equal to 1% glucose. A single colony from a plate freshly transformed cells of BL21 (DE3) pTrcKudzu yIDI DXS (kan) was used to inoculate 5 ml of LB plus kanamycin (50 µg/ml). The culture was incubated overnight at 25° C with shaking. The following day the overnight culture was diluted to an OD₆₀₀ of 0.05 in 25 ml of TM3 and 0.2% YE and 1% feedstock. The feedstock was corn stover, bagasse, or softwood pulp. Glucose was used as a positive control and no glucose was used as a negative control. Cultures were incubated at 30° C with shaking at 180 rpm. The culture was monitored for OD₆₀₀ and when it reached an OD₆₀₀ of ~0.8, cultures were analyzed at 1 and 3 hours for isoprene production as described in Example 1. Cultures are not induced. All cultures containing added feedstock produce isoprene equivalent to those of the glucose positive control. Experiments were done in duplicate and are shown in Figure 46.

IV. Production of isoprene from invert sugar in *E. coli*/pTrcKudzuIDIDXS

[0556] A single colony from a plate freshly transformed cells of BL21 (λDE3)/pTrcKudzu yIDI DXS (kan) was used to inoculate 5 mL of LB and kanamycin (50 µg/ml). The culture was incubated overnight at 25° C with shaking. The following day the overnight culture was diluted to an OD₆₀₀ of 0.05 in 25 ml of TM3 and 0.2% YE and 1% feedstock. Feedstock was glucose, inverted glucose or corn stover. The invert sugar feedstock (Danisco Invert Sugar) was prepared by enzymatically treating sucrose syrup. AFEX corn stover was prepared as described below (Part V). The cells were grown at 30° C and the first sample was measured when the cultures reached an OD₆₀₀ ~0.8-1.0 (0 hour). The cultures were analyzed for growth as measured by OD₆₀₀ and for isoprene production as in Example 1 at 0, 1 and 3 hours. Results are shown in Figure 47.

V. Preparation of hydrolysate from AFEX pretreated corn stover

[0557] AFEX pretreated corn stover was obtained from Michigan Biotechnology Institute. The pretreatment conditions were 60% moisture, 1:1 ammonia loading, and 90 °C for 30 minutes, then air dried. The moisture content in the AFEX pretreated corn stover was 21.27%. The contents of glucan and xylan in the AFEX pretreated corn stover were 31.7% and 19.1% (dry basis), respectively. The saccharification process was as follows; 20 g of AFEX pretreated corn stover was added into a 500 ml flask with 5 ml of 1 M sodium citrate buffer pH 4.8, 2.25 ml of Accellerase 1000, 0.1 ml of Grindamyl H121 (Danisco xylanase product from *Aspergillus niger* for bread-making industry), and 72.65 ml of DI water. The flask was put in an orbital shaker and incubated at 50° C for 96 hours. One sample was taken from the shaker and analyzed using HPLC. The hydrolysate contained 38.5 g/l of glucose, 21.8 g/l of xylose, and 10.3 g/l of oligomers of glucose and/or xylose.

VI. The effect of yeast extract on isoprene production in *E. coli* grown in fed-batch culture

[0558] Fermentation was performed at the 14-L scale as previously described with *E. coli* cells containing the pTrcKudzu yIDI DXS plasmid described above. Yeast extract (Bio Springer, Montreal, Quebec, Canada) was fed at an exponential rate. The total amount of yeast extract delivered to the fermentor was varied between 70-830 g during the 40 hour fermentation. Optical density of the fermentation broth was measured at a wavelength of 550 nm. The final optical density within the fermentors was proportional to the amount of yeast extract added (Figure 48A). The isoprene level in the off-gas from the fermentor was determined as previously described. The isoprene titer increased over the course of the fermentation (Figure 48B). The amount of isoprene produced was linearly proportional to the amount of fed yeast extract (Figure 48C).

VII. Production of isoprene in 500 L fermentation of pTrcKudzu DXS yIDI

[0559] A 500 liter fermentation of *E. coli* cells with a kudzu isoprene synthase, *S. cerevisiae* IDI, and *E. coli* DXS nucleic acids (*E. coli* BL21 (λDE3) pTrc Kudzu dxs yidi) was used to produce isoprene. The levels of isoprene varied from 50 to 300 µg/L over a time period of 15 hours. On the basis of the average isoprene concentrations, the average flow through the device and the extent of isoprene breakthrough, the amount of isoprene collected was calculated to be approximately 17 g.

VIII. Production of isoprene in 500 L fermentation of *E. coli* grown in fed-batch culture

Medium Recipe (per liter fermentation medium):

[0560] K_2HPO_4 7.5 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in dH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium gas (NH_3) and q.s. to volume. Glucose 10 g, thiamine $\cdot \text{HCl}$ 0.1 g, and antibiotic were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0561] Citric Acids $\cdot \text{H}_2\text{O}$ 40 g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30 g, NaCl 10 g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1 g, $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100 mg, H_3BO_3 100 mg, $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100 mg. Each component is dissolved one at a time in DI H_2O , pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with 0.22 micron filter.

[0562] Fermentation was performed in a 500-L bioreactor with *E. coli* cells containing the pTrcKudzu yIDI DXS plasmid. This experiment was carried out to monitor isoprene formation from glucose and yeast extract at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was prepared in soytone-yeast extract-glucose medium. After the inoculum grew to OD 0.15, measured at 550 nm, 20 ml was used to inoculate a bioreactor containing 2.5-L soytone-yeast extract-glucose medium. The 2.5-L bioreactor was grown at 30°C to OD 1.0 and 2.0-L was transferred to the 500-L bioreactor.

[0563] Yeast extract (Bio Springer, Montreal, Quebec, Canada) and glucose were fed at exponential rates. The total amount of glucose and yeast extract delivered to the bioreactor during the 50 hour fermentation was 181.2 kg and 17.6 kg, respectively. The optical density within the bioreactor over time is shown in Figure 49A. The isoprene level in the off-gas from the bioreactor was determined as previously described. The isoprene titer increased over the course of the fermentation (Figure 49B). The total amount of isoprene produced during the 50 hour fermentation was 55.1 g and the time course of production is shown in Figure 49C.

Example 8: Production of isoprene in *E. coli* expressing kudzu isoprene synthase and recombinant mevalonic acid pathway genes

I. Cloning the lower MVA pathway

[0564] The strategy for cloning the lower mevalonic pathway was as follows. Four genes of the mevalonic acid biosynthesis pathway; mevalonate kinase (MVK), phosphomevalonate kinase (PMK), diphosphomevalonate decarboxylase (MVD) and isopentenyl diphosphate isomerase genes were amplified by PCR from *S. cerevisiae* chromosomal DNA and cloned individually into the pCR BluntII TOPO plasmid (Invitrogen). In some cases, the *idi* gene was amplified from *E. coli* chromosomal DNA. The primers were designed such that an *E. coli* consensus RBS (AGGAGGT (SEQ ID NO:80) or AAGGAGG (SEQ ID NO:81)) was inserted at the 5' end, 8 bp upstream of the start codon and a *Pst*I site was added at the 3' end. The genes were then cloned one by one into the pTrcHis2B vector until the entire pathway was assembled.

[0565] Chromosomal DNA from *S. cerevisiae* S288C was obtained from ATCC (ATCC 204508D). The MVK gene was amplified from the chromosome of *S. cerevisiae* using primers MVKF (5'-AGGAGGTAAAAAACATGTCATTACCGTTCTTAACCTCTGC, SEQ ID NO:21) and MVK-Pst1-R (5'-ATGGCTGCAGGCCTATCGCAAATTAGCTTATGAAGTCCATGGTAAATTCGTG, SEQ ID NO:22) using PfuTurbo as per manufacturer's instructions. The correct sized PCR product (1370 bp) was identified by electrophoresis through a 1.2% E-gel (Invitrogen) and cloned into pZeroBLUNT TOPO. The resulting plasmid was designated pMVK1. The plasmid pMVK1 was digested with *Sac*I and *Taq*I restriction endonucleases and the fragment was gel purified and ligated into pTrcHis2B digested with *Sac*I and *Bst*BI. The resulting plasmid was named pTrcMVK1.

[0566] The second gene in the mevalonic acid biosynthesis pathway, PMK, was amplified by PCR using primers: *Pst*I-PMK1 R (5'-GAATTCGCCCTTCTGCAGCTACC, SEQ ID NO:23) and *Bsi*HKA I-PMK1 F (5'-CGACTGGTGCACCCTTAAGGAGGAAAAAACATGTCAG, SEQ ID NO:24). The PCR reaction was performed using Pfu Turbo polymerase (Stratagene) as per manufacturer's instructions. The correct sized product (1387 bp) was digested with *Pst*I and *Bsi*HKI and ligated into pTrcMVK1 digested with *Pst*I. The resulting plasmid was named pTrcKK. The

MVD and the *idi* genes were cloned in the same manner. PCR was carried out using the primer pairs PstI-MVD 1 R (5'-GTGCTGGAATTCGCCCTTCTGCAGC, SEQ ID NO:25) and NsiI-MVD 1 F (5'-GTAGATGCATGCAGAATTCGCCCTTAAGGAGG, SEQ ID NO:26) to amplify the MVD gene and PstI-YIDI 1 R (5'-CCTTCTGCAGGACGCGTTGTTATAGC, SEQ ID NO:27) and NsiI-YIDI 1 F (5'-CATCAATGCATCGCCCTTAGGAGGTAAAAAAAATGAC, SEQ ID NO:28) to amplify the yIDI gene. In some cases the IPP isomerase gene, *idi* from *E. coli* was used. To amplify *idi* from *E. coli* chromosomal DNA, the following primer set was used: PstI-CIDI 1 R (5'-GTGTGATGGATATCTGCAGAATTCG, SEQ ID NO:29) and NsiI-CIDI 1 F (5'-CATCAATGCATCGCCCTTAGGAGGTAAAAAACATG, SEQ ID NO:30). Template DNA was chromosomal DNA isolated by standard methods from *E. coli* FM5 (WO 96/35796 and WO 2004/033646, which are each hereby incorporated by reference in their entireties, particularly with respect to isolation of nucleic acids). The final plasmids were named pKKDIy for the construct encoding the yeast *idi* gene or pKKDIc for the construct encoding the *E. coli idi* gene. The plasmids were transformed into *E. coli* hosts BL21 for subsequent analysis. In some cases the isoprene synthase from kudzu was cloned into pKKDIy yielding plasmid pKKDIyIS.

[0567] The lower MVA pathway was also cloned into pTrc containing a kanamycin antibiotic resistance marker. The plasmid pTrcKKDIy was digested with restriction endonucleases *ApaI* and *PstI*, the 5930 bp fragment was separated on a 1.2% agarose E-gel and purified using the Qiagen Gel Purification kit according to the manufacturer's instructions. The plasmid pTrcKudzuKan, described in Example 7, was digested with restriction endonucleases *ApaI* and *PstI*, and the 3338 bp fragment containing the vector was purified from a 1.2% E-gel using the Qiagen Gel Purification kit. The 3338 bp vector fragment and the 5930 bp lower MVA pathway fragment were ligated using the Roche Quick Ligation kit. The ligation mix was transformed into *E. coli* TOP10 cells and transformants were grown at 37°C overnight with selection on LA containing kanamycin (50 µg/ml). The transformants were verified by restriction enzyme digestion and one was frozen as a stock. The plasmid was designated pTrcKanKKDIy.

II. Cloning a kudzu isoprene synthase gene into pTrcKanKKDIy

[0568] The kudzu isoprene synthase gene was amplified by PCR from pTrcKudzu, described in Example 1, using primers MCM50 5'-GATCATGCATTTCGCCCTTAGGAGGTAAAAAACATGTGTGCGACCTCTTCTCAATTACT (SEQ ID NO:31) and MCM53 5'-CGGTCGACGGATCCCTGCAGTTAGACATACATCAGCTG (SEQ ID NO:32). The resulting PCR fragment was cloned into pCR2.1 and transformed into *E. coli* TOP10. This fragment contains the coding sequence for kudzu isoprene synthase and an upstream region containing a RBS from *E. coli*. Transformants were incubated overnight at 37° C with selection on LA containing carbenicillin (50 µg/ml). The correct insertion of the fragment was verified by sequencing and this strain was designated MCM93.

[0569] The plasmid from strain MCM93 was digested with restriction endonucleases *Nsi*I and *Pst*I to liberate a 1724 bp insert containing the RBS and kudzu isoprene synthase. The 1724 bp fragment was separated on a 1.2% agarose E-gel and purified using the Qiagen Gel Purification kit according to the manufacturer's instructions. Plasmid pTrcKanKKDIy was digested with the restriction endonuclease *Pst*I, treated with SAP for 30 minutes at 37°C and purified using the Qiagen PCR cleanup kit. The plasmid and kudzu isoprene synthase encoding DNA fragment were ligated using the Roche Quick Ligation kit. The ligation mix was transformed into *E. coli* TOP10 cells and transformants were grown overnight at 37°C with selection on LA containing Kanamycin at 50 µg/ml. The correct transformant was verified by restriction digestion and the plasmid was designated pTrcKKDyIkISKan (Figures 24 and 25). This plasmid was transformed into BL21(λDE3) cells (Invitrogen).

III. Isoprene production from mevalonate in *E. coli* expressing the recombinant lower mevalonate pathway and isoprene synthase from kudzu.

[0570] Strain BL21/pTrcKKDyIkISKan was cultured in MOPS medium (Neidhardt *et al.*, (1974) *J. Bacteriology* 119:736-747) adjusted to pH 7.1 and supplemented with 0.5% glucose and 0.5% mevalonic acid. A control culture was also set up using identical conditions but without the addition of 0.5% mevalonic acid. The culture was started from an overnight seed culture with a 1% inoculum and induced with 500 µM IPTG when the culture had reached an OD₆₀₀ of 0.3 to 0.5. The cultures were grown at 30°C with shaking at 250 rpm. The production of isoprene was analyzed 3 hours after induction by using the head space assay

described in Example 1. Maximum production of isoprene was 6.67×10^4 nmol/L_{broth}/OD₆₀₀/hr where L_{broth} is the volume of broth and includes both the volume of the cell medium and the volume of the cells. The control culture not supplemented with mevalonic acid did not produce measurable isoprene.

IV. Cloning the upper MVA pathway

[0571] The upper mevalonate biosynthetic pathway, comprising two genes encoding three enzymatic activities, was cloned from *Enterococcus faecalis*. The *mvaE* gene encodes a protein with the enzymatic activities of both acetyl-CoA acetyltransferase and 3-hydroxy-3-methylglutaryl-CoA (HMG-CoA) reductase, the first and third proteins in the pathway, and the *mvaS* gene encodes second enzyme in the pathway, HMG-CoA synthase. The *mvaE* gene was amplified from *E. faecalis* genomic DNA (ATCC 700802D-5) with an *E. coli* ribosome binding site and a spacer in front using the following primers:

CF 07-60 (+) Start of *mvaE* w/ RBS + ATG start codon *SacI*

5' - GAGACATGAGCTCAGGAGGTAAAAAACATGAAAACAGTAGTTATTATTG
(SEQ ID NO:34)

CF 07-62 (-) Fuse *mvaE* to *mvaS* with RBS in between

5' - TTTATCAATCCCAATTGTCATGTTTTTTTACCTCCTTTATTGTTTTCTTAAATC
(SEQ ID NO:35)

[0572] The *mvaS* gene was amplified from *E. faecalis* genomic DNA (ATCC 700802D-5) with a RBS and spacer from *E. coli* in front using the following primers:

CF 07-61 (+) Fuse *mvaE* to *mvaS* with RBS in between 5' -

GATTTAAGAAAACAATAAAGGAGGTAAAAAACATGACAATTGGGATTGATAAA
(SEQ ID NO:36)

CF 07-102 (-) End of *mvaS* gene *BglII*

5' -GACATGACATAGATCTTTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:37)

[0573] The PCR fragments were fused together with PCR using the following primers:

CF 07-60 (+) Start of *mvaE* w/ RBS + ATG start codon *SacI*

5' -GAGACATGAGCTCAGGAGGTAAAAAACATGAAAACAGTAGTTATTATTG
(SEQ ID NO:34)

CF 07-102 (-) End of *mvaS* gene *Bgl*III

5'-GACATGACATAGATCTTTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:37)

[0574] The fusion PCR fragment was purified using a Qiagen kit and digested with the restriction enzymes *Sac*I and *Bgl*III. This digested DNA fragment was gel purified using a Qiagen kit and ligated into the commercially available vector pTrcHis2A, which had been digested with *Sac*I and *Bgl*III and gel purified.

[0575] The ligation mix was transformed into *E. coli* Top 10 cells and colonies were selected on LA and 50 µg/ml carbenicillin plates. A total of six colonies were chosen and grown overnight in LB and 50 µg/ml carbenicillin and plasmids were isolated using a Qiagen kit. The plasmids were digested with *Sac*I and *Bgl*III to check for inserts and one correct plasmid was sequenced with the following primers:

CF 07-58 (+) Start of *mvaE* gene

5' – ATGAAAACAGTAGTTATTATTGATGC (SEQ ID NO:38)

CF 07-59 (-) End of *mvaE* gene

5' – ATGTTATTGTTTTCTTAAATCATTTAAAATAGC (SEQ ID NO:39)

CF 07-82 (+) Start of *mvaS* gene

5' – ATGACAATTGGGATTGATAAAATTAG (SEQ ID NO:40)

CF 07-83 (-) End of *mvaS* gene

5' – TTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:41)

CF 07-86 (+) Sequence in *mvaE*

5' – GAAATAGCCCCATTAGAAGTATC (SEQ ID NO:42)

CF 07-87 (+) Sequence in *mvaE*

5' – TTGCCAATCATATGATTGAAAATC (SEQ ID NO:43)

CF 07-88 (+) Sequence in *mvaE*

5' – GCTATGCTTCATTAGATCCTTATCG (SEQ ID NO:44)

CF 07-89 (+) Sequence *mvaS*

5' – GAAACCTACATCCAATCTTTTGCCC (SEQ ID NO:45)

[0576] The plasmid called pTrcHis2AUpperPathway#1 was correct by sequencing and was transformed into the commercially available *E. coli* strain BL21. Selection was done on LA and 50 µg/ml carbenicillin. Two transformants were chosen and grown in LB and 50 µg/ml carbenicillin until they reached an OD₆₀₀ of 1.5. Both strains were frozen in a vial at -80° C in the presence of glycerol. Strains were designated CF 449 for pTrcHis2AUpperPathway#1 in BL21, isolate #1 and CF 450 for pTrcHis2AUpperPathway#1 in BL21, isolate #2. Both clones were found to behave identically when analyzed.

V. Cloning of UpperMVA Pathway into pCL1920

[0577] The plasmid pTrcHis2AUpperPathway was digested with the restriction endonuclease *SspI* to release a fragment containing pTrc-*mvaE-mvaS*-(His tag)-terminator. In this fragment, the his-tag was not translated. This blunt ended 4.5 kbp fragment was purified from a 1.2% E-gel using the Qiagen Gel Purification kit. A dephosphorylated, blunt ended 4.2 kbp fragment from pCL1920 was prepared by digesting the vector with the restriction endonuclease *PvuII*, treating with SAP and gel purifying from a 1.2% E-gel using the Qiagen Gel Purification kit. The two fragments were ligated using the Roche Quick Ligation Kit and transformed into TOP10 chemically competent cells. Transformants were selected on LA containing spectinomycin (50 µg/ml). A correct colony was identified by screening for the presence of the insert by PCR. The plasmid was designated pCL PtrcUpperPathway (Figures 26 and 27).

VI. Strains expressing the combined Upper and Lower Mevalonic Acid Pathways

[0578] To obtain a strain with a complete mevalonic acid pathway plus kudzu isoprene synthase, plasmids pTrcKKDyIkISkan and pCLpTrcUpperPathway were both transformed into BL21(λDE3) competent cells (Invitrogen) and transformants were selected on LA containing kanamycin (50 µg/ml) and Spectinomycin (50 µg/ml). The transformants were checked by plasmid prep to ensure that both plasmids were retained in the host. The strain was designated MCM127.

VII. Production of mevalonic acid from glucose in *E. coli*/pUpperpathway

[0579] Single colonies of the BL21/pTrcHis2A-*mvaE/mvaS* or FM5/p pTrcHis2A-*mvaE/mvaS* are inoculated into LB and carbenicillin (100 µg/ml) and are grown overnight at 37° C with shaking at 200 rpm. These cultures were diluted into 50 ml medium in 250 ml baffled flasks to an OD₆₀₀ of 0.1. The medium was TM3, 1 or 2% glucose, carbenicillin (100 µg/ml) or TM3, 1% glucose, hydrolyzed soy oil, and carbenicillin (100 µg/ml) or TM3 and biomass (prepared bagasse, corn stover or switchgrass). Cultures were grown at 30°C with shaking at 200 rpm for approximately 2-3 hours until an OD₆₀₀ of 0.4 was reached. At this point the expression from the *mvaE mvaS* construct was induced by the addition of IPTG (400 µM). Cultures were incubated for a further 20 or 40 hours with samples taken at 2 hour intervals to 6 hour post induction and then at 24, 36 and 48 hours as needed. Sampling was done by removing 1 ml of culture, measuring the OD₆₀₀, pelleting the cells in a microfuge, removing the supernatant and analyzing it for mevalonic acid.

[0580] A 14 liter fermentation of *E. coli* cells with nucleic acids encoding *Enterococcus faecalis* AA-CoA thiolase, HMG-CoA synthase, and HMG-CoA reductase polypeptides produced 22 grams of mevalonic acid with TM3 medium and 2% glucose as the cell medium. A shake flask of these cells produced 2-4 grams of mevalonic acid per liter with LB medium and 1% glucose as the cell culture medium. The production of mevalonic acid in these strains indicated that the MVA pathway was functional in *E. coli*.

VIII. Production of isoprene from *E. coli* BL21 containing the upper and lower MVA pathway plus kudzu isoprene synthase.

[0581] The following strains were created by transforming in various combinations of plasmids containing the upper and lower MVA pathway and the kudzu isoprene synthase gene as described above and the plasmids containing the *idi*, *dxs*, and *dxr* and isoprene synthase genes described in Example 7. The host cells used were chemically competent BL21(λDE3) and the transformations were done by standard methods. Transformants were selected on L agar containing kanamycin (50 µg/ml) or kanamycin plus spectinomycin (both at a concentration of 50 µg/ml). Plates were grown at 37° C. The resulting strains were designated as follows:

Grown on Kanamycin plus Spectinomycin (50 µg/ml each)

MCM127 - pCL Upper MVA and pTrcKKDyIkIS (kan) in BL21(λ DE3)

MCM131 - pCL1920 and pTrcKKDyIkIS (kan) in BL21(λ DE3)

MCM125 - pCL Upper MVA and pTrcHis2B (kan) in BL21(λ DE3)

Grown on Kanamycin (50 μ g/ml)

MCM64 - pTrcKudzu yIDI DXS (kan) in BL21(λ DE3)

MCM50 - pTrcKudzu (kan) in BL21(λ DE3)

MCM123 - pTrcKudzu yIDI DXS DXR (kan) in BL21(λ DE3)

[0582] The above strains were streaked from freezer stocks to LA and appropriate antibiotic and grown overnight at 37°C. A single colony from each plate was used to inoculate shake flasks (25 ml LB and the appropriate antibiotic). The flasks were incubated at 22° C overnight with shaking at 200 rpm. The next morning the flasks were transferred to a 37° C incubator and grown for a further 4.5 hours with shaking at 200 rpm. The 25 ml cultures were centrifuged to pellet the cells and the cells were resuspended in 5 ml LB and the appropriate antibiotic. The cultures were then diluted into 25 ml LB, % glucose, and the appropriate antibiotic to an OD₆₀₀ of 0.1. Two flasks for each strain were set up, one set for induction with IPTG (800 μ M) the second set was not induced. The cultures were incubated at 37°C with shaking at 250 rpm. One set of the cultures were induced after 1.50 hours (immediately following sampling time point 1). At each sampling time point, the OD₆₀₀ was measured and the amount of isoprene determined as described in Example 1. Results are presented in Table 3. The amount of isoprene made is presented as the amount at the peak production for the particular strain.

Table 3. Production of isoprene in *E. coli* strains

Strain	Isoprene (μ g/L _{broth} /hr/OD
MCM50	23.8
MCM64	289
MCM125	ND
MCM131	Trace

MCM127	874
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ND: not detected

Trace: peak present but not integrable.

IX. Analysis of mevalonic acid

[0583] Mevalonolactone (1.0 g, 7.7 mmol) (CAS# 503-48-0) was supplied from Sigma-Aldrich (WI, USA) as a syrup that was dissolved in water (7.7 mL) and was treated with potassium hydroxide (7.7 mmol) in order to generate the potassium salt of mevalonic acid. The conversion to mevalonic acid was confirmed by ¹H NMR analysis. Samples for HPLC analysis were prepared by centrifugation at 14,000 rpm for 5 minutes to remove cells, followed by the addition of a 300 µl aliquot of supernatant to 900 µl of H₂O. Perchloric acid (36 µl of a 70% solution) was then added followed by mixing and cooling on ice for 5 minutes. The samples were then centrifuged again (14,000 rpm for 5 min) and the supernatant transferred to HPLC. Mevalonic acid standards (20, 10, 5, 1 and 0.5 g/L) were prepared in the same fashion. Analysis of mevalonic acid (20 µL injection volume) was performed by HPLC using a BioRad Aminex 87-H+ column (300 mm by 7.0 mm) eluted with 5 mM sulfuric acid at 0.6 mL/min with refractive index (RI) detection. Under these conditions mevalonic acid eluted as the lactone form at 18.5 minutes.

X. Production of isoprene from *E. coli* BL21 containing the upper MVA pathway plus kudzu isoprene synthase

[0584] A 15-L scale fermentation of *E. coli* expressing mevalonic acid pathway polypeptides and Kudzu isoprene synthase was used to produce isoprene from cells in fed-batch culture. This experiment demonstrates that growing cells under glucose limiting conditions resulted in the production of 2.2 g/L of isoprene.

Medium Recipe (per liter fermentation medium):

[0585] The medium was generated using the following components per liter fermentation medium: K₂HPO₄ 7.5 g, MgSO₄ * 7H₂O 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in diH₂O. This solution was autoclaved. The

pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine * HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0586] The 1000X modified trace metal solution was generated using the following components: citric acids * H₂O 40 g, MnSO₄ * H₂O 30 g, NaCl 10 g, FeSO₄ * 7H₂O 1 g, CoCl₂ * 6H₂O 1 g, ZnSO * 7H₂O 1 g, CuSO₄ * 5H₂O 100 mg, H₃BO₃ 100 mg, and NaMoO₄ * 2H₂O 100 mg. Each component was dissolved one at a time in diH₂O, pH to 3.0 with HCl/NaOH, then q.s. to volume, and filter sterilized with a 0.22 micron filter.

[0587] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the pCL PtrcUpperPathway (Figure 26) and pTrcKKDyIkIS plasmids. This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into soytone-yeast extract-glucose medium. After the inoculum grew to OD 1.0 when measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0588] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 54 hour fermentation was 3.7 kg. Induction was achieved by adding isopropyl-beta-D-1-thiogalactopyranoside (IPTG). The IPTG concentration was brought to 25 µM when the optical density at 550 nm (OD₅₅₀) reached a value of 10. The IPTG concentration was raised to 50 µM when OD₅₅₀ reached 190. IPTG concentration was raised to 100 µM at 38 hours of fermentation. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 54. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 2.2 g/L (Fig. 55). The total amount of isoprene produced during the 54 hour fermentation was 15.9 g, and the time course of production is shown in Fig. 56.

XI. Isoprene fermentation from *E. coli* expressing genes from the mevalonic acid pathway and grown in fed-batch culture at the 15-L scale

[0589] A 15-L scale fermentation of *E. coli* expressing mevalonic acid pathway polypeptides and Kudzu isoprene synthase was used to produce isoprene from cells in fed-batch culture. This experiment demonstrates that growing cells under glucose limiting conditions resulted in the production of 3.0 g/L of isoprene.

Medium Recipe (per liter fermentation medium):

[0590] The medium was generated using the following components per liter fermentation medium: K_2HPO_4 7.5 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in dH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine $\cdot \text{HCl}$ 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0591] The 1000X modified trace metal solution was generated using the following components: citric acids $\cdot \text{H}_2\text{O}$ 40 g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30 g, NaCl 10 g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1 g, $\text{ZnSO} \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100 mg, H_3BO_3 100 mg, and $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100 mg. Each component was dissolved one at a time in dH_2O , pH to 3.0 with HCl/NaOH , then q.s. to volume, and filter sterilized with a 0.22 micron filter.

[0592] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids. This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0593] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time, the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 59 hour fermentation was 2.2 kg.

Induction was achieved by adding IPTG. The IPTG concentration was brought to 25 μ M when the optical density at 550 nm (OD_{550}) reached a value of 10. The IPTG concentration was raised to 50 μ M when OD_{550} reached 190. The OD_{550} profile within the bioreactor over time is shown in Fig. 93. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 3.0 g/L (Fig. 94). The total amount of isoprene produced during the 59 hour fermentation was 22.8 g, and the time course of production is shown in FIG 95. The molar yield of utilized carbon that went into producing isoprene during fermentation was 2.2%. The weight percent yield of isoprene from glucose was 1.0%.

XII. Isoprene fermentation from *E. coli* expressing genes from the mevalonic acid pathway and grown in fed-batch culture at the 15-L scale

[0594] A 15-L scale fermentation of *E. coli* expressing mevalonic acid pathway polypeptides, *Pueraria lobata* isoprene synthase, and Kudzu isoprene synthase was used to produce isoprene from cells in fed-batch culture. This experiment demonstrates that growing cells under glucose limiting conditions resulted in the production of 3.3 g/L of isoprene.

i) Construction of pCLPtrcUpperPathwayHGS2

[0595] The gene encoding isoprene synthase from *Pueraria lobata* was PCR-amplified using primers NsiI-RBS-HGS F (CTTGATGCATCCTGCATTGCCCCTTAGGAGG, SEQ ID NO:88) and pTrcR (CCAGGCAAATTCTGTTTTATCAG, SEQ ID NO:89), and pTrcKKDyIkIS as a template. The PCR product thus obtained was restriction-digested with *NsiI* and *PstI* and gel-purified. The plasmid pCL PtrcUpperPathway was restriction-digested with *PstI* and dephosphorylated using rAPid alkaline phosphatase (Roche) according to manufacturer's instructions.

[0596] These DNA fragments were ligated together and the ligation reaction was transformed into *E. coli* Top10 chemically competent cells (Invitrogen), plated on L agar containing spectinomycin (50 μ g/ml) and incubated overnight at 37°C. Plasmid DNA was prepared from 6 clones using the Qiaquick Spin Mini-prep kit. The plasmid DNA was digested with restriction enzymes *EcoRV* and *MluI* to identify a clone in which the insert had the right orientation (*i.e.*, the gene oriented in the same way as the pTrc promoter).

[0597] The resulting correct plasmid was designated pCLPtrcUpperPathwayHGS2. This plasmid was assayed using the headspace assay described herein and found to produce isoprene in *E. coli* Top10, thus validating the functionality of the gene. The plasmid was transformed into BL21(LDE3) containing pTrcKKDyIkIS to yield the strain BL21/pCLPtrcUpperPathwayHGS2-pTrcKKDyIkIS. This strain has an extra copy of the isoprene synthase compared to the BL21/pCL PtrcUpperMVA and pTrc KKDyIkIS strain (Example 8, part XI). This strain also had increased expression and activity of HMGS compared to the BL21/pCL PtrcUpperMVA and pTrc KKDyIkIS strain used in Example 8, part XI.

ii) Isoprene fermentation from *E. coli* expressing pCLPtrcUpperPathwayHGS2-pTrcKKDyIkIS and grown in fed-batch culture at the 15-L scale

Medium Recipe (per liter fermentation medium):

[0598] The medium was generated using the following components per liter fermentation medium: K_2HPO_4 7.5 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in diH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine * HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0599] The 1000X modified trace metal solution was generated using the following components: citric acids * H_2O 40 g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30 g, NaCl 10 g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1 g, $\text{ZnSO} \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100 mg, H_3BO_3 100 mg, and $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100 mg. Each component is dissolved one at a time in $\text{Di H}_2\text{O}$, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with 0.22 micron filter.

[0600] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the pCLPtrcUpperPathwayHGS2 and pTrc KKDyIkIS plasmids. This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single

colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0 measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0601] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 58 hour fermentation was 2.1 kg. Induction was achieved by adding IPTG. The IPTG concentration was brought to 25 μ M when the optical density at 550 nm (OD₅₅₀) reached a value of 9. The IPTG concentration was raised to 50 μ M when OD₅₅₀ reached 170. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 104. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 3.3 g/L (Fig. 105). The total amount of isoprene produced during the 58 hour fermentation was 24.5 g and the time course of production is shown in Fig. 106. The molar yield of utilized carbon that went into producing isoprene during fermentation was 2.5%. The weight percent yield of isoprene from glucose was 1.2%. Analysis showed that the activity of the isoprene synthase was increased by approximately 3-4 times that compared to BL21 expressing CL PtrcUpperMVA and pTrc KKDyIkIS plasmids (data not shown).

XIII. Chromosomal Integration of the Lower Mevalonate Pathway in *E. coli*.

[0602] A synthetic operon containing mevalonate kinase, mevalonate phosphate kinase, mevalonate pyrophosphate decarboxylase, and the IPP isomerase was integrated into the chromosome of *E. coli*. If desired, expression may be altered by integrating different promoters 5' of the operon.

[0603] Table 4 lists primers used for this experiment.

Table 4. Primers

MCM78	attTn7 up rev for integration construct	gcattgctcgagcggccgcTTTTAATCAAACATCCTGCCAA CTC (SEQ ID NO:91)
MCM79	attTn7 down rev for integration construct	gatcgaagggcgatcgTGTCACAGTCTGGCGAAACCG (SEQ ID NO:92)
MCM88	attTn7 up forw for integration construct	ctgaattctgcagatattTGTTTTTCCACTCTTCGTTCACTT T (SEQ ID NO:93)
MCM89	attTn7 down forw for	tctagagggcccAAGAAAAATGCCCCGCTTACG (SEQ

	integration construct	ID NO:94)
MCM104	GI1.2 promoter – MVK	Gatcgcgccgcccgttgacgatgccacatcctgagcaaataattcaaccac taattgtgagcggataacacaaggaggaaacagctatgtcattaccgttcttaact tc (SEQ ID NO:95)
MCM105	aspA terminator – yIDI	Gatcggggccccaagaaaaaaggcacgtcatctgacgtgcctttttattttaga cgcggtgttatagcattcta (SEQ ID NO:96)
MCM120	Forward of attTn7: attTn7 homology, GB marker homology	aaagtagccgaagatgacggtttgtcacatggagtggcaggatgtttgattaaa agcAATTAACCCTCACTAAAGGGCGG (SEQ ID NO:97)
MCM127	Rev complement of 1.2 GI: GB marker homology(extra long), promoter, RBS, ATG	AGAGTGTTCACCAAAAATAATAACCTTTCCCGG TGCAGAagttaagaacggtaatgacatagctgttcctccttgtgttatccgct cacaattagtgggtgaattattgtctcaggatgtggcatcgtcaagggcTAAT ACGACTCACTATAGGGCTCG (SEQ ID NO:98)

i) Target vector construction

[0604] The attTn7 site was selected for integration. Regions of homology upstream (attTn7 up) (primers MCM78 and MCM79) and downstream (attTn7 down) (primers MCM88 and MCM89) were amplified by PCR from MG1655 cells. A 50 μ L reaction with 1 μ L 10 μ M primers, 3 μ L ddH₂O, 45 μ L Invitrogen Platinum PCR Supermix High Fidelity, and a scraped colony of MG1655 was denatured for 2:00 at 94°C, cycled 25 times (2:00 at 94°C, 0:30 at 50°C, and 1:00 at 68°C), extended for 7:00 at 72°C, and cooled to 4°C. This resulting DNA was cloned into pCR2.1 (Invitrogen) according to the manufacturer's instructions, resulting in plasmids MCM278 (attTn7 up) and MCM252 (attTn7 down). The 832bp *ApaI-PvuI* fragment digested and gel purified from MCM252 was cloned into *ApaI-PvuI* digested and gel purified plasmid pR6K, creating plasmid MCM276. The 825bp *PstI-NotI* fragment digested and gel purified from MCM278 was cloned into *PstI-NotI* digested and gel purified MCM276, creating plasmid MCM281.

ii) Cloning of lower pathway and promoter

[0605] MVK-PMK-MVD-IDI genes were amplified from pTrcKKDyIkIS with primers MCM104 and MCM105 using Roche Expand Long PCR System according to the

manufacturer's instructions. This product was digested with *NotI* and *ApaI* and cloned into MCM281 which had been digested with *NotI* and *ApaI* and gel purified. Primers MCM120 and MCM127 were used to amplify CMR cassette from the GeneBridges FRT-gb2-Cm-FRT template DNA using Stratagene Pfu Ultra II. A PCR program of denaturing at 95°C for 4:00, 5 cycles of 95°C for 0:20, 55°C for 0:20, 72°C for 2:00, 25 cycles of 95°C for 0:20, 58°C for 0:20, 72°C for 2:00, 72°C for 10:00, and then cooling to 4°C was used with four 50µL PCR reactions containing 1µL ~10ng/µL template, 1µL each primer, 1.25 µL 10mM dNTPs, 5µL 10x buffer, 1µL enzyme, and 39.75µL ddH₂O. Reactions were pooled, purified on a Qiagen PCR cleanup column, and used to electroporate water-washed Pir1 cells containing plasmid MCM296. Electroporation was carried out in 2mM cuvettes at 2.5V and 200 ohms. Electroporation reactions were recovered in LB for 3hr at 30°C. Transformant MCM330 was selected on LA with CMP5, Kan50 (Figures 107 and 108A-108C).

iii) Integration into *E. coli* chromosome

[0606] Miniprep DNA (Qiaquick Spin kit) from MCM330 was digested with *SnaBI* and used to electroporate BL21(DE3) (Novagen) or MG1655 containing GeneBridges plasmid pRedET Carb. Cells were grown at 30°C to ~OD1 then induced with 0.4% L-arabinose at 37°C for 1.5 hours. These cells were washed three times in 4°C ddH₂O before electroporation with 2µL of DNA. Integrants were selected on L agar with containing chloramphenicol (5 µg/ml) and subsequently confirmed to not grow on L agar + Kanamycin (50 µg/ml). BL21 integrant MCM331 and MG1655 integrant MCM333 were frozen.

iv) Construction of pET24D-Kudzu encoding Kudzu isoprene synthase

[0607] The kudzu isoprene synthase gene was subcloned into the pET24d vector (Novagen) from the pCR2.1 vector (Invitrogen). In particular, the kudzu isoprene synthase gene was amplified from the pTrcKudzu template DNA using primers MCM50 5'-GATCATGCAT TCGCCCTTAG GAGGTAAAAA AACATGTGTG CGACCTCTTC TCAATTTACT (SEQ ID NO:99) and MCM53 5'-CGGTGACGG ATCCCTGCAG TTAGACATAC ATCAGCTG (SEQ ID NO:100). PCR reactions were carried out using Taq DNA Polymerase (Invitrogen), and the resulting PCR product was cloned into pCR2.1-TOPO TA cloning vector (Invitrogen), and transformed into *E. coli* Top10 chemically competent cells (Invitrogen). Transformants were plated on L agar containing carbenicillin (50 µg/ml) and incubated overnight at 37°C. Five ml Luria Broth cultures containing carbenicillin 50

μg/ml were inoculated with single transformants and grown overnight at 37°C. Five colonies were screened for the correct insert by sequencing of plasmid DNA isolated from 1 ml of liquid culture (Luria Broth) and purified using the QIAprep Spin Mini-prep Kit (Qiagen). The resulting plasmid, designated MCM93, contains the kudzu isoprene synthase coding sequence in a pCR2.1 backbone.

[0608] The kudzu coding sequence was removed by restriction endonuclease digestion with *PciI* and *BamHI* (Roche) and gel purified using the QIAquick Gel Extraction kit (Qiagen). The pET24d vector DNA was digested with *NcoI* and *BamHI* (Roche), treated with shrimp alkaline phosphatase (Roche), and purified using the QIAprep Spin Mini-prep Kit (Qiagen). The kudzu isoprene synthase fragment was ligated to the *NcoI/BamHI* digested pET24d using the Rapid DNA Ligation Kit (Roche) at a 5:1 fragment to vector ratio in a total volume of 20 μl. A portion of the ligation mixture (5 μl) was transformed into *E. coli* Top 10 chemically competent cells and plated on L agar containing kanamycin (50 μg/ml). The correct transformant was confirmed by sequencing and transformed into chemically competent BL21(λDE3)pLysS cells (Novagen). A single colony was selected after overnight growth at 37°C on L agar containing kanamycin (50 μg/ml). A map of the resulting plasmid designated as pET24D-Kudzu is shown in Figure 109. The sequence of pET24D-Kudzu (SEQ ID NO:101) is shown in Figures 110A and 110B. Isoprene synthase activity was confirmed using a headspace assay.

v) Production strains

[0609] Strains MCM331 and MCM333 were cotransformed with plasmids pCLP|upperpathway and either pTrcKudzu or pETKudzu, resulting in the strains shown in Table 5.
| |

Table 5. Production Strains

Background	Integrated Lower	Upper MVA plasmid	Isoprene synthase plasmid	Production Stain
BL21(DE3)	MCM331	pCLPtrcUpper Pathway	pTrcKudzu	MCM343
BL21(DE3)	MCM331	pCLPtrcUpper Pathway	pET24D-Kudzu	MCM335
MG1655	MCM333	pCLPtrcUpper	pTrcKudzu	MCM345

		Pathway		
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vi) Isoprene fermentation from *E. coli* expressing genes from the mevalonic acid pathway and grown in fed-batch culture at the 15-L scale.

Medium Recipe (per liter fermentation medium):

[0610] The medium was generated using the following components per liter fermentation medium: K_2HPO_4 7.5 g, $MgSO_4 \cdot 7H_2O$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in diH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine $\cdot$ HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0611] The 1000X modified trace metal solution was generated using the following components: citric acids $\cdot$ H_2O 40 g, $MnSO_4 \cdot H_2O$ 30 g, NaCl 10 g, $FeSO_4 \cdot 7H_2O$ 1 g, $CoCl_2 \cdot 6H_2O$ 1 g, $ZnSO \cdot 7H_2O$ 1 g, $CuSO_4 \cdot 5H_2O$ 100 mg, H_3BO_3 100 mg, and $NaMoO_4 \cdot 2H_2O$ 100 mg. Each component is dissolved one at a time in $Di H_2O$, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with a 0.22 micron filter.

[0612] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the *gl1.2* integrated lower MVA pathway described above and the pCL P_{trc}UpperMVA and p_{Trc}Kudzu plasmids. This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0613] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time, the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 57 hour fermentation was 3.9 kg. Induction was achieved by adding IPTG. The IPTG concentration was brought to 100 μ M

when the carbon dioxide evolution rate reached 100 mmol/L/hr. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 111A. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 1.6 g/L (Fig. 111B). The specific productivity of isoprene over the course of the fermentation is shown in Fig. 111C and peaked at 1.2 mg/OD/hr. The total amount of isoprene produced during the 57 hour fermentation was 16.2 g. The molar yield of utilized carbon that went into producing isoprene during fermentation was 0.9%. The weight percent yield of isoprene from glucose was 0.4%.

XIV. Production of isoprene from *E. coli* BL21 containing the kudzu isoprene synthase using glycerol as a carbon source

[0614] A 15-L scale fermentation of *E. coli* expressing Kudzu isoprene synthase was used to produce isoprene from cells fed glycerol in fed-batch culture. This experiment demonstrates that growing cells in the presence of glycerol (without glucose) resulted in the production of 2.2 mg/L of isoprene.

Medium Recipe (per liter fermentation medium):

[0615] The medium was generated using the following components per liter fermentation medium: K₂HPO₄ 7.5 g, MgSO₄ * 7H₂O 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in diH₂O. This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glycerol 5.1 g, thiamine * HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0616] The medium was generated using the following components per liter fermentation medium: citric acids * H₂O 40 g, MnSO₄ * H₂O 30 g, NaCl 10 g, FeSO₄ * 7H₂O 1 g, CoCl₂ * 6H₂O 1 g, ZnSO * 7H₂O 1 g, CuSO₄ * 5H₂O 100 mg, H₃BO₃ 100 mg, and NaMoO₄ * 2H₂O 100 mg. Each component was dissolved one at a time in diH₂O, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with a 0.22 micron filter.

[0617] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the pTrcKudzu plasmid. This experiment was carried out to monitor isoprene

formation from glycerol at the desired fermentation pH 7.0 and temperature 35°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LA broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into soytone-yeast extract-glucose medium and grown at 35°C. After the inoculum grew to OD 1.0, measured at 550 nm, 600 mL was used to inoculate a 7.5-L bioreactor.

[0618] Glycerol was fed at an exponential rate until cells reached an optical density at 550 nm (OD₅₅₀) of 153. The total amount of glycerol delivered to the bioreactor during the 36 hour fermentation was 1.7 kg. Other than the glucose in the inoculum, no glucose was added to the bioreactor. Induction was achieved by adding IPTG. The IPTG concentration was brought to 20 µM when the OD₅₅₀ reached a value of 50. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 57. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 2.2 mg/L (Fig. 58). The total amount of isoprene produced during the 54 hour fermentation was 20.9 mg, and the time course of production is shown in Fig. 59.

XV. Isoprene fermentation from *E. coli* expressing genes from the mevalonic acid pathway and grown in fed-batch culture at the 15-L scale using invert sugar as a carbon source

[0619] A 15-L scale fermentation of *E. coli* expressing mevalonic acid pathway polypeptides and Kudzu isoprene synthase was used to produce isoprene from cells fed invert sugar in fed-batch culture. This experiment demonstrates that growing cells in the presence of invert sugar resulted in the production of 2.4 g/L of isoprene.

Medium Recipe (per liter fermentation medium):

[0620] The medium was generated using the following components per liter fermentation medium: K₂HPO₄ 7.5 g, MgSO₄ * 7H₂O 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in diH₂O. This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Invert sugar 10 g, thiamine * HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0621] The 1000X modified trace metal solution was generated using the following components: citric acids * H₂O 40 g, MnSO₄ * H₂O 30 g, NaCl 10 g, FeSO₄ * 7H₂O 1 g, CoCl₂ * 6H₂O 1 g, ZnSO * 7H₂O 1 g, CuSO₄ * 5H₂O 100 mg, H₃BO₃ 100 mg, and NaMoO₄ * 2H₂O 100 mg. Each component is dissolved one at a time in Di H₂O, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with 0.22 micron filter.

[0622] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the pCL PtrcUpperMVA and pTrc KKDYIkIS plasmids. This experiment was carried out to monitor isoprene formation from invert sugar at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0623] Invert sugar was fed at an exponential rate until cells reached the stationary phase. After this time the invert sugar feed was decreased to meet metabolic demands. The total amount of invert sugar delivered to the bioreactor during the 44 hour fermentation was 2.4 kg. Induction was achieved by adding IPTG. The IPTG concentration was brought to 25 µM when the optical density at 550 nm (OD₅₅₀) reached a value of 9. The IPTG concentration was raised to 50 µM when OD₅₅₀ reached 200. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 96. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 2.4 g/L (Fig. 97). The total amount of isoprene produced during the 44 hour fermentation was 18.4 g and the time course of production is shown in Fig. 98. The molar yield of utilized carbon that went into producing isoprene during fermentation was 1.7%. The weight percent yield of isoprene from glucose was 0.8%.

Example 9. Construction of the upper and lower MVA pathway for integration into *Bacillus subtilis*

I. Construction of the Upper MVA pathway in *Bacillus subtilis*

[0624] The upper pathway from *Enterococcus faecalis* is integrated into *B. subtilis* under control of the *aprE* promoter. The upper pathway consists of two genes; *mvaE*, which

encodes for AACT and HMGR, and *mvaS*, which encodes for HMGS. The two genes are fused together with a stop codon in between, an RBS site in front of *mvaS*, and are under the control of the *aprE* promoter. A terminator is situated after the *mvaE* gene. The chloramphenicol resistance marker is cloned after the *mvaE* gene and the construct is integrated at the *aprE* locus by double cross over using flanking regions of homology.

[0625] Four DNA fragments are amplified by PCR such that they contain overhangs that will allow them to be fused together by a PCR reaction. PCR amplifications are carried out using Herculase polymerase according to manufacturer's instructions.

1: PaprE

CF 07-134 (+) Start of *aprE* promoter PstI

5'- GACATCTGCAGCTCCATTTTCTTCTGC (SEQ ID NO:82)

CF 07-94 (-) Fuse PaprE to *mvaE*

5'- CAATAATAACTACTGTTTTCACTCTTTACCCTCTCCTTTTAA (SEQ ID NO:83)

Template: *Bacillus subtilis* chromosomal DNA

2: *mvaE*

CF 07-93 (+) fuse *mvaE* to the *aprE* promoter (GTG start codon)

5'- TTAAAAGGAGAGGGTAAAGAGTGAAAACAGTAGTTATTATTG (SEQ ID NO:84)

CF 07-62 (-) Fuse *mvaE* to *mvaS* with RBS in between

5'- TTTATCAATCCCAATTGTCATGTTTTTTTACCTCCTTTATTGTTTTCTTAAATC
(SEQ ID NO:35)

Template: *Enterococcus faecalis* chromosomal DNA (from ATCC)

3. *mvaS*

CF 07-61 (+) Fuse *mvaE* to *mvaS* with RBS in between

5'-

GATTTAAGAAAACAATAAAGGAGGTAAAAAACATGACAATTGGGATTGATAAA
(SEQ ID NO:36)

CF 07-124 (-) Fuse the end of *mvaS* to the terminator

5'- CGGGGCCAAGGCCGGTTTTTTTTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:85)

Template: *Enterococcus faecalis* chromosomal DNA

4. *B. amyliquefaciens* alkaline serine protease terminator

CF 07-123 (+) Fuse the end of *mvaS* to the terminator

5'- ACCGTTTCGTTCTTATCGAACTAAAAAAAACCGGCCTTGGCCCCG (SEQ ID NO:86)

CF 07-46 (-) End of *B. amyliquefaciens* terminator BamHI

5'- GACATGACGGATCCGATTACGAATGCCGTCTC (SEQ ID NO:63)

Template: *Bacillus amyliquefaciens* chromosomal DNA

PCR Fusion Reactions

5. Fuse *mvaE* to *mvaS*

CF 07-93 (+) fuse *mvaE* to the *aprE* promoter (GTG start codon)

5'- TTAAAGGAGAGGGTAAAGAGTGAAAACAGTAGTTATTATTG (SEQ ID NO:84)

CF 07-124 (-) Fuse the end of *mvaS* to the terminator

5'- CGGGGCCAAGGCCGGTTTTTTTTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:85)

Template: #2 and 3 from above

6. Fuse *mvaE-mvaS* to *aprE* promoter

CF 07-134 (+) Start of *aprE* promoter PstI

5'- GACATCTGCAGCTCCATTTTCTTCTGC (SEQ ID NO:82)

CF 07-124 (-) Fuse the end of *mvaS* to the terminator

5'-CGGGGCCAAGGCCGGTTTTTTTTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:85)

Template #1 and #4 from above

7. Fuse *PaprE-mvaE-mvaS* to terminator

CF 07-134 (+) Start of *aprE* promoter *Pst*I

5'-GACATCTGCAGCTCCATTTTCTTCTGC (SEQ ID NO:82)

CF 07-46 (-) End of *B. amyliquefaciens* terminator *Bam*HI

5'-GACATGACGGATCCGATTACGAATGCCGTCTC (SEQ ID NO:63)

Template: #4 and #6

[0626] The product is digested with restriction endonucleases *Pst*I/*Bam*HI and ligated to pJM102 (Perego, M. 1993. Integrational vectors for genetic manipulation in *Bacillus subtilis*, p. 615–624. In A. L. Sonenshein, J. A. Hoch, and R. Losick (ed.), *Bacillus subtilis* and other gram-positive bacteria: biochemistry, physiology, and molecular genetics. American Society for Microbiology, Washington, D.C.) which is digested with *Pst*I/*Bam*HI. The ligation is transformed into *E.coli* TOP 10 chemically competent cells and transformants are selected on LA containing carbenicillin (50 µg/ml). The correct plasmid is identified by sequencing and is designated pJMUppperpathway2 (Figures 50 and 51). Purified plasmid DNA is transformed into *Bacillus subtilis aprEnprE Pxyl-comK* and transformants are selected on L agar containing chloramphenicol (5 µg/ml). A correct colony is selected and is plated sequentially on L agar containing chloramphenicol 10, 15 and 25 µg/ml to amplify the number of copies of the cassette containing the upper pathway.

[0627] The resulting strain is tested for mevalonic acid production by growing in LB containing 1% glucose and 1%. Cultures are analyzed by GC for the production of mevalonic acid.

[0628] This strain is used subsequently as a host for the integration of the lower mevalonic acid pathway.

[0629] The following primers are used to sequence the various constructs above.

Sequencing primers:

CF 07-134 (+) Start of *aprE* promoter PstI

5'- GACATCTGCAGCTCCATTTTCTTCTGC (SEQ ID NO:82)

CF 07-58 (+) Start of *mvaE* gene

5'- ATGAAAACAGTAGTTATTATTGATGC (SEQ ID NO:38)

CF 07-59 (-) End of *mvaE* gene

5'- ATGTTATTGTTTTCTTAAATCATTTAAAATAGC (SEQ ID NO:39)

CF 07-82 (+) Start of *mvaS* gene

5'- ATGACAATTGGGATTGATAAAATTAG (SEQ ID NO:40)

CF 07-83 (-) End of *mvaS* gene

5'- TTAGTTTCGATAAGAACGAACGGT (SEQ ID NO:41)

CF 07-86 (+) Sequence in *mvaE*

5'- GAAATAGCCCCATTAGAAGTATC (SEQ ID NO:42)

CF 07-87 (+) Sequence in *mvaE*

5'- TTGCCAATCATATGATTGAAAATC (SEQ ID NO:43)

CF 07-88 (+) Sequence in *mvaE*

5'- GCTATGCTTCATTAGATCCTTATCG (SEQ ID NO:44)

CF 07-89 (+) Sequence *mvaS*

5'- GAAACCTACATCCAATCTTTTGCCC (SEQ ID NO:45)

[0630] Transformants are selected on LA containing chloramphenicol at a concentration of 5 µg/ml. One colony is confirmed to have the correct integration by sequencing and is plated on LA containing increasing concentrations of chloramphenicol over several days, to a final

level of 25 µg/ml. This results in amplification of the cassette containing the genes of interest. The resulting strain is designated CF 455: pJMupperpathway#1 X *Bacillus subtilis* *aprEnprE* Pxyl *comK* (amplified to grow on LA containing chloramphenicol 25 µg/ml).

II. Construction of the Lower MVA pathway in *Bacillus subtilis*

[0631] The lower MVA pathway, consisting of the genes *mvk1*, *pmk*, *mpd* and *idi* are combined in a cassette consisting of flanking DNA regions from the *nprE* region of the *B. subtilis* chromosome (site of integration), the *aprE* promoter, and the spectinomycin resistance marker (see Figures 28 and 29). This cassette is synthesized by DNA2.0 and is integrated into the chromosome of *B. subtilis* containing the upper MVA pathway integrated at the *aprE* locus. The kudzu isoprene synthase gene is expressed from the replicating plasmid described in Example 4 and is transformed into the strain with both upper and lower pathways integrated.

Example 10: Exemplary isoprene compositions and methods of making them

I. Compositional analysis of fermentation off-gas containing isoprene

[0632] A 14 L scale fermentation was performed with a recombinant *E. coli* BL21 (DE3) strain containing two plasmids (pCL upperMev; pTrcKKDyIkIS encoding the full mevalonate pathway for isoprenoid precursor biosynthesis, an isoprenyl pyrophosphate isomerase from yeast, and an isoprene synthase from Kudzu. Fermentation off-gas from the 14 L tank was collected into 20 mL headspace vials at around the time of peak isoprene productivity (27.9 hours elapsed fermentation time, “EFT”) and analyzed by headspace GC/MS for volatile components.

[0633] Headspace analysis was performed with an Agilent 6890 GC/MS system fitted with an Agilent HP-5MS GC/MS column (30 m x 250 µm; 0.25 µm film thickness). A combiPAL autoinjector was used for sampling 500 µL aliquots from 20 mL headspace vials. The GC/MS method utilized helium as the carrier gas at a flow of 1 mL/min. The injection port was held at 250 °C with a split ratio of 50:1. The oven temperature was held at 37 °C for an initial 2 minute period, followed an increase to 237 °C at a rate of 25 °C/min for a total method time of 10 minutes. The Agilent 5793N mass selective detector scanned from m/z 29 to m/z 300. The limit of detection of this system is approximately 0.1 µg/L_{gas} or

approximately 0.1 ppm. If desired, more sensitive equipment with a lower limit of detection may be used.

[0634] The off-gas consisted of 99.925 % (v/v) permanent gases (N₂, CO₂ and O₂), approximately 0.075% isoprene (2-methyl-1,3-butadiene) (~750 ppmv, 2100 µg/L) and minor amounts (<50 ppmv) of ethanol, acetone, and two C5 prenyl alcohols. The amount of water vapor was not determined but was estimated to be equal to the equilibrium vapor pressure at 0 °C. The composition of the volatile organic fraction was determined by integration of the area under the peaks in the GC/MS chromatogram (Figs. 86A and 86B) and is listed in Table 6. Calibration curves for ethanol and acetone standards enabled the conversion of GC area to gas phase concentration in units of µg/L using standard methods.

Table 6. Composition of volatile organic components in fermentation off-gas. The off-gas was analyzed at the 27.9 hour time point of a fermentation using an *E. coli* BL21 (DE3) strain expressing a heterologous mevalonate pathway, an isoprenyl pyrophosphate isomerase from yeast, and an isoprene synthase from Kudzu.

<i>Compound</i>	<i>RT (min)</i>	<i>GC area</i>	<i>Area %</i>	<i>Conc. (µg/L)</i>
Ethanol	1.669	239005	0.84	62 +/- 6
Acetone	1.703	288352	1.02	42 +/- 4
Isoprene (2-methyl-1,3-butadiene)	1.829	27764544	97.81	2000 +/- 200
3-methyl-3-buten-1-ol	3.493	35060	0.12	<10
3-methyl-2-buten-1-ol	4.116	58153	0.20	<10

II. Measurement of trace volatile organic compounds (VOCs) co-produced with isoprene during fermentation of a recombinant *E. coli* strain

[0635] A 14 L scale fermentation was performed with a recombinant *E. coli* BL21 (DE3) strain containing two plasmids (pCL upperMev; pTrcKKDyIkIS) encoding the full mevalonate pathway for isoprenoid precursor biosynthesis, an isoprenyl pyrophosphate isomerase from yeast, and an isoprene synthase from Kudzu.

[0636] Fermentation off-gas was passed through cooled headspace vials in order to concentrate and identify trace volatile organic components. The off-gas from this fermentation was sampled at a rate of 1 L/min for 10 minutes through a 20 mL headspace vial packed with quartz wool (2g) and cooled to -78 °C with dry ice. The vial was recapped with a fresh vial cap and analyzed by headspace GC/MS for trapped VOCs using the conditions

described in Example 10, part I. The ratios of compounds observed in Figs. 87A-87D are a combination of overall level in the fermentation off-gas, the relative vapor pressure at -78 °C, and the detector response of the mass spectrometer. For example, the low level of isoprene relative to oxygenated volatiles (*e.g.*, acetone and ethanol) is a function of the high volatility of this material such that it does not accumulate in the headspace vial at -78 °C.

[0637] The presence of many of these compounds is unique to isoprene compositions derived from biological sources. The results are depicted in Figs. 87A-87D and summarized in Tables 7A and 7B.

Table 7A: Trace volatiles present in off-gas produced by *E. coli* BL21 (DE3) (pCL upperMev; pTrcKKDyIkIS) following cryo-trapping at -78°C.

<i>Compound</i>	<i>RT (min)</i>	<i>GC Area¹</i>	<i>Area%²</i>	<i>Ratio%³</i>
Acetaldehyde	1.542	4019861	4.841	40.14
Ethanol	1.634	10553620	12.708	105.39
Acetone	1.727	7236323	8.714	72.26
2-methyl-1,3-butadiene	1.777	10013714	12.058	100.00
1-propanol	1.987	163574	0.197	1.63
Diacetyl	2.156	221078	0.266	2.21
2-methyl-3-buten-2-ol	2.316	902735	1.087	9.01
2-methyl-1-propanol	2.451	446387	0.538	4.46
3-methyl-1-butanal	2.7	165162	0.199	1.65
1-butanol	2.791	231738	0.279	2.31
3-methyl-3-buten-1-ol	3.514	14851860	17.884	148.32
3-methyl-1-butanol	3.557	8458483	10.185	84.47
3-methyl-2-buten-1-ol	4.042	18201341	21.917	181.76
3-methyl-2-butenal	4.153	1837273	2.212	18.35
3-methylbutyl acetate	5.197	196136	0.236	1.96
3-methyl-3-buten-1-yl acetate	5.284	652132	0.785	6.51
2-heptanone	5.348	67224	0.081	0.67
2,5-dimethylpyrazine	5.591	58029	0.070	0.58
3-methyl-2-buten-1-yl acetate	5.676	1686507	2.031	16.84
6-methyl-5-hepten-2-one	6.307	101797	0.123	1.02
2,4,5-trimethylpyridine	6.39	68477	0.082	0.68
2,3,5-trimethylpyrazine	6.485	30420	0.037	0.30
(E)-3,7-dimethyl-1,3,6-octatriene	6.766	848928	1.022	8.48
(Z)-3,7-dimethyl-1,3,6-octatriene	6.864	448810	0.540	4.48
3-methyl-2-buten-1-yl butyrate	7.294	105356	0.127	1.05
Citronellal	7.756	208092	0.251	2.08
2,3-cycloheptenolpyridine	8.98	1119947	1.349	11.18

¹ GC area is the uncorrected area under the peak corresponding to the listed compound.

² Area % is the peak area expressed as a % relative to the total peak area of all compounds.

³ Ratio % is the peak area expressed as a % relative to the peak area of 2-methyl-1,3-butadiene.

Table 7B. Trace volatiles present in off-gas produced by *E. coli* BL21 (DE3) (pCL

upperMev; pTrcKKDyIkIS) following cryo-trapping at -196°C.

<i>Compound</i>	<i>RT (min)</i>	<i>GC Area¹</i>	<i>Area%²</i>	<i>Ratio%³</i>
Acetaldehyde	1.54	1655710	0.276	0.33
Methanethiol	1.584	173620	0.029	0.03
Ethanol	1.631	10259680	1.707	2.03
Acetone	1.722	73089100	12.164	14.43
2-methyl-1,3-butadiene	1.771	506349429	84.269	100.00
methyl acetate	1.852	320112	0.053	0.06
1-propanol	1.983	156752	0.026	0.03
Diacetyl	2.148	67635	0.011	0.01
2-butanone	2.216	254364	0.042	0.05
2-methyl-3-buten-2-ol	2.312	684708	0.114	0.14
ethyl acetate	2.345	2226391	0.371	0.44
2-methyl-1-propanol	2.451	187719	0.031	0.04
3-methyl-1-butanal	2.696	115723	0.019	0.02
3-methyl-2-butanone	2.751	116861	0.019	0.02
1-butanol	2.792	54555	0.009	0.01
2-pentanone	3.034	66520	0.011	0.01
3-methyl-3-buten-1-ol	3.516	1123520	0.187	0.22
3-methyl-1-butanol	3.561	572836	0.095	0.11
ethyl isobutyrate	3.861	142056	0.024	0.03
3-methyl-2-buten-1-ol	4.048	302558	0.050	0.06
3-methyl-2-butenal	4.152	585690	0.097	0.12
butyl acetate	4.502	29665	0.005	0.01
3-methylbutyl acetate	5.194	271797	0.045	0.05
3-methyl-3-buten-1-yl acetate	5.281	705366	0.117	0.14
3-methyl-2-buten-1-yl acetate	5.675	815186	0.136	0.16
(E)-3,7-dimethyl-1,3,6-octatriene	6.766	207061	0.034	0.04
(Z)-3,7-dimethyl-1,3,6-octatriene	6.863	94294	0.016	0.02
2,3-cycloheptenolpyridine	8.983	135104	0.022	0.03

¹ GC area is the uncorrected area under the peak corresponding to the listed compound.

² Area % is the peak area expressed as a % relative to the total peak area of all compounds.

³ Ratio % is the peak area expressed as a % relative to the peak area of 2-methyl-1,3-butadiene.

III. Absence of C5 hydrocarbon isomers in isoprene derived from fermentation.

[0638] Cryo-trapping of isoprene present in fermentation off-gas was performed using a 2 mL headspace vial cooled in liquid nitrogen. The off-gas (1 L/min) was first passed through a 20 mL vial containing sodium hydroxide pellets in order to minimize the accumulation of ice and solid CO₂ in the 2 mL vial (-196 °C). Approximately 10L of off-gas was passed through the vial, after which it was allowed to warm to -78 °C with venting, followed by resealing with a fresh vial cap and analysis by GC/MS.

[0639] GC/MS headspace analysis was performed with an Agilent 6890 GC/MS system using a 100µL gas tight syringe in headspace mode. A Zebron ZB-624 GC/MS column (30

m x 250 μ m; 1.40 μ m film thickness) was used for separation of analytes. The GC autoinjector was fitted with a gas-tight 100 μ L syringe, and the needle height was adjusted to allow the injection of a 50 μ L headspace sample from a 2 mL GC vial. The GC/MS method utilized helium as the carrier gas at a flow of 1 mL/min. The injection port was held at 200 °C with a split ratio of 20:1. The oven temperature was held at 37 °C for the 5 minute duration of the analysis. The Agilent 5793N mass selective detector was run in single ion monitoring (SIM) mode on m/z 55, 66, 67 and 70. Under these conditions, isoprene was observed to elute at 2.966 minutes (Fig. 88B). A standard of petroleum derived isoprene (Sigma-Aldrich) was also analyzed using this method and was found to contain additional C5 hydrocarbon isomers, which eluted shortly before or after the main peak and were quantified based on corrected GC area (Fig. 88A).

Table 8A: GC/MS analysis of petroleum-derived isoprene

<i>Compound</i>	<i>RT (min)</i>	<i>GC area</i>	<i>Area % of total C5 hydrocarbons</i>
2-methyl-1-butene	2.689	18.2 x 10 ³	0.017%
(Z)-2-pentene	2.835	10.6x 10 ⁴	0.101%
Isoprene	2.966	10.4x 10 ⁷	99.869%
1,3-cyclopentadiene (CPD)	3.297	12.8 x 10 ³	0.012%

Table 8B: GC/MS analysis of fermentation-derived isoprene (% total C5 hydrocarbons)

<i>Compound</i>	<i>RT (min)</i>	<i>Corrected GC Area</i>	<i>% of total C5 hydrocarbons</i>
Isoprene	2.966	8.1 x 10 ⁷	100%

[0640] In a separate experiment, a standard mixture of C5 hydrocarbons was analyzed to determine if the detector response was the same for each of the compounds. The compounds were 2-methyl-1-butene, 2-methyl-1,3-butadiene, (E)-2-pentene, (Z)-2-pentene and (E)-1,3-pentadiene. In this case, the analysis was performed on an Agilent DB-Petro column (100 m x 0.25 mm, 0.50 μ m film thickness) held at 50 °C for 15 minutes. The GC/MS method utilized helium as the carrier gas at a flow of 1 mL/min. The injection port was held at 200 °C with a split ratio of 50:1. The Agilent 5793N mass selective detector was run in full scan mode from m/z 19 to m/z 250. Under these conditions, a 100 μ g/L concentration of each standard produced the same detector response within experimental error.

IV. Compositions comprising isoprene adsorbed to a solid phase.

[0641] Biologically-produced isoprene was adsorbed to activated carbon resulting in a solid phase containing 50 to 99.9% carbon, 0.1% to 50% isoprene, 0.01% to 5% water, and minor amounts (<0.1%) of other volatile organic components.

[0642] Fermentation off-gas was run through a copper condensation coil held at 0 °C, followed by a granulated silica desiccant filter in order to remove water vapor. The dehumidified off-gas was then run through carbon containing filters (Koby Jr, Koby Filters, MA) to the point at which breakthrough of isoprene was detected in the filter exhaust by GC/MS. The amount of isoprene adsorbed to the cartridge can be determined indirectly by calculating the concentration in the off-gas, the overall flow rate and the percent breakthrough over the collection period. Alternately the adsorbed isoprene can be recovered from the filters by thermal, vacuum, or solvent-mediated desorption.

V. Collection and analysis of condensed isoprene.

[0643] Fermentation off-gas is dehumidified, and the CO₂ removed by filtration through a suitable adsorbant (*e.g.*, ascarite). The resulting off-gas stream is then run through a liquid nitrogen-cooled condenser in order to condense the VOCs in the stream. The collection vessel contains *t*-butyl catechol to inhibit the resulting isoprene condensate. The condensate is analyzed by GC/MS and NMR in order to determine purity using standard methods, such as those described herein.

VI. Production of prenyl alcohols by fermentation

[0644] Analysis of off-gas from an *E. coli* BL21 (DE3) strain expressing a Kudzu isoprene synthase revealed the presence of both isoprene and 3-methyl-3-buten-1-ol (isoprenol). The levels of the two compounds in the fermentation off-gas over the fermentation are shown in Fig. 89 as determined by headspace GC/MS. Levels of isoprenol (3-methyl-3-buten-1-ol, 3-MBA) attained was nearly 10 µg/L_{offgas} in this experiment. Additional experiments produced levels of approximately 20 µg/L_{offgas} in the fermentation off-gas.

Example 11: The de-coupling of growth and production of isoprene in *E. coli* expressing genes from the mevalonic acid pathway and fermented in a fed-batch culture

[0645] Example 11 illustrates the de-coupling of cell growth from mevalonic acid and isoprene production.

I. Fermentation Conditions

Medium Recipe (per liter fermentation medium):

[0646] The medium was generated using the following components per liter fermentation medium: K_2HPO_4 7.5 g, $MgSO_4 \cdot 7H_2O$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in diH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine $\cdot HCl$ 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0647] The 1000X modified trace metal solution was generated using the following components: citric acids $\cdot H_2O$ 40 g, $MnSO_4 \cdot H_2O$ 30 g, NaCl 10 g, $FeSO_4 \cdot 7H_2O$ 1 g, $CoCl_2 \cdot 6H_2O$ 1 g, $ZnSO \cdot 7H_2O$ 1 g, $CuSO_4 \cdot 5H_2O$ 100 mg, H_3BO_3 100 mg, and $NaMoO_4 \cdot 2H_2O$ 100 mg. Each component was dissolved one at a time in $Di H_2O$, pH to 3.0 with $HCl/NaOH$, then q.s. to volume, and filter sterilized with a 0.22 micron filter.

[0648] Fermentation was performed with *E. coli* cells containing the pTrcHis2AUpperPathway (also called pTrcUpperMVA, FIGs. 91 and 92A-92C) (50 $\mu g/ml$ carbenicillin) or the pCL PtrcUpperMVA (also called pCL PtrcUpperPathway (Fig. 26)) (50 $\mu g/ml$ spectinomycin) plasmids. For experiments in which isoprene was produced, the *E. coli* cells also contained the pTrc KKDyIkIS (50 $\mu g/ml$ kanamycin) plasmid. These experiments were carried out to monitor mevalonic acid or isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of an *E. coli* strain taken from a frozen vial was streaked onto an LA broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to optical density 1.0 when measured at 550 nm, it was used to inoculate the bioreactor.

[0649] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. Induction was achieved by adding IPTG. The mevalonic acid concentration in fermentation broth was determined by applying perchloric acid (Sigma-Aldrich # 244252) treated samples (0.3 M incubated at 4°C for 5 minutes) to an organic acids HPLC column (BioRad # 125-0140). The concentration was determined by comparing the broth mevalonic acid peak size to a calibration curve generated from mevalonolactone (Sigma-Aldrich # M4667) treated with perchloric acid to form D,L-mevalonate. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer is defined as the amount of isoprene produced per liter of fermentation broth.

II. Mevalonic acid production from *E. coli* BL21 (DE3) cells expressing the pTrcUpperMVA plasmid at a 150-L scale

[0650] BL21 (DE3) cells that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 45 mL of tryptone-yeast extract medium and incubated at 30°C with shaking at 170 rpm for 5 hours. This solution was transferred to a 5-L bioreactor of tryptone-yeast extract medium, and the cells were grown at 30 °C and 27.5 rpm until the culture reached an OD₅₅₀ of 1.0. The 5 L of inoculum was seeded into a 150-L bioreactor containing 45-kg of medium. The IPTG concentration was brought to 1.1 mM when the OD₅₅₀ reached a value of 10. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 60A. The mevalonic acid titer increased over the course of the fermentation to a final value of 61.3 g/L (Fig. 60B). The specific productivity profile throughout the fermentation is shown in Fig. 60C and a comparison to Fig. 60A illustrates the de-coupling of growth and mevalonic acid production. The total amount of mevalonic acid produced during the 52.5 hour fermentation was 4.0 kg from 14.1 kg of utilized glucose. The molar yield of utilized carbon that went into producing mevalonic acid during fermentation was 34.2%.

III. Mevalonic acid production from *E. coli* BL21 (DE3) cells expressing the pTrcUpperMVA plasmid at a 15-L scale

[0651] BL21 (DE3) cells that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 1.0 mM when the

OD₅₅₀ reached a value of 10. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 61A. The mevalonic acid titer increased over the course of the fermentation to a final value of 53.9 g/L (Fig. 61B). The specific productivity profile throughout the fermentation is shown in Fig. 61C and a comparison to Fig. 61A illustrates the de-coupling of growth and mevalonic acid production. The total amount of mevalonic acid produced during the 46.6 hour fermentation was 491 g from 2.1 kg of utilized glucose. The molar yield of utilized carbon that went into producing mevalonic acid during fermentation was 28.8%.

IV. Mevalonic acid production from *E. coli* FM5 cells expressing the pTrcUpperMVA plasmid at a 15-L scale

[0652] FM5 cells that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 1.0 mM when the OD₅₅₀ reached a value of 30. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 62A. The mevalonic acid titer increased over the course of the fermentation to a final value of 23.7 g/L (Fig. 62B). The specific productivity profile throughout the fermentation is shown in Fig. 62C and a comparison to Fig. 62A illustrates the de-coupling of growth and mevalonic acid production. The total amount of mevalonic acid produced during the 51.2 hour fermentation was 140 g from 1.1 kg of utilized glucose. The molar yield of utilized carbon that went into producing mevalonic acid during fermentation was 15.2%.

V. Isoprene production from *E. coli* BL21 (DE3) cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids at a 15-L scale

[0653] BL21 (DE3) cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 25 µM when the OD₅₅₀ reached a value of 10. The IPTG concentration was raised to 50 µM when OD₅₅₀ reached 190. The IPTG concentration was raised to 100 µM at 38 hours of fermentation. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 63A. The isoprene titer increased over the course of the fermentation to a final value of 2.2 g/L broth (Fig. 63B). The specific

productivity profile throughout the fermentation is shown in Fig. 63C and a comparison to Fig. 63A illustrates the de-coupling of growth and isoprene production. The total amount of isoprene produced during the 54.4 hour fermentation was 15.9 g from 2.3 kg of utilized glucose. The molar yield of utilized carbon that went into producing isoprene during fermentation was 1.53%.

VI. Isoprene production from *E. coli* BL21 (DE3) tuner cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids at a 15-L scale

[0654] BL21 (DE3) tuner cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 26 µM when the OD₅₅₀ reached a value of 10. The IPTG concentration was raised to 50 µM when OD₅₅₀ reached 175. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 64A. The isoprene titer increased over the course of the fermentation to a final value of 1.3 g/L broth (Fig. 64B). The specific productivity profile throughout the fermentation is shown in Fig. 64C and a comparison to Fig. 64A illustrates the de-coupling of growth and isoprene production. The total amount of isoprene produced during the 48.6 hour fermentation was 9.9 g from 1.6 kg of utilized glucose. The molar yield of utilized carbon that went into producing isoprene during fermentation was 1.34%.

VII. Isoprene production from *E. coli* MG1655 cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids at a 15-L scale

[0655] MG1655 cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 24 µM when the OD₅₅₀ reached a value of 45. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 65A. The isoprene titer increased over the course of the fermentation to a final value of 393 mg/L broth (Fig. 65B). The specific productivity profile throughout the fermentation is shown in Fig. 65C and a comparison to Fig. 65A illustrates the de-coupling of growth and isoprene production. The

total amount of isoprene produced during the 67.4 hour fermentation was 2.2 g from 520 g of utilized glucose. The molar yield of utilized carbon that went into producing isoprene during fermentation was 0.92%.

VIII. Isoprene production from *E. coli* MG1655ack-pta cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids at a 15-L scale

[0656] MG1655ack-pta cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 30 µM when the OD₅₅₀ reached a value of 10. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 66A. The isoprene titer increased over the course of the fermentation to a final value of 368 mg/L broth (Fig. 66B). The specific productivity profile throughout the fermentation is shown in Fig. 66C and a comparison to Fig. 66A illustrates the de-coupling of growth and isoprene production. The total amount of isoprene produced during the 56.7 hour fermentation was 1.8 g from 531 g of utilized glucose. The molar yield of utilized carbon that went into producing isoprene during fermentation was 0.73%.

IX. Isoprene production from *E. coli* FM5 cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids at a 15-L scale

[0657] FM5 cells expressing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids that were grown on a plate as explained above in Example 11, part I were inoculated into a flask containing 500 mL of tryptone-yeast extract medium and grown at 30 °C at 160 rpm to OD₅₅₀ 1.0. This material was seeded into a 15-L bioreactor containing 4.5-kg of medium. The IPTG concentration was brought to 27 µM when the OD₅₅₀ reached a value of 15. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 67A. The isoprene titer increased over the course of the fermentation to a final value of 235 mg/L broth (Fig. 67B). The specific productivity profile throughout the fermentation is shown in Fig. 67C and a comparison to Fig. 67A illustrates the de-coupling of growth and isoprene production. The total amount of isoprene produced during the 52.3 hour fermentation was 1.4 g from 948 g of utilized glucose. The molar yield of utilized carbon that went into producing isoprene during fermentation was 0.32%.

Example 12: Production of isoprene during the exponential growth phase of *E. coli* expressing genes from the mevalonic acid pathway and fermented in a fed-batch culture

[0658] Example 12 illustrates the production of isoprene during the exponential growth phase of cells.

Medium Recipe (per liter fermentation medium):

[0659] The medium was generated using the following components per liter fermentation medium: K_2HPO_4 7.5 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, and 1000X modified trace metal solution 1 ml. All of the components were added together and dissolved in dH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine $\cdot$ HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0660] The 1000X modified trace metal solution was generated using the following components: citric acids $\cdot$ H_2O 40 g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30 g, NaCl 10 g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1 g, $\text{ZnSO} \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100 mg, H_3BO_3 100 mg, and $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100 mg. Each component is dissolved one at a time in $\text{Di H}_2\text{O}$, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with 0.22 micron filter.

[0661] Fermentation was performed in a 15-L bioreactor with ATCC11303 *E. coli* cells containing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids. This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37°C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0662] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 50 hour fermentation was 2.0 kg. Induction was achieved by adding IPTG. The IPTG concentration was brought to 25 μM when the optical density at 550 nm (OD_{550}) reached a value of 10. The IPTG concentration was raised

to 50 μ M when OD₅₅₀ reached 190. The OD₅₅₀ profile within the bioreactor over time is shown in Fig. 99. The isoprene level in the off gas from the bioreactor was determined as described herein. The isoprene titer increased over the course of the fermentation to a final value of 1.4 g/L (Fig. 100). The total amount of isoprene produced during the 50 hour fermentation was 10.0 g. The profile of the isoprene specific productivity over time within the bioreactor is shown in Fig. 101. The molar yield of utilized carbon that contributed to producing isoprene during fermentation was 1.1%. The weight percent yield of isoprene from glucose was 0.5%.

Example 13: Flammability modeling and testing of isoprene

I. Summary of flammability modeling and testing of isoprene

[0663] Flammability modeling and experiments were performed for various hydrocarbon/oxygen/nitrogen/water/carbon dioxide mixtures. This modeling and experimental tested was aimed at defining isoprene and oxygen/nitrogen flammability curves under specified steam and carbon monoxide concentrations at a fixed pressure and temperature. A matrix of the model conditions is shown in Table 9, and a matrix of the experiments performed is shown in Table 10.

Table 9. Summary of Modeled Isoprene Flammability

Series	Temperature (°C)	Pressure (psig)	Steam Concentration (wt%)	Carbon Dioxide Concentration (wt. %)	Isoprene Concentration (vol. %)	Oxygen Concentration (vol. %)
A	40	0	0	0	Varying	Varying
B	40	0	4	0	Varying	Varying
C	40	0	0	5	Varying	Varying
D	40	0	0	10	Varying	Varying
E	40	0	0	15	Varying	Varying
F	40	0	0	20	Varying	Varying
G	40	0	0	30	Varying	Varying

Table 10. Summary of Isoprene Flammability Tests

Series Number	Temperature (°C)	Pressure (psig)	Steam Concentration (vol. %)	Isoprene Concentration (vol. %)	Oxygen Concentration (vol. %)
1	40	0	0	Varying	Varying
2	40	0	4	Varying	Varying

II. Description of calculated adiabatic flame temperature (CAFT) model

[0664] Calculated adiabatic flame temperatures (CAFT) along with a selected limit flame temperature for combustion propagation were used to determine the flammability envelope for isoprene. The computer program used in this study to calculate the flame temperatures is the NASA Glenn Research Center CEA (Chemical Equilibrium with Applications) software.

[0665] There are five steps involved in determining the flammability envelope using an adiabatic flame temperature model for a homogeneous combustion mechanism (where both the fuel and oxidant are in the gaseous state): selection of the desired reactants, selection of the test condition, selection of the limit flame temperature, modification of the reactants, and construction of a flammability envelope from calculations.

[0666] In this first step, selection of desired reactants, a decision must be made as to the reactant species that will be present in the system and the quantities of each. In many cases the computer programs used for the calculations have a list of reactant and product species. If any of the data for the species to be studied are not found in the program, they may be obtained from other sources such as the JANAF tables or from the internet. In this current model data for water, nitrogen, oxygen and carbon dioxide were present in the program

database. The program database did not have isoprene as a species; therefore the thermodynamic properties were incorporated manually.

[0667] The next step is to decide whether the initial pressure and temperature conditions that the combustion process is taking place in. In this model the pressure was 1 atmosphere (absolute) and the temperature was 40°C, the boiling point of isoprene.

[0668] The limit flame temperature for combustion can be either selected based on theoretical principles or determined experimentally. Each method has its own limitations.

[0669] Based on prior studies, the limit flame temperatures of hydrocarbons fall in the range of 1000 K to 1500 K. For this model, the value of 1500 K was selected. This is the temperature at which the reaction of carbon monoxide to carbon dioxide (a highly exothermic reaction and constitutes a significant proportion of the flame energy) becomes self sustaining.

[0670] Once the limit flame temperature has been decided upon, model calculations are performed on the given reactant mixture (species concentrations) and the adiabatic flame temperature is determined. Flame propagation is considered to have occurred only if the temperature is greater than the limit flame temperature. The reactant mixture composition is then modified to create data sets for propagation and non-propagation mixtures.

[0671] This type of model shows good agreement with the experimentally determined flammability limits. Regions outside the derived envelope are nonflammable and regions within it are flammable. The shape of the envelope forms a nose. The nose of the envelope is related to the limiting oxygen concentration (LOC) for gaseous fuels.

III. Results from calculated adiabatic flame temperature (CAFT) model

[0672] Plotted in Figs. 68 through 74 are the CAFT model results for Series A to G, respectively. The figures plot the calculated adiabatic flame temperature (using the NASA CEA program) as a function of fuel concentration (by weight) for several oxygen/nitrogen ratios (by weight). The parts of the curve that are above 1500 K, the selected limit flame temperature, contain fuel levels sufficient for flame propagation. The results may be difficult to interpret in the form presented in Figs. 68 through 74. Additionally, the current form is not conducive to comparison with experimental data which is generally presented in terms of volume percent.

[0673] Using Series A as an example the data in Fig. 68 can be plotted in the form of a traditional flammability envelope. Using Fig. 68 and reading across the 1500 K temperature line on the ordinate one can determine the fuel concentration for this limit flame temperature by dropping a tangent to the abscissa for each curve (oxygen to nitrogen ratio) that it intersects. These values can then be tabulated as weight percent of fuel for a given weight percent of oxidizer (Fig. 75A). Then knowing the composition of the fuel (100 wt.% isoprene) and the composition of the oxidizer (relative content of water, oxygen and nitrogen) molar quantities can be established.

[0674] From these molar quantities percentage volume concentrations can be calculated. The concentrations in terms of volume percent can then be plotted to generate a flammability envelope (Fig. 75B). The area bounded by the envelope is the explosible range and the area excluded is the non-explosible range. The “nose” of the envelope is the limiting oxygen concentration. Figs. 76A and 76B contain the calculated volume concentrations for the flammability envelope for Series B generated from data presented in Fig. 69. A similar approach can be used on data presented in Figs. 70-74.

IV. Flammability testing experimental equipment and procedure

[0675] Flammability testing was conducted in a 4 liter high pressure vessel. The vessel was cylindrical in shape with an inner diameter of 6” and an internal height of 8.625”. The temperature of the vessel (and the gases inside) was maintained using external heaters that were controlled by a PID controller. To prevent heat losses, ceramic wool and reflective insulation were wrapped around the pressure vessel. Type K thermocouples were used to measure the temperature of the gas space as well as the temperature of the vessel itself. Fig. 77 illustrates the test vessel.

[0676] Before a test was ran, the vessel was evacuated and purged with nitrogen to ensure that any gases from previous tests were removed. A vacuum was then pulled on the vessel. The pressure after this had been done was typically around 0.06 bar(a). Due to the nitrogen purging, the gas responsible for this initial pressure was assumed to be nitrogen. Using partial pressures, water, isoprene, nitrogen, and oxygen were then added in the appropriate amounts to achieve the test conditions in question. A magnetically driven mixing fan within the vessel ensured mixing of the gaseous contents. The gases were allowed to mix for about 2 minutes with the fan being turned off approximately 1 minute prior to ignition.

[0677] The igniter was comprised of a 1.5 ohm nicrome coil and an AC voltage source on a timer circuit. Using an oscilloscope, it was determined that 34.4 VAC were delivered to the igniter for 3.2 seconds. A maximum current of 3.8 amps occurred approximately halfway into the ignition cycle. Thus, the maximum power was 131 W and the total energy provided over the ignition cycle was approximately 210 J.

[0678] Deflagration data was acquired using a variable reluctance Validyne DP215 pressure transducer connected to a data acquisition system. A gas mixture was considered to have deflagrated if the pressure rise was greater than or equal to 5%.

V. Results of flammability testing

[0679] The first experimental series (Series 1) was run at 40°C and 0 psig with no steam. Running tests at varying concentrations of isoprene and oxygen produced the flammability curve shown in Fig. 78A. The data points shown in this curve are only those that border the curve. A detailed list of all the data points taken for this series is shown in Figs. 80A and 80B.

[0680] Fig. 78B summarizes the explosibility data points shown in Fig. 78A. Fig. 78C is a comparison of the experimental data with the CAFT model predicted flammability envelope. The model agrees very well with the experimental data. Discrepancies may be due to the non-adiabatic nature of the test chamber and limitations of the model. The model looks at an infinite time horizon for the oxidation reaction and does not take into consideration any reaction kinetic limitation.

[0681] Additionally, the model is limited by the number of equilibrium chemical species that are in its database and thus may not properly predict pyrolytic species. Also, the flammability envelope developed by the model uses one value for a limit flame temperature (1500K). The limit flame temperature can be a range of values from 1,000K to 1,500K depending on the reacting chemical species. The complex nature of pyrolytic chemical species formed at fuel concentrations above the stoichiometric fuel/oxidizer level is one reason why the model may not accurately predict the upper flammable limit for this system.

[0682] The second experimental series (Series 2) was run at 40°C and 0 psig with a fixed steam concentration of 4%. Running tests at varying concentrations of isoprene and oxygen produced the flammability curve shown in Fig. 79A. The data points shown in this curve are

only those that border the curve. A detailed list of all the data points taken for this series is shown in Fig. 81. Due to the similarity between the data in Series 1 only the key points of lower flammable limit, limiting oxygen concentration, and upper flammable limits were tested. The addition of 4% steam to the test mixture did not significantly change the key limits of the flammability envelope. It should be noted that higher concentrations of steam/water and or other inertants may influence the flammability envelope.

[0683] Fig. 79B summarizes the explosibility data points shown in Fig. 79A. Fig. 79C is a comparison of the experimental data with the CAFT model predicted flammability envelope. The model agrees very well with the experimental data. Discrepancies may be due to the same factors described in Series 1

V. Calculation of Flammability Limits of Isoprene in Air at 3 Atmospheres of Pressure

[0684] The methods described in Example 13, parts I to IV were also used to calculate the flammability limits of isoprene at an absolute system pressure of 3 atmospheres and 40°C. These results were compared to those of Example 13, parts I to IV at an absolute system pressure of 1 atmosphere and 40°C. This higher pressure was tested because the flammability envelope expands or grows larger as the initial system pressure is increased. The upper flammability limit is affected the most, followed by the limiting oxygen composition. The lower flammability limit is the least affected (*see*, for example, “Bulletin 627 – Flammability Characteristics of Combustible Gases and Vapors” written by Michael G. Zabetakis and published by the former US Bureau of Mines (1965), which is hereby incorporated by reference in its entirety, particular with respect to the calculation of flammability limits).

[0685] In Figure 82, the calculated adiabatic flame temperature is plotted as a function of isoprene (fuel) concentration, expressed in weight percent of the total fuel/nitrogen/oxygen, where the system pressure was initially 3 atmospheres. The calculated flame temperatures are very similar to those determined initially in the 1 atmosphere system (Fig. 83). As a result, when flammability envelopes are generated using the calculated adiabatic flammability data, the curves are very similar (see Figs. 84 and 85). Therefore, based on these theoretical calculations, a system pressure increase from 1 atmosphere to 3 atmosphere does not result in a significant increase/broadening of the flammability envelope. If desired, these

model results may be validated using experimental testing (such as the experimental testing described herein at a pressure of 1 atmosphere).

VII. Summary of flammability studies

[0686] A calculated adiabatic temperature model was developed for the flammability envelope of the isoprene/oxygen/nitrogen/water/ carbon dioxide system at 40°C and 0 psig. The CAFT model that was developed agreed well with the experimental data generated by the tests conducted in this work. The experimental results from Series 1 and 2 validated the model results from Series A and B.

Example 14: Production of isoprene in *E. coli* expressing *M. mazei* mevalonate kinase and *P. alba* isoprene synthase

I. Construction of vectors and strains encoding *M. mazei* mevalonate kinase (MVK) and *P. alba* isoprene synthase

(i) Construction of strain EWL201 (BL21, Cm-GI1.2-KKDyI)

[0687] *E. coli* BL21 (Novagen brand, EMD Biosciences, Inc.) was a recipient strain, transduced with MCM331 P1 lysate (lysate prepared according to the method described in Ausubel, *et al.*, *Current Protocols in Molecular Biology*. John Wiley and Sons, Inc.). Transductants were selected for by spreading cells onto L Agar and 20 µg/µl chloramphenicol. The plates were incubated overnight at 30°C. Analysis of transductants showed no colonies on control plates (water + cells control plate for reversion and water and P1 lysate control plate for lysate contamination).

[0688] Four transductants were picked and used to inoculate 5 mL L Broth and 20 µg/µl chloramphenicol. The cultures were grown overnight at 30°C with shaking at 200 rpm. To make genomic DNA preps of each transductant for PCR analysis, 1.5mL of overnight cell culture were centrifuged. The cell pellet was resuspended with 400µl Resuspension Buffer (20mM Tris, 1mM EDTA, 50mM NaCl, pH 7.5) and 4µl RNase, DNase-free (Roche) was added. The tubes were incubated at 37°C for 30 minutes followed by the addition of 4µl 10% SDS and 4µl of 10mg/ml Proteinase K stock solution (Sigma-Aldrich). The tubes were incubated at 37°C for 1 hour. The cell lysate was transferred into 2ml Phase Lock Light Gel

tubes (Eppendorf) and 200µl each of saturated phenol pH7.9 (Ambion Inc.) and chloroform were added. The tubes were mixed well and microcentrifuged for 5 minutes. A second extraction was done with 400µl chloroform and the aqueous layer was transferred to a new eppendorf tube. The genomic DNA was precipitated by the addition of 1ml of 100% ethanol and centrifugation for 5 minutes. The genomic DNA pellet was washed with 1ml 70% ethanol. The ethanol was removed and the genomic DNA pellet was allowed to air dry briefly. The genomic DNA pellet was resuspended with 200µl TE.

[0689] Using Pfu Ultra II DNA polymerase (Stratagene) and 200ng/µl of genomic DNA as template, 2 different sets of PCR reaction tubes were prepared according to manufacturer's protocol. For set 1, primers MCM130 and GB Cm-Rev (Table 11) were used to ensure transductants were successfully integrated into the attTn7 locus. PCR parameters for set 1 were 95°C for 2 minutes (first cycle only), 95°C for 25 seconds, 55°C for 25 seconds, 72°C for 25 seconds (repeat steps 2-4 for 28 cycles), 72°C for 1 minute. For set 2, primers MVD For and MVD Rev (Table 11) were used to ensure that the gi1.2-KKDyI operon integrated properly. PCR parameters for set 2 were 95°C for 2 minutes (first cycle only), 95°C for 25 seconds, 55°C for 25 seconds, 72°C for 10 seconds (repeat steps 2-4 for 28 cycles), 72°C for 1 minute. Analysis of PCR amplicons on a 1.2% E-gel (Invitrogen Corp.) showed that all 4 transductant clones were correct (picked one and designated as strain EWL201).

ii) Construction of Strain EWL204 (BL21, loopout-GI1.2-KKDyI)

[0690] The chloramphenicol marker was looped out of strain EWL201 using plasmid pCP20 as described by Datsenko and Wanner (2000) (Datsenko *et al.*, *Proc Natl. Acad. Sci USA* 97:6640-6645, 2000). One-step inactivation of chromosomal genes in *Escherichia coli* K-12 using PCR products. (Datsenko *et al.*, *PNAS*, 97: 6640-6645, 2000). EWL201 cells were grown in L Broth to midlog phase and then washed three times in ice-cold, sterile water. An aliquot of 50µl of cell suspension was mixed with 1µl of pCP20 and the cell suspension mixture was electroporated in a 2mm cuvette (Invitrogen Corp.) at 2.5 Volts and 25µF using a Gene Pulser Electroporator (Bio-Rad Inc.). 1ml of LB was immediately added to the cells, then transferred to a 14ml polypropylene tube (Sarstedt) with a metal cap.

[0691] Cells were allowed to recover by growing for 1 hour at 30°C. Transformants were selected on L Agar and 20µg/µl chloramphenicol and 50µg/µl carbenicillin and incubated at

30°C overnight. The next day, a single clone was grown in 10ml L Broth and 50µg/µl carbenicillin at 30°C until early log phase. The temperature of the growing culture was then shifted to 42°C for 2 hours. Serial dilutions were made, the cells were then spread onto LA plates (no antibiotic selection), and incubated overnight at 30°C. The next day, 20 colonies were picked and patched onto L Agar (no antibiotics) and LA and 20µg/µl chloramphenicol plates. Plates were then incubated overnight at 30°C. Cells able to grow on LA plates, but not LA and 20µg/µl chloramphenicol plates, were deemed to have the chloramphenicol marker looped out (picked one and designated as strain EWL204).

iii) Construction of plasmid pEWL230 (pTrc *P. alba*)

[0692] Generation of a synthetic gene encoding *Populus alba* isoprene synthase (*P. alba* HGS) was outsourced to DNA2.0 Inc. (Menlo Park, CA) based on their codon optimization method for *E. coli* expression. The synthetic gene was custom cloned into plasmid pET24a (Novagen brand, EMD Biosciences, Inc.) and delivered lyophilized (Figures 112, 113A and 113B).

[0693] A PCR reaction was performed to amplify the *P. alba* isoprene synthase (*P. alba* HGS) gene using pET24 *P. alba* HGS as the template, primers MCM182 and MCM192, and Herculase II Fusion DNA polymerase (Stratagene) according to manufacturer's protocol. PCR conditions were as follows: 95°C for 2 minutes (first cycle only), 95°C for 25 seconds, 55°C for 20 seconds, 72°C for 1 minute, repeat for 25 cycles, with final extension at 72°C for 3 minutes. The *P. alba* isoprene synthase PCR product was purified using QIAquick PCR Purification Kit (Qiagen Inc.).

[0694] *P. alba* isoprene synthase PCR product was then digested in a 20µl reaction containing 1µl *Bsp*HI endonuclease (New England Biolabs) with 2µl 10X NEB Buffer 4. The reaction was incubated for 2 hours at 37°C. The digested PCR fragment was then purified using the QIAquick PCR Purification Kit. A secondary restriction digest was performed in a 20µl reaction containing 1µl *Pst*I endonuclease (Roche) with 2µl 10X Buffer H. The reaction was incubated for 2 hours at 37°C. The digested PCR fragment was then purified using the QIAquick PCR Purification Kit. Plasmid pTrcHis2B (Invitrogen Corp.) was digested in a 20µl reaction containing 1µl *Nco*I endonuclease (Roche), 1µl *Pst*I endonuclease, and 2µl 10X Buffer H. The reaction was incubated for 2 hours at 37°C. The

digested pTrcHis2B vector was gel purified using a 1.2% E-gel (Invitrogen Corp.) and extracted using the QIAquick Gel Extraction Kit (Qiagen) (Figure 114). Using the compatible cohesive ends of *Bsp*HI and *Nco*I sites, a 20 μ l ligation reaction was prepared containing 5 μ l *P. alba* isoprene synthase insert, 2 μ l pTrc vector, 1 μ l T4 DNA ligase (New England Biolabs), 2 μ l 10X ligase buffer, and 10 μ l ddH₂O. The ligation mixture was incubated at room temperature for 40 minutes. The ligation mixture was desalted by floating a 0.025 μ m nitrocellulose membrane filter (Millipore) in a petri dish of ddH₂O and applying the ligation mixture gently on top of the nitrocellulose membrane filter for 30 minutes at room temperature. MCM446 cells (See section II) were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. An aliquot of 50 μ l of cell suspension was mixed with 5 μ l of desalted pTrc *P. alba* HGS ligation mix. The cell suspension mixture was electroporated in a 2mm cuvette at 2.5 Volts and 25 μ Fd using a Gene Pulser Electroporator. 1ml of LB is immediately added to the cells, then transferred to a 14ml polypropylene tube (Sarstedt) with a metal cap.

[0695] Cells were allowed to recover by growing for 2 hour at 30°C. Transformants were selected on L Agar and 50 μ g/ μ l carbenicillin and 10mM mevalonic acid and incubated at 30°C. The next day, 6 transformants were picked and grown in 5ml L Broth and 50 μ g/ μ l carbenicillin tubes overnight at 30°C. Plasmid preps were performed on the overnight cultures using QIAquick Spin Miniprep Kit (Qiagen). Due to the use of BL21 cells for propagating plasmids, a modification of washing the spin columns with PB Buffer 5X and PE Buffer 3X was incorporated to the standard manufacturer's protocol for achieving high quality plasmid DNA. Plasmids were digested with *Pst*I in a 20 μ l reaction to ensure the correct sized linear fragment. All 6 plasmids were the correct size and shipped to Quintara Biosciences (Berkeley, CA) for sequencing with primers MCM65, MCM66, EL1000 (Table 11). DNA sequencing results showed all 6 plasmids were correct. Picked one and designated plasmid as EWL230 (Figures 57, 58A and 58B).

iv) Construction of plasmid pEWL244 (pTrc *P. alba*-mMVK)

[0696] A PCR reaction was performed to amplify the *Methanosarcina mazei* (*M. mazei*) MVK gene using MCM376 as the template (see section v), primers MCM165 and MCM177 (see Table 11), and Pfu Ultra II Fusion DNA polymerase (Stratagene) according to manufacturer's protocol. PCR conditions were as follows: 95°C for 2 minutes (first cycle

only), 95°C for 25 seconds, 55°C for 25 seconds, 72°C for 18 seconds, repeat for 28 cycles, with final extension at 72°C for 1 minute. The *M. mazei* MVK PCR product was purified using QIAquick PCR Purification Kit (Qiagen Inc.).

[0697] The *M. mazei* MVK PCR product was then digested in a 40µl reaction containing 8µl PCR product, 2µl *PmeI* endonuclease (New England Biolabs), 4µl 10X NEB Buffer 4, 4µl 10X NEB BSA, and 22µl of ddH₂O. The reaction was incubated for 3 hours at 37°C. The digested PCR fragment was then purified using the QIAquick PCR Purification Kit. A secondary restriction digest was performed in a 47µl reaction containing 2µl *NsiI* endonuclease (Roche), 4.7µl 10X Buffer H, and 40µl of *PmeI* digested *M. mazei* MVK fragment. The reaction was incubated for 3 hours at 37°C. The digested PCR fragment was then gel purified using a 1.2% E-gel and extracted using the QIAquick Gel Extraction Kit. Plasmid EWL230 was digested in a 40µl reaction containing 10µl plasmid, 2µl *PmeI* endonuclease, 4µl 10X NEB Buffer 4, 4µl 10X NEB BSA, and 20µl of ddH₂O. The reaction was incubated for 3 hours at 37°C. The digested PCR fragment was then purified using the QIAquick PCR Purification Kit. A secondary restriction digest was performed in a 47µl reaction containing 2µl *PstI* endonuclease, 4.7µl 10X Buffer H, and 40µl of *PmeI* digested EWL230 linear fragment. The reaction was incubated for 3 hours at 37°C. The digested PCR fragment was then gel purified using a 1.2% E-gel and extracted using the QIAquick Gel Extraction Kit (Figure 117). Using the compatible cohesive ends of *NsiI* and *PstI* sites, a 20µl ligation reaction was prepared containing 8µl *M. mazei* MVK insert, 3µl EWL230 plasmid, 1µl T4 DNA ligase, 2µl 10X ligase buffer, and 6µl ddH₂O. The ligation mixture was incubated at overnight at 16°C. The next day, the ligation mixture was desalted by floating a 0.025µm nitrocellulose membrane filter in a petri dish of ddH₂O and applying the ligation mixture gently on top of the nitrocellulose membrane filter for 30 minutes at room temperature. MCM446 cells were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. An aliquot of 50µl of cell suspension was mixed with 5µl of desalted pTrc P.alba-mMVK ligation mix. The cell suspension mixture was electroporated in a 2mm cuvette at 2.5 Volts and 25µF using a Gene Pulser Electroporator. 1ml of LB is immediately added to the cells, then the cells are transferred to a 14ml polypropylene tube with a metal cap. Cells were allowed to recover by growing for 2 hour at 30°C. Transformants were selected on LA and 50µg/µl carbenicillin and 5mM mevalonic acid

plates and incubated at 30°C. The next day, 6 transformants were picked and grown in 5ml LB and 50µg/µl carbenicillin tubes overnight at 30°C. Plasmid preps were performed on the overnight cultures using QIAquick Spin Miniprep Kit. Due to the use of BL21 cells for propagating plasmids, a modification of washing the spin columns with PB Buffer 5X and PE Buffer 3X was incorporated to the standard manufacturer's protocol for achieving high quality plasmid DNA. Plasmids were digested with PstI in a 20µl reaction to ensure the correct sized linear fragment. Three of the 6 plasmids were the correct size and shipped to Quintara Biosciences for sequencing with primers MCM65, MCM66, EL1000, EL1003, and EL1006 (Table 11). DNA sequencing results showed all 3 plasmids were correct. Picked one and designated plasmid as EWL244 (Figures 118, 119A and 199B).

v) Construction of plasmid MCM376 - MVK from *M. mazei* archaeal Lower in pET200D.

[0698] The MVK ORF from the *M. mazei* archaeal Lower Pathway operon (Figures 131A-C) was PCR amplified using primers MCM161 and MCM162 (Table 11) using the Invitrogen Platinum HiFi PCR mix. 45 µL of PCR mix was combined with 1 µL template, 1 µL of each primer at 10 µM, and 2 µL water. The reaction was cycled as follows: 94°C for 2:00 minutes; 30 cycles of 94°C for 0:30 minutes, 55°C for 0:30 minutes and 68°C for 1:15 minutes; and then 72°C for 7:00 minutes, and 4°C until cool. 3 µL of this PCR reaction was ligated to Invitrogen pET200D plasmid according to the manufacturer's protocol. 3 µL of this ligation was introduced into Invitrogen TOP10 cells, and transformants were selected on LA/kan50. A plasmid from a transformant was isolated and the insert sequenced, resulting in MCM376 (Figures 131A-C).

vi) Construction of strain EWL251 (BL21(DE3), Cm-GI1.2-KKDyI, pTrc P.alba-mMVK)

[0699] MCM331 cells (which contain chromosomal construct gi1.2KKDyI encoding *S. cerevisiae* mevalonate kinase, mevalonate phosphate kinase, mevalonate pyrophosphate decarboxylase, and IPP isomerase) were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. Mixed 50µl of cell suspension with 1µl of plasmid EWL244. The cell suspension mixture was electroporated in a 2mm cuvette at 2.5 Volts and 25uFd using a Gene Pulser Electroporator. 1ml of LB is immediately added to the cells, then the cells were transferred to a 14ml polypropylene tube with a metal cap. Cells were allowed to recover by growing for 2 hours at 30°C. Transformants were selected on LA and 50µg/µl

carbenicillin and 5mM mevalonic acid plates and incubated at 37°C. One colony was selected and designated as strain EWL251.

vii) Construction of strain EWL256 (BL21(DE3), Cm-GI1.2-KKDyI, pTrc P.alba-mMVK, pCL Upper MVA)

[0700] EWL251 cells were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. Mixed 50µl of cell suspension with 1µl of plasmid MCM82 (which is pCL PtrcUpperPathway encoding *E. faecalis* mvaE and mvaS). The cell suspension mixture was electroporated in a 2mm cuvette at 2.5 Volts and 25uFd using a Gene Pulser Electroporator. 1ml of LB was immediately added to the cells, then transferred to a 14ml polypropylene tube with a metal cap. Cells were allowed to recover by growing for 2 hour at 30°C. Transformants were selected on LA and 50µg/µl carbenicillin and 50µg/µl spectinomycin plates and incubated at 37°C. Picked one colony and designated as strain EWL256.

Table 11: Primer Sequences

Primer name	Primer sequence
MCM130	ACCAATTGCACCCGGCAGA (SEQ ID NO:109)
GB Cm Rev	GCTAAAGCGCATGCTCCAGAC (SEQ ID NO:110)
MVD For	GACTGGCCTCAGATGAAAGC (SEQ ID NO:111)
MVD Rev	CAAACATGTGGCATGGAAAG (SEQ ID NO:112)
MCM182	GGGCCCCGTTTAAACTTTAACTAGACTCTGCAGTTAGCGTTCAAACGGCAGAA (SEQ ID NO:113)
MCM192	CGCATGCATGTCATGAGATGTAGCGTGTCCACCGAAAA (SEQ ID NO:114)
MCM65	ACAATTTACACAGGAAACAGC (SEQ ID NO:115)
MCM66	CCAGGCAAATTCTGTTTTATCAG (SEQ ID NO:116)
EL1000	GCACTGTCTTTCCGTCTGCTGC (SEQ ID NO: 117)
MCM165	GCGAACGATGCATAAAGGAGGTAAAAAACATGGTATCCTGTTCTGCGCCGGGTAAGATTTACCTG (SEQ ID NO:118)
MCM177	GGGCCCCGTTTAAACTTTAACTAGACTTTAATCTACTTTCAGACCTTGC (SEQ ID NO:119)
EL1003	GATAGTAACGGCTGCGCTGCTACC (SEQ ID NO:120)
EL1006	GACAGCTTATCATCGACTGCACG (SEQ ID NO:121)
MCM161	CACCATGGTATCCTGTTCTGCG (SEQ ID NO:122)
MCM162	TTAATCTACTTTCAGACCTTGC (SEQ ID NO:123)

II. Construction of MCM442-449: BL21 and BL21(DE3) with FRT-cmR-FRT-gil.x-mKKDyI

i) Construction of Template for Recombination

[0701] FRT-based recombination cassettes, and plasmids for Red/ET-mediated integration and antibiotic marker loopout were obtained from Gene Bridges GmbH (Germany).

Procedures using these materials were carried out according to Gene Bridges protocols.

Primers MCM193 and MCM195 were used to amplify the resistance cassette from the FRT-gb2-Cm-FRT template using Stratagene Herculase II Fusion kit according to the manufacturer's protocol. The 50µL reaction was cycled as follows: 95°C, 2 minutes; (95°C, 20 seconds, 55°C, 20 seconds, 72°C, 1 minute) x 5, (95°C, 20 seconds, 60°C, 20 seconds, 72°C, 1 minute) x 25; 72°C, 3 minutes; 4°C until cool. The amplicon was purified by a

Qiagen PCR column according to the manufacturer's protocol and eluted in 30µL EB (Elution Buffer). DNA was digested with *NdeI* and *PciI* in a 20µL reaction with 1x Roche H buffer and 0.5µL BSA. Plasmid MCM376 was digested in a 10µL reaction containing 1µL each of *NdeI*, *NcoI*, and Roche H buffer. Reactions proceeded overnight at 37°C, and then cut DNA was purified on Qiagen PCR columns and eluted in 30µL EB. The PCR product was ligated into MCM376 in a reaction containing 1µL vector, 3µL PCR product, 1µL Roche Quick Ligase Buffer 2, 5µL Buffer1, and 1µL Ligase. The reaction proceeded at room temperature for 3 hours and then 5µL was transformed into Invitrogen TOP10 cells according to the manufacturer's protocol. Transformants were selected on L agar (LA) and chloramphenicol (10 µg/mL) at 37°C overnight.

[0702] Transformant colonies were patched onto LA containing chloramphenicol (30 µg/mL) and kanamycin (50 µg/mL) for storage and sent to Quintara (Berkeley, CA) for sequencing. Four clones, one each with the four different nucleotides at the "N" in primer MCM195, were found to have the correct sequence for the inserted promoter. Clones were grown in 5mL LB containing chloramphenicol (30 µg/mL) and kanamycin (50 µg/mL) and used for the preparation of plasmid DNA. This plasmid was retransformed into TOP10 cells and strains were frozen as:

Table 12: MCM484-487

MCM484	cmR-gi1.6-MVK(mazei) in pET (clone A1-3, variable nt A)
MCM485	cmR-gi1.0-MVK(mazei) in pET (clone B4-6, variable nt C)
MCM486	cmR-gi1.2-MVK(mazei) in pET (clone C1-5, variable nt G)
MCM487	cmR-gi1.5-MVK(mazei) in pET (clone C3-3, variable nt T)

ii) Creation of Recombination Target Strains MCM349 and MCM441

[0703] The chloramphenicol resistance (cmR) marker was looped out of strain MCM331 using plasmid pGB706 (GeneBridges) according to Manufacturer's instructions. MCM331 cells were grown to mid-log in LB and washed three times in iced, sterile water. A 1µL aliquot of pGB706 DNA was added to 50µL of cell suspension and this mixture was electroporated in a 2mm cuvette at 2.5 volts, 25uF followed immediately by recovery in 500µL LB for one hour at 30°C. Transformants were selected on LB containing tetracycline (5 µg/mL) at 30°C. The following day, a clone was grown up at 30°C in LB containing tetracycline (5 µg/mL) until visibly turbid (OD₆₀₀~0.5-0.8). This culture was streaked onto

LB and grown overnight at 37°C. A clone that was unable to grow on LB containing chloramphenicol (10 µg/mL) or LB containing tetracycline (5 µg/mL) was frozen as MCM348. Plasmid MCM356 (pRedET carbencillin; GeneBridges) was electroporated in as described above and transformants were selected on LB containing carbenicillin (50 µg/mL) at 30°C. A clone was grown in LB carbenicillin (50 µg/mL) at 30°C and frozen as MCM349.

[0704] Strain MCM441 was created by electrotransforming plasmid MCM356 into EWL204 as above.

iii) Recombination of FRT-cmR-FRT-gi1.x-mMVK into MCM349 and MCM441

[0705] Plasmids MCM484-487 were used as template for PCR amplification with primers MCM120 and MCM196 and Herculase II Fusion kit, according to the manufacturer's protocol. Three reactions per template were carried out, with 0, 1, or 3 µL DMSO. The 50 µL reactions were cycled as follows: 95°C, 2 minutes; (95°C, 20 seconds; 55°C 20 seconds; 72°C, 1.5 minutes) for five cycles; (95°C, 20 seconds; 60°C 20 seconds; 72°C, 1.5 minutes) for 25 cycles; 72°C for 3 minutes; 4°C, overnight. The three reactions from a given template were pooled and purified on Qiagen PCR columns and eluted with 30 µL EB at 60°C. 5 µL DNA was digested with 1 µL *DpnI* in 1x Roche Buffer A for 3 hours at 37°C. This DNA was then microdialyzed against excess water for 30 minutes.

[0706] Strains were grown in 5mL LB containing carbenicillin (50 µg/mL) from fresh streaks at 30°C to an OD600 of ~0.5. 40mM L-arabinose was added and cultures were incubated at 37°C for 1.5 hours. Cells were harvested and electroporated with 3 µL dialyzed amplicons above, and then recovered in 500 µL SOC at 37°C for 1.5 hours. Transformants were selected on LA plates containing chloramphenicol (5 µg/mL) at 37°C.

[0707] Kanamycin sensitive clones were screened by PCR for insertion of the amplicon. PCR products from positive clones were sequenced to verify the sequence of inserted DNA. Amplicons were consistent with the FRT-gi1.2-yKKDyI at attTn7 in MCM441 and 348 being replaced by FRT-cmR-FRT-gi1.x-mKKDyI (The yK and mK designations refer to the mevalonate kinase from *Saccharomyces cerevisiae* and *Methanosarcina mazei* respectively).

Table 13A: The following strains were grown in LB containing chloramphenicol (5 µg/mL) and frozen.

Strain ID	Name	Parent	Recombination Amplicon Template
MCM442	BL21(DE3) cmR-gi1.6mKKDyI A1, clone37 (A)	MCM349	MCM484
MCM443	BL21(DE3) cmR-gi1.0mKKDyI B4, clone27 (C)	MCM349	MCM485
MCM444	BL21(DE3) cmR-gi1.2mKKDyI C1, clone16 (G)	MCM349	MCM486
MCM445	BL21(DE3) cmR-gi1.5mKKDyI C3, clone7 (T)	MCM349	MCM487
MCM446	BL21 cmR-gi1.6mKKDyI A1-3 (A)	MCM441	MCM484
MCM447	BL21 cmR-gi1.0mKKDyI B4-6 (C)	MCM441	MCM485
MCM448	BL21 cmR-gi1.2mKKDyI C1-5 (G)	MCM441	MCM486
MCM449	BL21 cmR-gi1.5mKKDyI C3-3 (T)	MCM441	MCM487

Table 13B: Primers

MCM120	AAAGTAGCCGAAGATGACGGTTTGTACATGGAGTTGGCAGGAT GTTTGATTAAAAGCAATTAACCCTCACTAAAGGGCGG (SEQ ID NO:97)
MCM193	GATATACATATGAATTAACCCTCACTAAAGG (SEQ ID NO:124)
MCM195	GCATGCATGACATGTTTTTTTACCTCCTTTGTTATCCGCTCACAAAT TAGTGGTTGAATTATTTGCTCAGGATGTGGCATNGTCAAGGGCG CGGCCGCGATCTAATACGACTCACTATAGGGCTCG (SEQ ID NO:125)
MCM196	AGGCTCTCAACTCTGACATGTTTTTTTCCTCCTTAAGGGTGCAGG CCTATCGCAAATTAGCTTAATCTACTTTCAGACCTTGCTCGG (SEQ ID NO:126)

III. The effect of yeast extract on isoprene production in *E. coli* expressing genes from the mevalonic acid pathway and grown in fed-batch culture at the 15-L scale

Medium Recipe (per liter fermentation medium):

[0708] K₂HPO₄ 7.5 g, MgSO₄ * 7H₂O 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in diH₂O. This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine * HCl 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified Trace Metal Solution:

[0709] Citric Acids * H₂O 40 g, MnSO₄ * H₂O 30 g, NaCl 10 g, FeSO₄ * 7H₂O 1 g, CoCl₂ * 6H₂O 1 g, ZnSO₄ * 7H₂O 1 g, CuSO₄ * 5H₂O 100 mg, H₃BO₃ 100 mg, NaMoO₄ * 2H₂O 100 mg. Each component is dissolved one at a time in Di H₂O, pH to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with a 0.22 micron filter.

[0710] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (gi1.2KKDyI), and high expression of mevalonate kinase from *M. mazei* and isoprene synthase from *P. alba* (pTrcAlba-mMVK). This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 30°C. A frozen vial of the *E. coli* strain was thawed and inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 15-L bioreactor bringing the initial volume to 5-L.

i) Production of isoprene in *E.coli* cells (EL256) grown in fed-batch culture without yeast extract feeding

[0711] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 67 hour fermentation was 3.9 kg. Induction was achieved by adding isopropyl-beta-D-1-thiogalactopyranoside (IPTG). The IPTG concentration was brought to 102 µM when the optical density at 550 nm (OD₅₅₀) reached a value of 9. The IPTG concentration was raised to 192 µM when OD₅₅₀ reached 140. The OD₅₅₀ profile within the bioreactor over time is shown in Figure 125A. The isoprene level in the off gas from the bioreactor was determined using a Hiden mass spectrometer. The isoprene titer increased over the course of the fermentation to a final value of 35.6 g/L (Figure 125B). The total amount of isoprene produced during the 67 hour fermentation was 320.6 g and the time course of production is shown in Figure 125C. The metabolic activity profile, as measured by TCER, is shown in Figure 125D. The molar yield of utilized carbon that went into producing isoprene during fermentation was 17.9%. The weight percent yield of isoprene from glucose was 8.1%.

ii) Production of isoprene in *E.coli* cells (EL256) grown in fed-batch culture with yeast extract feeding

[0712] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 68 hour fermentation was 7.1 kg. A total of 1.06 kg of yeast extract was also fed during the fermentation. Induction was achieved by adding IPTG. The IPTG concentration was brought to 208 μ M when the optical density at 550 nm (OD_{550}) reached a value of 7. The IPTG concentration was raised to 193 μ M when OD_{550} reached 180. The OD_{550} profile within the bioreactor over time is shown in Figure 126A. The isoprene level in the off gas from the bioreactor was determined using a Hiden mass spectrometer. The isoprene titer increased over the course of the fermentation to a maximum value of 32.2 g/L (Figure 126B). The total amount of isoprene produced during the 68 hour fermentation was 395.5 g and the time course of production is shown in Figure 126C. The time course of volumetric productivity is shown in Figure 126D and shows that an average rate of 1.1 g/L/hr was maintained for between 23 and 63 hours. The metabolic activity profile, as measured by CER, is shown in Figure 126D. The molar yield of utilized carbon that went into producing isoprene during fermentation was 10.3%. The weight percent yield of isoprene from glucose was 5.2%.

IV. Production of isoprene from different carbon sources in *E. coli* harboring the mevalonic acid (MVA) pathway and isoprene synthase (EWL256)

Media Recipe (per liter fermentation media):

[0713] K_2HPO_4 13.6 g, KH_2PO_4 13.6g, $MgSO_4 \cdot 7H_2O$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, $(NH_4)_2SO_4$ 3.2 g, yeast extract 0.2 g, 1000X Modified Trace Metal Solution 1 ml. All of the components were dissolved sequentially in diH_2O . The pH was adjusted to 6.8 with ammonium hydroxide (30%) and brought to volume. Media was filter sterilized with a 0.22 micron filter. Carbon source was added to a final concentration of 1%. Required antibiotics were added after sterilization and pH adjustment.

1000X Trace Metal Solution (per liter fermentation media):

[0714] Citric Acids $\cdot H_2O$ 40 g, $MnSO_4 \cdot H_2O$ 30 g, NaCl 10 g, $FeSO_4 \cdot 7H_2O$ 1 g, $CoCl_2 \cdot 6H_2O$ 1 g, $ZnSO_4 \cdot 7H_2O$ 1 g, $CuSO_4 \cdot 5H_2O$ 100 mg, H_3BO_3 100 mg, $NaMoO_4 \cdot$

2H₂O 100 mg. Each component was dissolved one at a time in diH₂O, pH to 3.0 with HCl/NaOH, and then brought to volume and filter sterilized with a 0.22 micron filter.

i) Preparation of AFEX biomass hydrolysate

[0715] AFEX pretreated corn stover was hydrolyzed to prepare biomass hydrolysate containing both xylose, glucose and acetate.

[0716] AFEX pretreated corn stover, received from Michigan Biotechnology Institute, was used. The pretreatment conditions were, 60% moisture, 1:1 ammonia loading, and 90 °C for 30 minutes, then air dried. The moisture content in the AFEX pretreated corn stover was 21.27%. Content of glucan and xylan in the AFEX pretreated corn stover were 31.7% and 19.1% (dry basis) respectively. The enzyme used was accellerase 1000, Grindamyl H121 (Danisco xylanase product from *Aspergillus niger* for bread-making industry).

[0717] For saccharification, 20 g of AFEX pretreated corn stover was added into a 500 ml flask, together with 5 ml of 1 M pH 4.8 sodium citrate buffer, 2.25 ml of Accellerase 1000, 0.1 ml of Grindamyl H121, and 72.65 ml of DI water. The flask was put in an orbital shaker, and incubated at 50°C for 96 hours.

[0718] For analysis, one sample was taken from the shaker, and analyzed using HPLC. The hydrolysate contained 37.2 g/l of glucose and 24.3 g/L of xylose, and 7.6 g/L of oligomers of glucose and/or xylose. Additionally, the hydrolysate also contains 1.17 g/L acetate.

ii) Experimental procedure

[0719] An inoculum of the *E. coli* strain EWL256 containing the MVA pathway and isoprene synthase was taken from a frozen vial and streaked onto an LB broth agar plate containing spectinomycin (50 µg/mL) and carbinicillin (50 µg/mL) and incubated at 30°C overnight. A single colony was inoculated into TM3 media containing glucose, xylose, glycerol, acetate or biomass as only carbon source and grown overnight at 30°C. Cells grow on acetate reached a significantly lower optical density. Cells grown on glucose, glycerol, biomass hydrolysate or acetate were diluted into 20 mL of TM3 media containing the respective carbon sources to reach an optical density of between 0.1 measured at 600nm. A negative control not containing any carbon source was prepared from the glucose overnight

culture. A separate experiment was performed with glucose and xylose, where the cultures were diluted to an optical density of 0.05. All culture conditions (except for acetate and glycerol) were tested in duplicates and the presented results are averaged between these cultures. Production of isoprene was induced with 200 μ M IPTG from the beginning of the experiment. The flasks were incubated at 30°C in an orbital shaker (200 rpm) and growth was followed by measuring optical density. After the glucose fed cultures had reached an optical density of approximately 0.4, samples were analyzed for isoprene production from all the tested carbon sources every hour for three hours. Samples of 100 μ L were transferred in duplicates to 2 mL glass vials, sealed and incubated for 30 min at 30°C. The bacteria were then heat killed by incubation at 80°C for 8 minutes. The amount of produced isoprene was measured using GC-MS and specific productivity (μ g/L*hr) was calculated.

iii) Results

[0720] Significant production of isoprene could be demonstrated during growth on all the tested carbon sources. These carbon sources are examples of common alcohols, organic acids, sugars containing 5 or 6 carbon units (C_5 or C_6), and biomass hydrolysate.

[0721] The initial growth rate on biomass hydrolysate was comparable to the growth rate on glucose (Figure 127A). The initial specific productivity during growth on biomass hydrolysate was significantly higher than during growth on glucose. This demonstrates that biomass hydrolysate can be used as an efficient source of carbon for the production of isoprene. The specific productivity declined after 255 minutes of growth on biomass hydrolysate (Figure 127B). The bacteria had a slower growth rate with xylose as only carbon source when compared to glucose (Figure 127C), but a significant specific isoprene productivity was measured (Figure 127D). This shows that both C_5 and C_6 sugars can be utilized for the production of isoprene via the mevalonate acid pathway.

[0722] Suprisingly, bacteria grown on acetate as the only carbon source had a specific productivity of isoprene approximately twice as high as during growth on glucose (Figure 127A). The bacteria grew slower on acetate when compared to glucose (Figure 127B), but the performed experiment demonstrates that acetate can also be used as a carbon source for the production of isoprene. Acetate was also present in the biomass hydrolysate as measured by HPLC.

[0723] The bacteria grew well with glycerol as only carbon source (Figure 127A) and significant production of isoprene was demonstrated (Figure 127B). This shows that common alcohols may also be used as carbon sources for production of isoprene via the mevalonate acid pathway.

Example 15: Expression of isoprene-synthase from plant in *Streptomyces* sp.

[0724] The gene for isoprene synthase Kudzu was obtained from plasmid pJ201:19813. Plasmid pJ201:19813 encodes isoprene synthase from *Pueraria lobata* (Kudzu plant) and was codon-optimized for *Pseudomonas fluorescens*, *Pseudomonas putida*, *Rhodopseudomonas palustris* and *Corynebacterium* (Figures 137A-137C (SEQ ID NO:137)). Digestion of plasmid pJ201:19813 with restriction enzymes NdeI and BamHI liberated gene iso19813 that was ligated into the *Streptomyces-E.coli* shuttle vector pUWL201PW (Doumith *et al.*, *Mol. Gen. Genet.* 264: 477-485, 2000; Figure 129) to generate pUWL201_iso. Successful cloning was verified by restriction analysis of pUWL201_iso. Expression of isoprene synthase iso19813 was under control of the *erm*-promoter which allows for constitutive expression in *Streptomyces* species, but not for expression in *E. coli*.

[0725] pUWL201PW (no insert) and pUWL201_iso were introduced in *Streptomyces albus* J1074 (Sanchez *et al.*, *Chem. Biol.* 9:519-531, 2002) by transformation of protoplasts as described by Hopwood *et al.*, *The John Innes Foundation, Norwich*, 1985.

[0726] A 200 µl aliquot of protoplast suspensions was transformed with 1.9 µg pUWL201PW or 2.9 µg pUWL201_iso. After incubation overnight at 28°C on non-selective R5-agarplates, positive transformants were selected by further incubation for 4 days in R3-overlay agar containing thiostrepton (250 µg/ml). Thiostrepton resistant transformants were examined for presence of the pUWL-plasmids by plasmid preparation using Plasmid Mini Kit (Qiagen). Prepared plasmid DNA was reintroduced in *E. coli* DH5α to generate sufficient amounts of plasmid DNA to be analyzed by restriction analysis. Positive transformants were selected on ampicillin-containing L-agar plates and insert analysis was done by digestion of plasmid DNA with NdeI and BamHI endonucleases. Isoprene synthase was identified as a 1.7 kb fragment in positive pUWL201 iso clones while in the control strains (pUWL201PW) no such fragment was observed.

[0727] Wild type strain and transformants of *S. albus* containing control plasmid pUWL201PW or isoprene synthase encoding pUWL201_iso were analyzed for isoprene formation. Strains were cultivated in duplicate on solid media (tryptic soy broth agar, TSB; 2.5 ml) in presence or absence of thiostrepton (200 µg/ml) and incubated for 4 days at 28°C in sealed head-space vials (total volume 20 ml). 500 µl head-space samples (end point measurements) were analyzed by GC-MS in SIM-mode and isoprene was identified according to reference retention times and molecular masses (67 m/z). Isoprene present in head-space samples was quantified by previously generated calibration curves. While wild-type *S. albus* and control strains harboring pUWL201PW produced isoprene in concentrations slightly higher than the detection limit (0.04 – 0.07 ppm), *S. albus* harboring pUWL201_iso produced isoprene in at least tenfold excess compared to controls (0.75 ppm; Figure 130). The results demonstrate successful expression of plant-derived isoprene synthase in a prokaryotic organism of the *Actinomycetes* group.

Example 16: Production of isoprene or mevalonate from fatty acid or palm oil in *E. coli* *fadR atoC* LS5218 containing the upper or upper and lower Mevalonic Acid pathway plus kudzu isoprene synthase.

[0728] *Escherichia coli fadR atoC* strain LS5218 (#6966) was obtained from the Coli Genetic Stock Center. FadR encodes a transcription repressor that negatively regulates expression of the genes encoding fatty acid degradation enzymes (Campbell *et al.*, *J. Bacteriol.* 183: 5982-5990, 2001). AtoC is a response regulator in a two-component regulatory system wherein AtoS regulates acetolactate metabolism. The *fadR atoC* strain allows constitutive expression of the fatty acid degradation genes and incorporates long chain fatty acids into long-chain-length polyhydroxyalkanoates. When palm oil is used as a carbon source for either mevalonate or isoprene production, the palm oil was converted to glycerol plus fatty acid. Methods for this are well known in the art, and it can be done either enzymatically by incubation with a lipase (for example Porcine pancreatic lipase, *Candida rugosa* lipase, or other similar lipases) or chemically by saponification with a base such as sodium hydroxide.

i) *E. coli fadR atoC* strain expressing the upper Mevalonic Acid pathway

[0729] Strain WW4 was created by electroporating pCLPtrcUpperPathway into LS5218 using standard methods (Sambrooke *et al.*, Molecular Cloning: A Laboratory Manual, 2nd ed.,

Cold Spring Harbor, 1989). Incorporation of the plasmid was demonstrated by the production of mevalonic acid (MVA) when cells were cultured in TM3 medium supplemented with either C12 fatty acid (FA) or palm oil as the carbon source. To demonstrate production of MVA by WW4 from fatty acid, cells from an overnight culture were diluted 1 to 100 into 5 mL of modified TM3 medium (TM3 without yeast extract) supplemented with 0.25% C12 FA (Sigma cat # L9755). The first sign of MVA production (24 mg/L) was apparent after overnight incubation at 30°C of the IPTG induced culture. Production increased over three days with the final level of 194 mg/L of MVA produced. To demonstrate production of MVA by WW4 from oil, cells from an overnight culture were diluted 1 to 100 into modified TM3 medium supplemented with 200 mg of digested palm oil per 5 mL of TM3 medium. The first sign of MVA production (50 mg/L) was apparent after overnight incubation of the IPTG induced culture at 30°C. Production increased over three days with a final level of 500 mg/L of MVA produced.

ii) *E. coli fadR atoC* strain expressing the upper and lower MVA pathway plus kudzu isoprene synthase

[0730] *Escherichia coli* strain WW4 (LS5218 *fadR atoC* pCLPtrcUpperPathway) was transformed with pMCM118 [pTrcKKDyIkIS] to yield WW10. The incorporation of the plasmid was demonstrated by evidence of production of isoprene when the strain was cultured in TM3 and glucose and induced with IPTG (100, 300, or 900 μ M). The strain was relatively sensitive to IPTG and showed a significant growth defect even at 100 μ M IPTG. These results are shown in Figure 128A.

[0731] To test isoprene production from dodecanoic acid, WW10 was cultured overnight in L broth containing spectinomycin (50 μ g/ml), and kanamycin (50 μ g/ml) at 37°C with shaking at 200 rpm. The cells were washed with modified TM3 medium by centrifugation and resuspension in their original culture volume with this medium. The washed and resuspended cells from this starter culture were diluted 1 to 100 and 1 to 10 into 5 mL of modified TM3 medium containing 0.125% C12 Fatty Acid (Sigma cat # L9755).

[0732] To demonstrate production of mevalonate from palm oil, the oil was predigested with lipase at 37°C and 250 rpm for several days to release the fatty acids (evidence of hydrolysis was judged by the foam formed when tubes were shaken).

[0733] In addition, a culture was set up by diluting the washed cells at 1 to 10 into modified TM3 medium contained in test tubes with palm oil. A further tube was set up by the addition of 0.125% C12FA to the remainder (2.5 mL) of the washed cells without further dilution (bioconversion). After 3.75 hours of growth at 30°C with shaking at 250 rpm all of the cultures were induced by the addition of 50 µM IPTG. Incubation was continued for 4 hours after which time 200 µL of each of the cultures was assayed for isoprene accumulation with a modified head space assay (1 hour accumulation at 30°C with shaking at 500 rpm). An additional isoprene assay was conducted by a 12 hour incubation of the assay glass block prior to GCMS analysis. Incubation of the induced cultures was continued overnight and 200 µL aliquots were again assayed for isoprene production (1 hour, 30 deg, 500 rpm Shel-Lab shaker) the following morning. Analysis of these cultures showed the production of significant levels of isoprene. The highest levels of isoprene were observed in the culture which was seeded at 1/10 dilution from the overnight starter culture after it had been incubated and induced overnight. This result suggests that this culture continued to grow and increase in cell density. These results are shown in Figure 128B. Cell density could not be measured directly because the fatty acid suspension had a turbid appearance. Cell density of this culture was therefore determined by plating an aliquot of the culture and showed 8×10^7 colony forming units. This corresponds approximately to an OD₆₀₀ of 0.1. Nevertheless, this culture provided significant isoprene production; no isoprene is observed for similar strains without the pathway described in this example.

Example 17: Improvement of isoprene production by constitutive expression of *ybhE* in *E. coli*.

[0734] This example shows production of isoprene in a strain constitutively expressing *ybhE* (*pgl*) compared to a control strain with wild type *ybhE*. The gene *ybhE* (*pgl*) encodes a 6-phosphogluconolactonase that suppresses posttranslational gluconylation of heterologously expressed proteins and improves product solubility and yield while also improving biomass yield and flux through the pentose phosphate pathway (Aon *et al. Applied and Environmental Microbiology*, 74(4): 950-958, 2008).

[0735] The BL21 strain of *E. coli* producing isoprene (EWL256) was constructed with constitutive expression of the *ybhE* gene on a replicating plasmid pBBR1MCS5(Gentamycin) (obtained from Dr. K. Peterson, Louisiana State University).

[0736] FRT-based recombination cassettes, and plasmids for Red/ET-mediated integration and antibiotic marker loopout were obtained from Gene Bridges GmbH (Germany). Procedures using these materials were carried out according to Gene Bridges protocols. Primers Pgl-F and PglGI1.5-R were used to amplify the resistance cassette from the FRT-gb2-Cm-FRT template using Stratagene Herculanase II Fusion kit according to the manufacturer's protocol. The PCR reaction (50 μ L final volume) contained: 5 μ L buffer, 1 μ L template DNA (FRT-gb2-Cm-F from Gene Bridges), 10 pmols of each primer, and 1.5 μ L 25mM dNTP mix, made to 50 μ L with dH₂O. The reaction was cycled as follows: 1 x 2 minutes, 95°C then 30 cycles of (30 seconds at 95°C; 30 seconds at 63°C; 3 minutes at 72°C).

[0737] The resulting PCR product was purified using the QiaQuick PCR purification kit (Qiagen) and electroporated into electrocompetent MG1655 cells harboring the pRed-ET recombinase-containing plasmid as follows. Cells were prepared by growing in 5 mLs of L broth to and OD₆₀₀~0.6 at 30°C. The cells were induced for recombinase expression by the addition of 4% arabinose and allowed to grow for 30 minutes at 30°C followed by 30 minutes of growth at 37°C. An aliquot of 1.5 mLs of the cells was washed 3-4 times in ice cold dH₂O. The final cell pellet was resuspended in 40 μ L of ice cold dH₂O and 2-5 μ L of the PCR product was added. The electroporation was carried out in 1-mm gap cuvettes, at 1.3 kV in a Gene Pulser Electroporator (Bio-Rad Inc.). Cells were recovered for 1-2 hours at 30°C and plated on L agar containing chloramphenicol (5 μ g/mL). Five transformants were analyzed by PCR and sequencing using primers flanking the integration site (2 primer sets: pgl and 49 rev and 3' EcoRV-pglstop; Bottom Pgb2 and Top GB's CMP (946)). A correct transformant was selected and this strain was designated MG1655 GI1.5-pgl::CMP.

[0738] The chromosomal DNA of MG1655 GI1.5-pgl::CMP was used as template to generate a PCR fragment containing the FRT-CMP-FRT-GI1.5 - ybhE construct. This construct was cloned into pBBR1MCS5(Gentamycin) as follows. The fragment, here on referred to as CMP-GI1.5-pgl, was amplified using the 5' primer Pglconfirm-F and 3' primer 3' EcoRV-pglstop. The resulting fragment was cloned using the Invitrogen TOPO-Blunt cloning kit into the plasmid vector pCR-Blunt II-TOPO as suggested from the manufacturer. The *Nsi*I fragment harboring the CMP-GI1.5-pgl fragment was cloned into the *Pst*I site of pBBR1MCS5(Gentamycin). A 20 μ L ligation reaction was prepared containing 5 μ L CMP-GI1.5-pgl insert, 2 μ L pBBR1MCS5(Gentamycin) vector, 1 μ L T4 DNA ligase (New England

Biolabs), 2µl 10X ligase buffer, and 10µl ddH₂O. The ligation mixture was incubated at room temperature for 40 minutes then 2-4 µL were electroporated into electrocompetent Top10 cells (Invitrogen) using the parameters disclosed above. Transformants were selected on L agar containing 10 µg/ml chloramphenicol and 5 µg/ml Gentamycin. The sequence of the selected clone was determined using a number of the primers described above as well as with the in-house T3 and Reverse primers provided by Sequetech, CA. This plasmid was designated pBBRCMPGI1.5-pgl (Figures 135A-B and SEQ ID NO:136).

[0739] Plasmid pBBRCMPGI1.5-pgl was electroporated into EWL256, as described above in Example 10 and transformants were plated on L agar containing Chloramphenicol (10 µg/mL), Gentamycin (5 µg/mL), spectinomycin (50 µg/mL), and carbenicillin (50 µg/mL). One transformant was selected and designated RM11608-2.

Primers:

Pgl-F

5'-

ACCGCCAAAAGCGACTAATTTTAGCTGTTACAGTCAGTTGAATTAACCCTCACTA
AAGGGCGGCCGC-3' (SEQ ID NO:129)

PglGI1.5-R

5'-

GCTGGCGATATAAACTGTTTGCTTCATGAATGCTCCTTTGGGTTACCTCCGGGAA
ACGCGGTTGATTTGTTTAGTGGTTGAATTATTTGCTCAGGATGTGGCATAGTCAA
GGGCGTGACGGCTCGCTAATACGACTCACTATAGGGCTCGAG-3' (SEQ ID NO:130)

3' EcoRV-pglstop: 5'-CTT GAT ATC TTA GTG TGC GTT AAC CAC CAC (SEQ ID
NO:131)

pgl +49 rev: CGTGAATTTGCTGGCTCTCAG (SEQ ID NO:132)

Bottom Pgb2: GGTTTAGTTCCTCACCTTGTC (SEQ ID NO:133)

Top GB's CMP (946): ACTGAAACGTTTTTCATCGCTC (SEQ ID NO:134)

Pglconfirm-F

5'-ACCGCCAAAAGCGACTAATTTTAGCT-3' (SEQ ID NO:135)

i) Small scale analysis

Media Recipe (per liter fermentation media):

[0740] K_2HPO_4 13.6 g, KH_2PO_4 13.6 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, $(\text{NH}_4)_2\text{SO}_4$ 3.2 g, yeast extract 1 g, 1000X Trace Metals Solution 1 ml. All of the components were added together and dissolved in diH_2O . The pH was adjusted to 6.8 with ammonium hydroxide (30%) and brought to volume. Media was filter-sterilized with a 0.22 micron filter. Glucose 5.0 g and antibiotics were added after sterilization and pH adjustment.

1000X Trace Metal Solution (per liter fermentation media):

[0741] Citric Acid * H_2O 40g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30g, NaCl 10g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1g, $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ 1g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100mg, H_3BO_3 100mg, $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100mg. Each component is dissolved one at a time in diH_2O . The pH is adjusted to 3.0 with HCl/NaOH, and then the solution is brought to volume and filter-sterilized with a 0.22 micron filter.

a) Experimental procedure

[0742] Isoprene production was analyzed by growing the strains in a CelleratorTM from MicroReactor Technologies, Inc. The working volume in each of the 24 wells was 4.5 mL. The temperature was maintained at 30°C, the pH setpoint was 7.0, the oxygen flow setpoint was 20 sccm and the agitation rate was 800 rpm. An inoculum of *E. coli* strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 30°C. A single colony was inoculated into media with antibiotics and grown overnight. The bacteria were diluted into 4.5 mL of media with antibiotics to reach an optical density of 0.05 measured at 550 nm.

[0743] Off-gas analysis of isoprene was performed using a gas chromatograph-mass spectrometer (GC-MS) (Agilent) headspace assay. Sample preparation was as follows: 100 μL of whole broth was placed in a sealed GC vial and incubated at 30°C for a fixed time of 30 minutes. Following a heat kill step, consisting of incubation at 70°C for 5 minutes, the sample was loaded on the GC.

[0744] Optical density (OD) at a wavelength of 550 nm was obtained using a microplate reader (Spectramax) during the course of the run. Specific productivity was obtained by dividing the isoprene concentration ($\mu\text{g/L}$) by the OD reading and the time (hour).

[0745] The two strains EWL256 and RM11608-2 were assessed at 200 and 400 μM IPTG induction levels. Samples were analyzed for isoprene production and cell growth (OD550) at 1, 2.5, 4.75, and 8 hours post-induction. Samples were done in duplicate.

b) Results

[0746] The experiment demonstrated that at 2 different concentrations of IPTG the strain expressing the ybhE (*pgl*) had a dramatic 2-3 fold increase in specific productivity of isoprene compared to the control strain.

ii) Isoprene fermentation from *E. coli* expressing *M. mazei* mevalonate kinase, *P. alba* isoprene synthase, and *pgl* over-expression (RHM11608-2) and grown in fed-batch culture at the 15-L scale

Medium Recipe (per liter fermentation medium)

[0747] K_2HPO_4 7.5 g, $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ 2 g, citric acid monohydrate 2 g, ferric ammonium citrate 0.3 g, yeast extract 0.5 g, 1000X Modified Trace Metal Solution 1 ml. All of the components were added together and dissolved in diH_2O . This solution was autoclaved. The pH was adjusted to 7.0 with ammonium hydroxide (30%) and q.s. to volume. Glucose 10 g, thiamine $\cdot \text{HCl}$ 0.1 g, and antibiotics were added after sterilization and pH adjustment.

1000X Modified trace Metal Solution:

[0748] Citric Acids $\cdot \text{H}_2\text{O}$ 40 g, $\text{MnSO}_4 \cdot \text{H}_2\text{O}$ 30 g, NaCl 10 g, $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ 1 g, $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ 1 g, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ 100 mg, H_3BO_3 100 mg, $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ 100 mg. Each component is dissolved one at a time in $\text{Di H}_2\text{O}$, pH to 3.0 with HCl/NaOH , then q.s. to volume and filter sterilized with a 0.22 micron filter.

[0749] Fermentation was performed in a 15-L bioreactor with BL21 (DE3) *E. coli* cells containing the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (*gi1.2KKDyI*), high expression of mevalonate kinase from *M. mazei* and

isoprene synthase from *P. alba* (pTrcAlba-mMVK), and high expression of *pgl* (pBBR-pgl). This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH 7.0 and temperature 34°C. A frozen vial of the *E. coli* strain was thawed and inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 15-L bioreactor bringing the initial volume to 5-L.

[0750] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 40 hour (59 hour) fermentation was 3.1 kg (4.2 kg at 59 hour). Induction was achieved by adding IPTG. The IPTG concentration was brought to 110 μ M when the optical density at 550 nm (OD₅₅₀) reached a value of 4. The IPTG concentration was raised to 192 μ M when OD₅₅₀ reached 150. The OD₅₅₀ profile within the bioreactor over time is shown in Figure 136A. The isoprene level in the off gas from the bioreactor was determined using a Hiden mass spectrometer. The isoprene titer increased over the course of the fermentation to a maximum value of 33.2 g/L at 40 hours (48.6 g/L at 59 hours) (Figure 136B). The isoprene titer increased over the course of the fermentation to a maximum value of 40.0 g/L at 40 hours (60.5 g/L at 59 hours) (Figure 136C). The total amount of isoprene produced during the 40-hour (59-hour) fermentation was 281.3 g (451.0 g at 59 hours) and the time course of production is shown in Figure 136D. The time course of volumetric productivity is shown in Figure 136E and shows that an average rate of 1.0 g/L/hr was maintained between 0 and 40 hours (1.4 g/L/hour between 19 and 59 hour). The metabolic activity profile, as measured by CER, is shown in Figure 136F. The molar yield of utilized carbon that went into producing isoprene during fermentation was 19.6% at 40 hours (23.6% at 59 hours). The weight percent yield of isoprene from glucose was 8.9% at 40 hours (10.7% at 59 hours)

Example 18. Isoprene Polymerization

Preparation of Isoprene Samples for Polymerization

(a) Preparation of 1000X Modified Trace Metal Solution:

[0751] Each of the following components is dissolved one at a time in Di H₂O: Citric Acid * H₂O (40 g), MnSO₄ * H₂O (30 g), NaCl (10 g), FeSO₄ * 7H₂O (1 g), CoCl₂ * 6H₂O (1 g),

ZnSO₄ * 7H₂O (1 g), CuSO₄ * 5H₂O (100 mg), H₃BO₃ (100 mg), NaMoO₄ * 2H₂O (100 mg). The pH was adjusted to 3.0 with HCl/NaOH, then q.s. to volume and filter sterilized with a 0.22 micron filter.

(b) Preparation of Fermentation Medium:

[0752] Each liter of fermentation medium contained K₂HPO₄ (7.5 g), MgSO₄ * 7H₂O (2 g), citric acid monohydrate (2 g), ferric ammonium citrate (0.3 g), yeast extract (0.5 g), 1000X Modified Trace Metal Solution (1 ml). All of the components were added together and dissolved in diH₂O. This solution was autoclaved. The pH was adjusted to 7.0 with ammonium gas (NH₃) and q.s. to volume. Glucose (10 g), thiamine * HCl (0.1 g), and antibiotic were added after sterilization and pH adjustment.

(c) Collection of Isoprene Samples for Purification and Polymerization:

[0753] Isoprene was collected by adsorption on activated charcoal by passing the fermentation exhaust across canisters of activated charcoal arranged in parallel on an exhaust manifold.

(d) Preparation of Isoprene Polymerization Sample A from Glucose using E. coli

[0754] Fermentation was performed at pH 7.0 and 30°C in a 15-L bioreactor with BL21 (DE3) E. coli cells containing the pCL PtrcUpperMVA and pTrc KKDyIkIS plasmids. An inoculum of E. coli strain taken from a frozen vial was streaked onto an LB broth agar plate (with antibiotics) and incubated at 37 °C. A single colony was inoculated into tryptone-yeast extract medium. After the inoculum grew to OD 1.0, measured at 550 nm, 500 mL was used to inoculate a 5-L bioreactor.

[0755] Glucose was fed at an exponential rate until cells reached the stationary phase. After this time the glucose feed was decreased to meet metabolic demands. The total amount of glucose delivered to the bioreactor during the 54 hour fermentation was 3.7 kg. Induction was achieved by adding isopropyl-beta-D-1-thiogalactopyranoside (IPTG). The IPTG concentration was brought to 25 µM when the optical density at 550 nm (OD₅₅₀) reached a value of 10. The IPTG concentration was raised to 50 µM when OD₅₅₀ reached 190. IPTG concentration was raised to 100 µM at 38 hours of fermentation. The OD₅₅₀ profile within the bioreactor over time is shown in Figure 138. The isoprene titer increased over the course

of the fermentation to a final value of 2.2 g/L (Figure 139). The total amount of isoprene produced during the 54 hour fermentation was 15.9 g and the time course of production is shown in Figure 140. The molar yield of utilized carbon that went into producing isoprene during fermentation was 1.53%. (See Figures 138-140).

(e) Preparation of Isoprene Polymerization Sample B from Glucose and Yeast Extract using *E. coli*

[0756] Isoprene formation from glucose and yeast extract was performed at pH 7.0 and 30°C in a 500-L bioreactor with *E. coli* cells containing the pTrcKudzu + yIDI + DXS plasmid. An inoculum of *E. coli* strain taken from a frozen vial was prepared in soytone-yeast extract-glucose medium. After the inoculum grew to OD 0.15, measured at 550 nm, 20 mL was used to inoculate a bioreactor containing 2.5-L tryptone-yeast extract medium. The 2.5-L bioreactor was grown at 30 °C to OD 1.0 and 2.0-L was transferred to the 500-L bioreactor. Yeast extract (Bio Springer, Montreal, Quebec, Canada) and glucose were fed at exponential rates. The total amount of glucose and yeast extract delivered to the bioreactor during the 50 hour fermentation was 181.2 kg and 17.6 kg, respectively. The optical density within the bioreactor over time is shown in Figure 141. The isoprene titer increased over the course of the fermentation (Figure 142). The total amount of isoprene produced during the 50 hour fermentation was 55.1 g and the time course of production is shown in Figure 143.

Isoprene Desorption from Activated Charcoal (Method A):

[0757] Activated charcoal (130 g), which had been exposed to a stream of fermentor off-gas, was placed into a 1000 mL flask along with a stir bar. Cyclohexane (563 mL) was added to the flask and the slurry was agitated for 2 hours. Vacuum was applied (100 mbar) via an in-line cryogenic trap (30 mL capacity, immersed in liq. nitrogen). Four fractions were collected and combined to yield an isoprene/cyclohexane solution (2.1 wt% isoprene, total volume = 53.1 g). This solution was vacuum distilled at 100 mbar and a new isoprene/cyclohexane solution was collected (yield = 10.1g), which was dried over 3A molecular sieves. GC analysis of this solution indicated an isoprene content of 7.7 wt.%.

Isoprene Desorption from Activated Charcoal (Method B):

[0758] Activated charcoal (65 g), which had been exposed to a stream of fermentor off-gas, was placed into a 500 mL flask along with a stir bar. Jarytherm DBT (250 g) was added to

the charcoal and the slurry was agitated for 2 hours. Vacuum was applied (5mbar) via an in-line cryogenic trap (30 mL capacity, immersed in liq. nitrogen). After 1 hour the trap was warmed to ambient temperature. Two liquid phases were present in the trap (total weight 1.82 g). The organic phase was diluted with cyclohexane (3.26 g), decanted, and dried over 3A molecular sieves. GC analysis of this solution indicated an isoprene content of 27.3 wt.%, or 1.22 g).

Preparation of Neodymium Catalyst:

[0759] Neodymium versatate (2.68 mL, 0.51 M in hexane,), triisobutylaluminum (54 mL, 1.0 M in hexane), and diethylaluminum chloride (3.40 mL, 1.0 M in hexane) were drawn up into plastic syringes fitted with steel cannula. The first two components were added to a solution of 1,3-butadiene in hexane (22.4 mL, 15 wt.% 1,3-butadiene, placed into a 100 mL glass vessel with septum top, and agitated for 0.5 h at ambient temperature. The last component was added to the solution after which it was heat-aged for 0.5 h at 65°C. The final solution was clear and yellow. The concentration of the solution based on neodymium was 0.0164 M.

Preparation of Titanium Catalyst:

[0760] A 100 mL glass reaction vessel with septum inlet and containing a magnetic stirbar was placed in an ice bath at 0°C, charged with n-hexane (5.07 mL, anhydrous), and with neat TiCl₄ (1.5 mL, 13.7 mmol) under vigorous agitation. Separately, a solution was generated consisting of diphenyl ether (1.2 mL, 7.6 mmol) and triisobutylaluminum (14.6 mL, 12.6 mmol, 25 wt.% solution in hexane). The solution was added to the reaction vessel over the course of 5 minutes. A brown precipitate formed during the addition. The suspension was stirred for 10 minutes and was then stored at -40°C for future use.

Polymerization:

[0761] Samples of polyisoprene derived primarily from glucose were produced by polymerizing Isoprene Polymerization Sample A with Neodymium catalyst and n-BuLi. Samples of polyisoprene derived from cofermentation of glucose and yeast extract were produced by polymerizing Isoprene Polymerization Sample B with Neodymium catalyst, titanium catalyst, n-BuLi catalyst, and emulsion free radical polymerization. Representative polymerization conditions are described below.

Solution Polymerization of Isoprene with Neodymium Catalyst:

[0762] A 4 mL screw top glass vial with Teflon coated stir bar was annealed in an oven for 3 h at 150°C. The vial was fitted with a Teflon faced silicone septum and open-top cap. Using a syringe, it was then charged with an isoprene solution (1.5 g, 7.7 wt.% in cyclohexane, anhydrous). Neodymium catalyst solution (60 µL) was injected into the vial with a micro-syringe. The vial was placed onto a stirrer/hotplate regulated to 65°C, with the stir bar spinning at 500 rpm. After 15 minutes the solution became noticeably more viscose. After a reaction time of 1.5 h the reaction was quenched with a solution of isopropanol and butylated hydroxytoluene, (BHT), (30 µL, 10 wt.% BHT). A 100 mg sample of the cement was removed for GPC analysis. The remaining polymer cement was dried under ambient conditions. The isolated polymer weighed 110 mg, was determined to have a weight average molecular weight of 935,000 (by GPC) and a cis-mirrostructure content of greater than 90% (by ¹³C-NMR).

Solution Polymerization of Isoprene with Ti Catalyst:

[0763] A 4 mL screw top glass vial and Teflon coated stir bar was annealed in an oven for 3 h at 150°C. The vial was fitted with a pre-scored Teflon faced silicone septum and open-top cap. Using a syringe, it was then charged with an isoprene solution (1.5 g, 7.7 wt.% in cyclohexane, anhydrous). The titanium catalyst suspension was magnetically stirred and a sample was removed (70 µL) with a disposable tip pipette, which was then added to the reaction vial through the pre-scored septum. The reaction vial septum was replaced with a solid cap, and the vial was placed onto a stirrer/hotplate regulated to 65°C, with the stir bar spinning at 500 rpm. After 5 minutes the solution became noticeably more viscose. After a reaction time of 1.5 h the reaction was quenched with a solution of isopropanol and butylated hydroxytoluene, (BHT), (30 µL, 10 wt.% BHT). A 100 mg sample of the cement was removed for GPC analysis. The remaining polymer cement was dried under ambient conditions. The isolated polymer weighed 108 mg, had a weight average molecular weight of 221,000 (by GPC), and had a cis-mirocstructure content of greater than 94% (by ¹³C-NMR).

Emulsion Polymerization of Isoprene:

[0764] A 20 mL vial was used as a polymerization vessel. The metal cap was pierced twice with an awl and cardboard linear was replaced with a rubber gasket and Teflon linear. The vial was rinsed with deionized water and dried under nitrogen.

[0765] To the vial was added 7.05 g deionized water, 1.14 g of 10% soap (potassium salt of mixed fatty acids), 174 mg of 10% ammonium persulfate solution, and 24 mg of n-dodecane thiol. The flask was purge for 30 seconds with nitrogen and capped. To the vial through the rubber/Teflon gasket was charged 3 mL of bio-HG (2.033 grams of isoprene). The vial was placed in a standard bottle polymerization bath (a second blank vial allows the vial to fit in a 4 oz bottle holder). The mixture was tumbled for 25.5 hours at 65°C (+/- 0.2°C).

Work-up:

[0766] The latex was transferred to 50 mL pear shaped flask and diluted with 10 mL of water. Un-reacted volatile organic was removed by evaporating 2 mL of water under vacuum (54 mmHg, 40 – 50°C). To the latex was added an antioxidant dispersion, 140 mg of 50% active polyphenolic AO (Bostex 24). The latex was coagulated by adding it to a dilute acid solution (12 mL of 18% sulfuric acid in 150 mL RO water). The polymer coagulated into a single large piece which was pressed and washed with RO water. The sample was off white soft rubbery mass. The yield was 1.24 grams of wet crumb.

[0767] The final total solids content ($TSC = 100 \times \text{dried weight} / \text{wet weight}$) was 18.9 wt% or an approximate conversion of 84%.

Polymerization of Isoprene with Butyllithium:

[0768] Butyllithium (1,6 M in hexane) was diluted with n-hexane (anhydrous) in a ratio of 1:10. The solution was titrated against a standard N-pivaloyl-o-benzylaniline in THF. A solution of isoprene in cyclohexane (4 mL) was dried by passing it through a small column containing heat treated silica gel.

[0769] A 4 mL glass vial (oven dried at 150°C) was charged with a small Teflon coated magnetic stir bar and a solution of isoprene in cyclohexane (1.35 g, 21.5 wt %). Butyllithium (0.14 M, hexane) was added via syringe and the vial was heated to 65°C on a stirrer/hot plate

for 3 h. The polymer reaction was quenched with a BHT/iso-propanol solution (10 wt % BHT in iso-propanol). All volatiles were removed under vacuum. This procedure yielded 290 mg of polymer which represents a theoretical yield of about 100%. This polymer was determined by GPC analysis to have a weight average molecular weight (M_w) of 17,880 and was determined by ^{13}C NMR to have a cis-microstructure content of 67%; a trans-microstructure content of 25%, and a 3,4-microstructure content of 8%.

GPC Analysis of Polymers:

[0770] Size Exclusion Chromatography (SEC) is a well established technique to measure polymer molecular weight and polydispersity (M_w/M_n). Two Polymer Laboratories C microgel columns in series were utilized with tetrahydrofuran as the carrier solvent at a flow rate of 0.7 ml/min and a column temperature of 40°C. SEC was performed using a Wyatt Technologies miniDawn light scattering detector coupled with a Hewlett Packard 1047A refractive index detector. Polystyrene standards were used to calibrate the instrument.

NMR Analysis of Polymers:

[0771] Polymer microstructures were determined by ^{13}C -NMR analysis on a Varian Unity-Plus 400 MHz spectrometer in chloroform-*d* solvent.

Table 14: Data from $^{13}\text{C}/^{12}\text{C}$ Isotope Analyses

Entry	Sample (note: PI = polyisoprene)	$\delta^{13}\text{C}$
1	PI from sugar beet invert sugar	-34.98
2	Commercial PI from isobutylene	-34.43
3	Commercial PI from isobutylene	-34.42
4	Guayule rubber	-31.10
5	Palm oil	-30.03
6	Palm oil	-30.00
7	Natural rubber (Neco)	-28.11
8	Natural rubber (Pumpic)	-27.92
9	Natural rubber (Negato)	-27.86
10	Natural rubber (Nivco)	-27.79
11	Natural rubber (Naplo)	-27.74
12	Natural rubber (Krado 1)	-27.68
13	Natural rubber (Krado 1)	-27.55
14	Natural rubber (Krado 2)	-27.54
15	Natural rubber (Krado 2)	-27.52
16	Natural rubber (Krado 2)	-27.49
17	Natural rubber (Nolo)	-27.38
18	Yeast extract	-25.70

19	Yeast extract	-25.68
20	Commercial PI from extractive distillation (Sample 2)	-23.83
21	Commercial PI from extractive distillation (Sample 2)	-23.83
22	Sugar from softwood pulp (Sample 2)	-23.25
23	Sugar from softwood pulp (Sample 1)	-23.00
24	Sugar from softwood pulp (Sample 1)	-22.96
25	Commercial PI from extractive distillation (Sample 3)	-22.95
26	Commercial PI from extractive distillation (Sample 3)	-22.95
27	Commercial PI from extractive distillation (Sample 3)	-22.94
28	Commercial PI from extractive distillation (Sample 3)	-22.92
29	Commercial PI from extractive distillation (Sample 3)	-22.90
30	Commercial PI from extractive distillation (Sample 3)	-22.89
31	Commercial PI from extractive distillation (Sample 3)	-22.89
32	Commercial PI from extractive distillation (Sample 3)	-22.89
33	Commercial PI from extractive distillation (Sample 3)	-22.87
34	Commercial PI from extractive distillation (Sample 3)	-22.84
35	Commercial PI from extractive distillation (Sample 1)	-22.63
36	Commercial PI from extractive distillation (Sample 1)	-22.62
37	Commercial PI from extractive distillation (Sample 1)	-22.54
38	PI from Isoprene Sample B (emulsion polymerization)	-19.67
39	PI from Isoprene Sample B (Neodymium catalyst)	-19.14
40	PI from Isoprene Sample B (Neodymium catalyst)	-18.80
41	PI from Isoprene Sample B (Neodymium catalyst)	-18.37
42	PI from Isoprene Sample B (n-BuLi catalyst)	-18.12
43	PI from Isoprene Sample B (n-BuLi catalyst)	-18.12
44	Invert Sugar (Sample 1)	-15.37
45	Invert Sugar (Sample 2)	-15.36
46	Invert Sugar (Sample 1)	-15.34
47	Invert Sugar (Sample 1)	-15.31
48	Invert Sugar (Sample 1)	-15.25
49	PI from Isoprene Sample A (Neodymium catalyst)	-14.85
50	PI from Isoprene Sample A (n-BuLi catalyst)	-14.69
51	PI from Isoprene Sample A (n-BuLi catalyst)	-14.69
52	PI from Isoprene Sample A (n-BuLi catalyst)	-14.66
53	Glucose from bagasse (sample 2)	-13.19
54	Glucose from bagasse (sample 1)	-13.00
55	Glucose from bagasse (sample 1)	-12.93
56	Glucose from corn stover (sample 2)	-11.42
57	Glucose from corn stover (sample 1)	-11.23
58	Glucose from corn stover (sample 1)	-11.20
59	Cornstarch	-11.12
60	Cornstarch	-11.11
61	Cornstarch	-11.10
62	Cornstarch	-11.07
63	Glucose	-10.73

[0772] Unless defined otherwise, the meanings of all technical and scientific terms used herein are those commonly understood by one of skill in the art to which this invention belongs. Singleton, *et al.*, Dictionary of Microbiology and Molecular Biology, 2nd ed., John Wiley and Sons, New York (1994), and Hale & Marham, The Harper Collins Dictionary of Biology, Harper Perennial, N.Y. (1991) provide one of skill with a general dictionary of many of the terms used in this invention. It is to be understood that this invention is not limited to the particular methodology, protocols, and reagents described, as these may vary. One of skill in the art will also appreciate that any methods and materials similar or equivalent to those described herein can also be used to practice or test the invention.

[0773] The headings provided herein are not limitations of the various aspects or embodiments of the invention which can be had by reference to the specification as a whole.

[0774] For use herein, unless clearly indicated otherwise, use of the terms “a”, “an,” and the like refers to one or more. The singular terms “a,” “an,” and “the” include the plural reference unless the context clearly indicates otherwise

[0775] Reference to “about” a value or parameter herein includes (and describes) embodiments that are directed to that value or parameter per se. For example, description referring to “about X” includes description of “X.” Numeric ranges are inclusive of the numbers defining the range.

[0776] It is understood that aspects and embodiments of the invention described herein include “comprising,” “consisting,” and “consisting essentially of” aspects and embodiments.

[0777] It is intended that every maximum numerical limitation given throughout this specification includes every lower numerical limitation, as if such lower numerical limitations were expressly written herein. Every minimum numerical limitation given throughout this specification will include every higher numerical limitation, as if such higher numerical limitations were expressly written herein. Every numerical range given throughout this specification will include every narrower numerical range that falls within such broader numerical range, as if such narrower numerical ranges were all expressly written herein.

Appendix 1

Exemplary 1-deoxy-D-xylulose-5-phosphate synthase nucleic acids and polypeptides

ATH: AT3G21500(DXPS1)	MSU: MS1059(dxS)
AT4G15560(CLA1) AT5G11380(DXPS3)	APL: APL_0207(dxS)
OSA: 4338768 4340090 4342614	XFA: XF2249
CME: CMF089C	XFT: PD1293(dxS)
PFA: MAL13P1.186	XCC: XCC2434(dxS)
TAN: TA20470	XCB: XC_1678
TPV: TP01_0516	XCV: XCV2764(dxS)
ECO: b0420(dxS)	XAC: XAC2565(dxS)
ECJ: JW0410(dxS)	XOO: XOO2017(dxS)
ECE: Z0523(dxS)	XOM: XOO_1900(XOO1900)
ECS: ECs0474	VCH: VC0889
ECC: c0531(dxS)	VVU: VV1_0315
ECI: UTI89_C0443(dxS)	VVY: VV0868
ECP: ECP_0479	VPA: VP0686
ECV: APECO1_1590(dxS)	VFI: VF0711
ECW: EcE24377A_0451(dxS)	PPR: PBPR0805
ECX: EcHS_A0491	PAE: PA4044(dxS)
STY: STY0461(dxS)	PAU: PA14_11550(dxS)
STT: t2441(dxS)	PAP: PSPA7_1057(dxS)
SPT: SPA2301(dxS)	PPU: PP_0527(dxS)
SEC: SC0463(dxS)	PST: PSPTO_0698(dxS)
STM: STM0422(dxS)	PSB: Psyr_0604
YPE: YPO3177(dxS)	PSP: PSPPH_0599(dxS)
YPK: y1008(dxS)	PFL: PFL_5510(dxS)
YPM: YP_0754(dxS)	PFO: Pfl_5007
YPA: YPA_2671	PEN: PSEEN0600(dxS)
YPN: YPN_0911	PMY: Pmen_3844
YPP: YPDSF_2812	PAR: Psyc_0221(dxS)
YPS: YPTB0939(dxS)	PCR: Pcryo_0245
YPI: YpsIP31758_3112(dxS)	ACI: ACIAD3247(dxS)
SFL: SF0357(dxS)	SON: SO_1525(dxS)
SFX: S0365(dxS)	SDN: Sden_2571
SFV: SFV_0385(dxS)	SFR: Sfri_2790
SSN: SSON_0397(dxS)	SAZ: Sama_2436
SBO: SBO_0314(dxS)	SBL: Sbal_1357
SDY: SDY_0310(dxS)	SLO: Shew_2771
ECA: ECA1131(dxS)	SHE: Shewmr4_2731
PLU: plu3887(dxS)	SHM: Shewmr7_2804
BUC: BU464(dxS)	SHN: Shewana3_2901
BAS: BUsg448(dxS)	SHW: Sputw3181_2831
WBR: WGLp144(dxS)	ILO: IL2138(dxS)
SGL: SG0656	CPS: CPS_1088(dxS)
KPN: KPN_00372(dxS)	PHA: PSHAa2366(dxS)
BFL: Bfl238(dxS)	PAT: Patl_1319
BPN: BPEN_244(dxS)	SDE: Sde_3381
HIN: HI1439(dxS)	PIN: Ping_2240
HIT: NTHI1691(dxS)	MAQ: Maqu_2438
HIP: CGSHiEE_04795	MCA: MCA0817(dxS)
HIQ: CGSHiGG_01080	FTU: FTT1018c(dxS)
H DU: HD0441(dxS)	FTF: FTF1018c(dxS)
HSO: HS_0905(dxS)	FTW: FTW_0925(dxS)
PMU: PM0532(dxS)	FTL: FTL_1072

FTH: FTH_1047(dxs)
FTA: FTA_1131(dxs)
FTN: FTN_0896(dxs)
NOC: Noc_1743
AEH: Mlg_1381
HCH: HCH_05866(dxs)
CSA: Csal_0099
ABO: ABO_2166(dxs)
AHA: AHA_3321(dxs)
BCI: BCI_0275(dxs)
RMA: Rmag_0386
VOK: COSY_0360(dxs)
NME: NMB1867
NMA: NMA0589(dxs)
NMC: NMC0352(dxs)
NGO: NGO0036
CVI: CV_2692(dxs)
RSO: RSc2221(dxs)
REU: Reut_A0882
REH: H16_A2732(dxs)
RME: Rmet_2615
BMA: BMAA0330(dxs)
BMV: BMASAVP1_1512(dxs)
BML: BMA10299_1706(dxs)
BMN: BMA10247_A0364(dxs)
BXE: Bxe_B2827
BUR: Bcep18194_B2211
BCN: Bcen_4486
BCH: Bcen2424_3879
BAM: Bamb_3250
BPS: BPSS1762(dxs)
BPM: BURPS1710b_A0842(dxs)
BPL: BURPS1106A_A2392(dxs)
BPD: BURPS668_A2534(dxs)
BTE: BTH_II0614(dxs)
BPE: BP2798(dxs)
BPA: BPP2464(dxs)
BBR: BB1912(dxs)
RFR: Rfer_2875
POL: Bpro_1747
PNA: Pnap_1501
AJS: Ajs_1038
MPT: Mpe_A2631
HAR: HEAR0279(dxs)
MMS: mma_0331
NEU: NE1161(dxs)
NET: Neut_1501
NMU: Nmul_A0236
EBA: ebA4439(dxs)
AZO: azo1198(dxs)
DAR: Daro_3061
TBD: Tbd_0879
MFA: Mfla_2133
HPY: HP0354(dxs)
HPJ: jhp0328(dxs)
HPA: HPAG1_0349
HHE: HH0608(dxs)
HAC: Hac_0968(dxs)
WSU: WS1996
TDN: Tmden_0475
CJE: Cj0321(dxs)
CJR: CJE0366(dxs)
CJJ: CJJ81176_0343(dxs)
CJU: C8J_0298(dxs)
CJD: JJD26997_1642(dxs)
CFF: CFF8240_0264(dxs)
CCV: CCV52592_1671(dxs) CCV52592_1722
CHA: CHAB381_1297(dxs)
CCO: CCC13826_1594(dxs)
ABU: Abu_2139(dxs)
NIS: NIS_0391(dxs)
SUN: SUN_2055(dxs)
GSU: GSU0686(dxs-1) GSU1764(dxs-2)
GME: Gmet_1934 Gmet_2822
PCA: Pcar_1667
PPD: Ppro_1191 Ppro_2403
DVU: DVU1350(dxs)
DVL: Dvul_1718
DDE: Dde_2200
LIP: LI0408(dxs)
DPS: DP2700
ADE: Adeh_1097
MXA: MXAN_4643(dxs)
SAT: SYN_02456
SFU: Sfum_1418
PUB: SAR11_0611(dxs)
MLO: mlr7474
MES: Meso_0735
SME: SMc00972(dxs)
ATU: Atu0745(dxs)
ATC: AGR_C_1351
RET: RHE_CH00913(dxs)
RLE: RL0973(dxs)
BME: BMEI1498
BMF: BAB1_0462(dxs)
BMS: BR0436(dxs)
BMB: BruAb1_0458(dxs)
BOV: BOV_0443(dxs)
BJA: bl12651(dxs)
BRA: BRADO2161(dxs)
BBT: BBta_2479(dxs)
RPA: RPA0952(dxs)
RPB: RPB_4460
RPC: RPC_1149
RPD: RPD_4305
RPE: RPE_1067
NWI: Nwi_0633
NHA: Nham_0778
BHE: BH04350(dxs)
BQU: BQ03540(dxs)
BBK: BARBAKC583_0400(dxs)
CCR: CC_2068
SIL: SPO0247(dxs)
SIT: TM1040_2920

RSP: RSP_0254(dxSA) RSP_1134(dxS)
JAN: Jann_0088 Jann_0170
RDE: RD1_0101(dxS) RD1_0548(dxS)
MMR: Mmar10_0849
HNE: HNE_1838(dxS)
ZMO: ZMO1234(dxS) ZMO1598(dxS)
NAR: Saro_0161
SAL: Sala_2354
ELI: ELI_12520
GOX: GOX0252
GBE: GbCGDNIH1_0221 GbCGDNIH1_2404
RRU: Rru_A0054 Rru_A2619
MAG: amb2904
MGM: Mmc1_1048
SUS: Acid_1783
BSU: BG11715(dxS)
BHA: BH2779
BAN: BA4400(dxS)
BAR: GBAA4400(dxS)
BAA: BA_4853
BAT: BAS4081
BCE: BC4176(dxS)
BCA: BCE_4249(dxS)
BCZ: BCZK3930(dxS)
BTK: BT9727_3919(dxS)
BTL: BALH_3785(dxS)
BLI: BL01523(dxS)
BLD: BLi02598(dxS)
BCL: ABC2462(dxS)
BAY: RBAM_022600
BPU: BPUM_2159
GKA: GK2392
GTN: GTNG_2322
LMO: lmo1365(ktB)
LMF: LMOF2365_1382(dxS)
LIN: lin1402(ktB)
LWE: lwe1380(ktB)
LLA: L108911(dxSA) L123365(dxSB)
LLC: LACR_1572 LACR_1843
LLM: llmg_0749(dxSB)
SAK: SAK_0263
LPL: lp_2610(dxS)
LJO: LJ0406
LAC: LBA0356
LSL: LSL_0209(dxS)
LGA: LGAS_0350
STH: STH1842
CAC: CAC2077 CA_P0106(dxS)
CPE: CPE1819
CPF: CPF_2073(dxS)
CPR: CPR_1787(dxS)
CTC: CTC01575
CNO: NT01CX_1983
CTH: Cthe_0828
CDF: CD1207(dxS)
CBO: CBO1881(dxS)
CBA: CLB_1818(dxS)
CBH: CLC_1825(dxS)
CBF: CLI_1945(dxS)
CKL: CKL_1231(dxS)
CHY: CHY_1985(dxS)
DSY: DSY2348
DRM: Dred_1078
PTH: PTH_1196(dxS)
SWO: Swol_0582
CSC: Csac_1853
TTE: TTE1298(dxS)
MTA: Moth_1511
MPE: MYPE730
MGA: MGA_1268(dxS)
MTU: Rv2682c(dxS1) Rv3379c(dxS2)
MTC: MT2756(dxS)
MBO: Mb2701c(dxS1) Mb3413c(dxS2)
MLE: ML1038(dxS)
MPA: MAP2803c(dxS)
MAV: MAV_3577(dxS)
MSM: MSMEG_2776(dxS)
MMC: Mmcs_2208
CGL: NCgl1827(cgl1902)
CGB: cg2083(dxS)
CEF: CE1796
CDI: DIP1397(dxS)
CJK: jk1078(dxS)
NFA: nfa37410(dxS)
RHA: RHA1_ro06843
SCO: SCO6013(SC1C3.01)
SCO6768(SC6A5.17)
SMA: SAV1646(dxS1) SAV2244(dxS2)
TWH: TWT484
TWS: TW280(Dxs)
LXX: Lxx10450(dxS)
CMI: CMM_1660(dxSA)
AAU: AAur_1790(dxS)
PAC: PPA1062
TFU: Tfu_1917
FRA: Francci3_1326
FAL: FRAAL2088(dxS)
ACE: Ace1_1393
SEN: SACE_1815(dxS) SACE_4351
BLO: BL1132(dxS)
BAD: BAD_0513(dxS)
FNU: FN1208 FN1464
RBA: RB2143(dxS)
CTR: CT331(dxS)
CTA: CTA_0359(dxS)
CMU: TC0608
CPN: CPn1060(ktB_2)
CPA: CP0790
CPJ: CPj1060(ktB_2)
CPT: CpB1102
CCA: CCA00304(dxS)
CAB: CAB301(dxS)
CFE: CF0699(dxS)
PCU: pc0619(dxS)

TPA: TP0824
 TDE: TDE1910(dxS)
 LIL: LA3285(dxS)
 LIC: LIC10863(dxS)
 LBJ: LBJ_0917(dxS)
 LBL: LBL_0932(dxS)
 SYN: sll1945(dxS)
 SYW: SYNW1292(DxS)
 SYC: syc1087_c(dxS)
 SYF: Synpcc7942_0430
 SYD: Syncc9605_1430
 SYE: Syncc9902_1069
 SYG: sync_1410(dxS)
 SYR: SynRCC307_1390(dxS)
 SYX: SynWH7803_1223(dxS)
 CYA: CYA_1701(dxS)
 CYB: CYB_1983(dxS)
 TEL: tll0623
 GVI: gll0194
 ANA: alr0599
 AVA: Ava_4532
 PMA: Pro0928(dxS)
 PMM: PMM0907(DxS)
 PMT: PMT0685(dxS)
 PMN: PMN2A_0300
 PMI: PMT9312_0893
 PMB: A9601_09541(dxS)
 PMC: P9515_09901(dxS)

PMF: P9303_15371(dxS)
 PMG: P9301_09521(dxS)
 PMH: P9215_09851
 PMJ: P9211_08521
 PME: NATL1_09721(dxS)
 TER: Tery_3042
 BTH: BT_1403 BT_4099
 BFR: BF0873 BF4306
 BFS: BF0796(dxS) BF4114
 PGI: PG2217(dxS)
 CHU: CHU_3643(dxS)
 GFO: GFO_3470(dxS)
 FPS: FP0279(dxS)
 CTE: CT0337(dxS)
 CPH: Cpha266_0671
 PVI: Cvib_0498
 PLT: Plut_0450
 DET: DET0745(dxS)
 DEH: cbdb_A720(dxS)
 DRA: DR_1475
 DGE: Dgeo_0994
 TTH: TTC1614
 TTJ: TTHA0006
 AAE: aq_881
 TMA: TM1770
 PMO: Pmob_1001

Exemplary acetyl-CoA-acetyltransferase nucleic acids and polypeptides

HSA: 38(ACAT1) 39(ACAT2)
 PTR: 451528(ACAT1)
 MCC: 707653(ACAT1) 708750(ACAT2)
 MMU: 110446(Acat1) 110460(Acat2)
 RNO: 25014(Acat1)
 CFA: 484063(ACAT2) 489421(ACAT1)
 GGA: 418968(ACAT1)
 421587(RCJMB04_34i5)
 XLA: 379569(MGC69098) 414622(MGC81403)
 414639(MGC81256)
 444457(MGC83664)
 XTR: 394562(ACAT2)
 DRE: 30643(ACAT2)
 SPU: 759502(LOC759502)
 DME: Dmel_CG10932 Dmel_CG9149
 CEL: T02G5.4 T02G5.7 T02G5.8(kat-1)
 ATH: AT5G48230(ACAT2/EMB1276)
 OSA: 4326136 4346520
 CME: CMA042C CME087C
 SCE: YPL028W(ERG10)
 AGO: AGOS_ADR165C
 PIC: PICST_31707(ERG10)
 CAL: CaO19.1591(erg10)
 CGR: CAGL0L12364g
 SPO: SPBC215.09c

MGR: MGG_01755 MGG_13499
 ANI: AN1409.2
 AFM: AFUA_6G14200 AFUA_8G04000
 AOR: AO090103000012 AO0901030000406
 CNE: CNC05280
 UMA: UM03571.1
 DDI: DDB_0231621
 PFA: PF14_0484
 TET: TTHERM_00091590
 TTHERM_00277470 TTHERM_00926980
 TCR: 511003.60
 ECO: b2224(atoB)
 ECJ: JW2218(atoB) JW5453(yqeF)
 ECE: Z4164(yqeF)
 ECS: ECs3701
 ECC: c2767(atoB) c3441(yqeF)
 ECI: UTI89_C2506(atoB) UTI89_C3247(yqeF)
 ECP: ECP_2268 ECP_2857
 ECV: APECO1_3662(yqeF)
 APECO1_4335(atoB) APECO1_43352(atoB)
 ECX: EcHS_A2365
 STY: STY3164(yqeF)
 STT: t2929(yqeF)
 SPT: SPA2886(yqeF)
 SEC: SC2958(yqeF)

STM: STM3019(yqeF)
 SFL: SF2854(yqeF)
 SFX: S3052(yqeF)
 SFV: SFV_2922(yqeF)
 SSN: SSN_2283(atoB) SSN_3004(yqeF)
 SBO: SBO_2736(yqeF)
 ECA: ECA1282(atoB)
 ENT: Ent638_3299
 SPE: Spro_0592
 HIT: NTHI0932(atoB)
 XCC: XCC1297(atoB)
 XCB: XC_2943
 XCV: XCV1401(thIA)
 XAC: XAC1348(atoB)
 XOO: XOO1881(atoB)
 XOM: XOO_1778(XOO1778)
 VCH: VCA0690
 VCO: VC0395_0630
 VVU: VV2_0494 VV2_0741
 VVY: VVA1043 VVA1210
 VPA: VPA0620 VPA1123 VPA1204
 PPR: PBPRB1112 PBPRB1840
 PAE: PA2001(atoB) PA2553 PA3454 PA3589
 PA3925
 PAU: PA14_38630(atoB)
 PPU: PP_2051(atoB) PP_2215(fadAx) PP_3754
 PP_4636
 PPF: Pput_2009 Pput_2403 Pput_3523
 Pput_4498
 PST: PSPTO_0957(phbA-1)
 PSPTO_3164(phbA-2)
 PSB: Psyr_0824 Psyr_3031
 PSP: PSPPH_0850(phbA1)
 PSPPH_2209(phbA2)
 PFL: PFL_1478(atoB-2) PFL_2321 PFL_3066
 PFL_4330(atoB-2) PFL_5283
 PFO: Pfl_1269 Pfl_1739 Pfl_2074 Pfl_2868
 PEN: PSEEN3197 PSEEN3547(fadAx)
 PSEEN4635(phbA)
 PMY: Pmen_1138 Pmen_2036 Pmen_3597
 Pmen_3662 Pmen_3820
 PAR: Psys_0252 Psys_1169
 PCR: Pcryo_0278 Pcryo_1236 Pcryo_1260
 PRW: PsysPRwf_2011
 ACI: ACIAD0694 ACIAD1612
 ACIAD2516(atoB)
 SON: SO_1677(atoB)
 SDN: Sden_1943
 SFR: Sfri_1338 Sfri_2063
 SAZ: Sama_1375
 SBL: Sbal_1495
 SBM: Shew185_1489
 SBN: Sbal195_1525
 SLO: Shew_1667 Shew_2858
 SPC: Sputcn32_1397
 SSE: Ssed_1473 Ssed_3533
 SPL: Spea_2783

SHE: Shewmr4_2597
 SHM: Shewmr7_2664
 SHN: Shewana3_2771
 SHW: Sputw3181_2704
 ILO: IL0872
 CPS: CPS_1605 CPS_2626
 PHA: PSHAa0908 PSHAa1454(atoB)
 PSHAa1586(atoB)
 PAT: Patl_2923
 SDE: Sde_3149
 PIN: Ping_0659 Ping_2401
 MAQ: Maqu_2117 Maqu_2489 Maqu_2696
 Maqu_3162
 CBU: CBU_0974
 LPN: lpg1825(atoB)
 LPF: lpl1789
 LPP: lpp1788
 NOC: Noc_1891
 AEH: Mlg_0688 Mlg_2706
 HHA: Hhal_1685
 HCH: HCH_05299
 CSA: Csal_0301 Csal_3068
 ABO: ABO_0648(fadAx)
 MMW: Mmwy11_0073 Mmwy11_3021
 Mmwy11_3053 Mmwy11_3097 Mmwy11_4182
 AHA: AHA_2143(atoB)
 CVI: CV_2088(atoB) CV_2790(phaA)
 RSO: RSc0276(atoB) RSc1632(phbA)
 RSc1637(bktB) RSc1761(RS02948)
 REU: Reut_A0138 Reut_A1348 Reut_A1353
 Reut_B4561 Reut_B4738
 Reut_B5587 Reut_C5943 Reut_C6062
 REH: H16_A0170 H16_A0867 H16_A0868
 H16_A0872 H16_A1297
 H16_A1438(phaA) H16_A1445(bktB)
 H16_A1528 H16_A1713 H16_A1720
 H16_A1887 H16_A2148 H16_B0380
 H16_B0381 H16_B0406 H16_B0662
 H16_B0668 H16_B0759 H16_B1369
 H16_B1771
 RME: Rmet_0106 Rmet_1357 Rmet_1362
 Rmet_5156
 BMA: BMA1316 BMA1321(phbA) BMA1436
 BMV: BMASAVP1_A1805(bktB)
 BMASAVP1_A1810(phbA)
 BML: BMA10299_A0086(phbA)
 BMA10299_A0091
 BMN: BMA10247_1076(bktB)
 BMA10247_1081(phbA)
 BXE: Bxe_A2273 Bxe_A2335 Bxe_A2342
 Bxe_A4255 Bxe_B0377 Bxe_B0739
 Bxe_C0332 Bxe_C0574 Bxe_C0915
 BVI: Bcep1808_0519 Bcep1808_1717
 Bcep1808_2877 Bcep1808_3594
 Bcep1808_4015 Bcep1808_5507
 Bcep1808_5644

BUR: Bcep18194_A3629 Bcep18194_A5080
 Bcep18194_A5091
 Bcep18194_A6102 Bcep18194_B0263
 Bcep18194_B1439
 Bcep18194_C6652 Bcep18194_C6802
 Bcep18194_C6874
 Bcep18194_C7118 Bcep18194_C7151
 Bcep18194_C7332
 BCN: Bcen_1553 Bcen_1599 Bcen_2158
 Bcen_2563 Bcen_2998 Bcen_6289
 BCH: Bcen2424_0542 Bcen2424_1790
 Bcen2424_2772 Bcen2424_5368
 Bcen2424_6232 Bcen2424_6276
 BAM: Bamb_0447 Bamb_1728 Bamb_2824
 Bamb_4717 Bamb_5771 Bamb_5969
 BPS: BPSL1426 BPSL1535(phbA) BPSL1540
 BPM: BURPS1710b_2325(bktB)
 BURPS1710b_2330(phbA)
 BURPS1710b_2453(atoB-2)
 BPL: BURPS1106A_2197(bktB)
 BURPS1106A_2202(phbA)
 BPD: BURPS668_2160(bktB)
 BURPS668_2165(phbA)
 BTE: BTH_I2144 BTH_I2256 BTH_I2261
 PNU: Pnuc_0927
 BPE: BP0447 BP0668 BP2059
 BPA: BPP0608 BPP1744 BPP3805 BPP4216
 BPP4361
 BBR: BB0614 BB3364 BB4250 BB4804
 BB4947
 RFR: Rfer_0272 Rfer_1000 Rfer_1871
 Rfer_2273 Rfer_2561 Rfer_2594
 Rfer_3839
 POL: Bpro_1577 Bpro_2140 Bpro_3113
 Bpro_4187
 PNA: Pnap_0060 Pnap_0458 Pnap_0867
 Pnap_1159 Pnap_2136 Pnap_2804
 AAV: Aave_0031 Aave_2478 Aave_3944
 Aave_4368
 AJS: Ajs_0014 Ajs_0124 Ajs_1931 Ajs_2073
 Ajs_2317 Ajs_3548
 Ajs_3738 Ajs_3776
 VEI: Veis_1331 Veis_3818 Veis_4193
 DAC: Daci_0025 Daci_0192 Daci_3601
 Daci_5988
 MPT: Mpe_A1536 Mpe_A1776 Mpe_A1869
 Mpe_A3367
 HAR: HEAR0577(phbA)
 MMS: mma_0555
 NEU: NE2262(bktB)
 NET: Neut_0610
 EBA: ebA5202 p2A409(tioL)
 AZO: azo0464(fadA1) azo0469(fadA2)
 azo2172(thlA)
 DAR: Daro_0098 Daro_3022
 HPA: HPAG1_0675
 HAC: Hac_0958(atoB)

GME: Gmet_1719 Gmet_2074 Gmet_2213
 Gmet_2268 Gmet_3302
 GUR: Gura_3043
 BBA: Bd0404(atoB) Bd2095
 DOL: Dole_0671 Dole_1778 Dole_2160
 Dole_2187
 ADE: Adeh_0062 Adeh_2365
 AFW: Anae109_0064 Anae109_1504
 MXA: MXAN_3791
 SAT: SYN_02642
 SFU: Sfum_2280 Sfum_3582
 RPR: RP737
 RCO: RC1134 RC1135
 RFE: RF_0163(paaJ)
 RBE: RBE_0139(paaJ)
 RAK: A1C_05820
 RBO: A1I_07215
 RCM: A1E_04760
 PUB: SAR11_0428(thlA)
 MLO: mlr3847
 MES: Meso_3374
 PLA: Plav_1573 Plav_2783
 SME: SMa1450 SMc03879(phbA)
 SMD: Smed_0499 Smed_3117 Smed_5094
 Smed_5096
 ATU: Atu2769(atoB) Atu3475
 ATC: AGR_C_5022(phbA) AGR_L_2713
 RET: RHE_CH04018(phbA_{ch})
 RHE_PC00068(ypc00040)
 RHE_PF00014(phbA_f)
 RLE: RL4621(phaA) pRL100301 pRL120369
 BME: BMEI0274 BMEII0817
 BMF: BAB1_1783(phbA-1) BAB2_0790(phbA-2)
 BMS: BR1772(phbA-1) BRA0448(phbA-2)
 BMB: BruAb1_1756(phbA-1)
 BruAb2_0774(phbA-2)
 BOV: BOV_1707(phbA-1)
 OAN: Oant_1130 Oant_3107 Oant_3718
 Oant_4020
 BJA: bli0226(atoB) bli3949 bli7400 bli7819
 blr3724(phbA)
 BRA: BRADO0562(phbA) BRADO0983(pimB)
 BRADO3110 BRADO3134(atoB)
 BBT: BBta_3558 BBta_3575(atoB)
 BBta_5147(pimB) BBta_7072(pimB)
 BBta_7614(phbA)
 RPA: RPA0513(pcaF) RPA0531
 RPA3715(pimB)
 RPB: RPB_0509 RPB_0525 RPB_1748
 RPC: RPC_0504 RPC_0636 RPC_0641
 RPC_0832 RPC_1050 RPC_2005
 RPC_2194 RPC_2228
 RPD: RPD_0306 RPD_0320 RPD_3105
 RPD_3306
 RPE: RPE_0168 RPE_0248 RPE_3827
 NWI: Nwi_3060

XAU: Xaut_3108 Xaut_4665
CCR: CC_0510 CC_0894 CC_3462
SIL: SPO0142(bktB) SPO0326(phbA) SPO0773
SPO3408
SIT: TM1040_0067 TM1040_2790
TM1040_3026 TM1040_3735
RSP: RSP_0745 RSP_1354 RSP_3184
RSH: Rsph17029_0022 Rsph17029_2401
Rsph17029_3179 Rsph17029_3921
RSQ: Rsph17025_0012 Rsph17025_2466
Rsph17025_2833
JAN: Jann_0262 Jann_0493 Jann_4050
RDE: RD1_0025 RD1_0201(bktB)
RD1_3394(phbA)
PDE: Pden_2026 Pden_2663 Pden_2870
Pden_2907 Pden_4811 Pden_5022
DSH: Dshi_0074 Dshi_3066 Dshi_3331
MMR: Mmar10_0697
HNE: HNE_2706 HNE_3065 HNE_3133
NAR: Saro_0809 Saro_1069 Saro_1222
Saro_2306 Saro_2349
SAL: Sala_0781 Sala_1244 Sala_2896
Sala_3158
SWI: Swit_0632 Swit_0752 Swit_2893
Swit_3602 Swit_4887 Swit_5019
Swit_5309
ELI: ELI_01475 ELI_06705 ELI_12035
GBE: GbCGDNIH1_0447
ACR: Acry_1847 Acry_2256
RRU: Rru_A0274 Rru_A1380 Rru_A1469
Rru_A1946 Rru_A3387
MAG: amb0842
MGM: Mmc1_1165
ABA: Acid345_3239
BSU: BG11319(mmgA) BG13063(yhfS)
BHA: BH1997 BH2029 BH3801(mmgA)
BAN: BA3687 BA4240 BA5589
BAR: GBAA3687 GBAA4240 GBAA5589
BAA: BA_0445 BA_4172 BA_4700
BAT: BAS3418 BAS3932 BAS5193
BCE: BC3627 BC4023 BC5344
BCA: BCE_3646 BCE_4076 BCE_5475
BCZ: BCZK3329(mmgA) BCZK3780(thl)
BCZK5044(atoB)
BCY: Bcer98_2722 Bcer98_3865
BTK: BT9727_3379(mmgA) BT9727_3765(thl)
BT9727_5028(atoB)
BTL: BALH_3262(mmgA) BALH_3642(fadA)
BALH_4843(atoB)
BLI: BL03925(mmgA)
BLD: BLi03968(mmgA)
BCL: ABC0345 ABC2989 ABC3617
ABC3891(mmgA)
BAY: RBAM_022450
BPU: BPUM_2374(yhfS) BPUM_2941
BPUM_3373
OIH: OB0676 OB0689 OB2632 OB3013

GKA: GK1658 GK3397
SAU: SA0342 SA0534(vraB)
SAV: SAV0354 SAV0576(vraB)
SAM: MW0330 MW0531(vraB)
SAR: SAR0351(thl) SAR0581
SAS: SAS0330 SAS0534
SAC: SACOL0426 SACOL0622(atoB)
SAB: SAB0304(thl) SAB0526
SAA: SAUSA300_0355
SAUSA300_0560(vraB)
SAO: SAOUHSC_00336 SAOUHSC_00558
SAJ: SaurJH9_0402
SAH: SaurJH1_0412
SEP: SE0346 SE2384
SER: SERP0032 SERP0220
SHA: SH0510(mvaC) SH2417
SSP: SSP0325 SSP2145
LMO: lmo1414
LMF: LMOF2365_1433
LIN: lin1453
LWE: lwe1431
LLA: L11745(thiL) L25946(fadA)
LLC: LACR_1665 LACR_1956
LLM: llmg_0930(thiL)
SPY: SPy_0140 SPy_1637(atoB)
SPZ: M5005_Spy_0119 M5005_Spy_0432
M5005_Spy_1344(atoB)
SPM: spyM18_0136 spyM18_1645(atoB)
SPG: SpyM3_0108 SpyM3_1378(atoB)
SPS: SPs0110 SPs0484
SPH: MGAS10270_Spy0121
MGAS10270_Spy0433
MGAS10270_Spy1461(atoB)
SPI: MGAS10750_Spy0124
MGAS10750_Spy0452
MGAS10750_Spy1453(atoB)
SPJ: MGAS2096_Spy0123
MGAS2096_Spy0451
MGAS2096_Spy1365(atoB)
SPK: MGAS9429_Spy0121
MGAS9429_Spy0431
MGAS9429_Spy1339(atoB)
SPF: SpyM50447(atoB2)
SPA: M6_Spy0166 M6_Spy0466 M6_Spy1390
SPB: M28_Spy0117 M28_Spy0420
M28_Spy1385(atoB)
SAK: SAK_0568
LJO: LJ1609
LAC: LBA0626(thiL)
LSA: LSA1486
LDB: Ldb0879
LBU: LBUL_0804
LBR: LVIS_2218
LCA: LSEL_1787
LGA: LGAS_1374
LRE: Lreu_0052
EFA: EF1364

OOE: OEOE_0529
 STH: STH2913 STH725 STH804
 CAC: CAC2873 CA_P0078(thiL)
 CPE: CPE2195(atoB)
 CPF: CPF_2460
 CPR: CPR_2170
 CTC: CTC00312
 CNO: NT01CX_0538 NT01CX_0603
 CDF: CD1059(thiA1) CD2676(thiA2)
 CBO: CBO3200(thi)
 CBE: Cbei_0411 Cbei_3630
 CKL: CKL_3696(thiA1) CKL_3697(thiA2)
 CKL_3698(thiA3)
 AMT: Amet_4630
 AOE: Clos_0084 Clos_0258
 CHY: CHY_1288 CHY_1355(atoB) CHY_1604
 CHY_1738
 DSY: DSY0632 DSY0639 DSY1567 DSY1710
 DSY2402 DSY3302
 DRM: Dred_0400 Dred_1491 Dred_1784
 Dred_1892
 SWO: Swol_0308 Swol_0675 Swol_0789
 Swol_1486 Swol_1934 Swol_2051
 TTE: TTE0549(paaJ)
 MTA: Moth_1260
 MTU: Rv1135A Rv1323(fadA4)
 Rv3546(fadA5)
 MTC: MT1365(phbA)
 MBO: Mb1167 Mb1358(fadA4)
 Mb3576(fadA5) Mb3586c(fadA6)
 MBB: BCG_1197 BCG_1385(fadA4)
 BCG_3610(fadA5) BCG_3620c(fadA6)
 MLE: ML1158(fadA4)
 MPA: MAP2407c(fadA3) MAP2436c(fadA4)
 MAV: MAV_1544 MAV_1573 MAV_1863
 MAV_5081
 MSM: MSMEG_2224 MSMEG_4920
 MUL: MUL_0357
 MVA: Mvan_1976 Mvan_1988 Mvan_4305
 Mvan_4677 Mvan_4891
 MGI: Mflv_1347 Mflv_1484 Mflv_2040
 Mflv_2340 Mflv_4356 Mflv_4368
 MMC: Mmcs_1758 Mmcs_1769 Mmcs_3796
 Mmcs_3864
 MKM: Mkms_0251 Mkms_1540 Mkms_1805
 Mkms_1816 Mkms_2836 Mkms_3159
 Mkms_3286 Mkms_3869 Mkms_3938
 Mkms_4227 Mkms_4411 Mkms_4580
 Mkms_4724 Mkms_4764 Mkms_4776
 MJL: Mjls_0231 Mjls_1739 Mjls_1750
 Mjls_2819 Mjls_3119 Mjls_3235
 Mjls_3800 Mjls_3850 Mjls_4110 Mjls_4383
 Mjls_4705 Mjls_4876
 Mjls_5018 Mjls_5063 Mjls_5075
 CGL: NCgl2309(cgl2392)
 CGB: cg2625(pcaF)
 CEF: CE0731 CE2295

CJK: jk1543(fadA3)
 NFA: nfa10750(fadA4)
 RHA: RHA1_ro01455 RHA1_ro01623
 RHA1_ro01876 RHA1_ro02517(catF)
 RHA1_ro03022 RHA1_ro03024
 RHA1_ro03391 RHA1_ro03892
 RHA1_ro04599 RHA1_ro05257
 RHA1_ro08871
 SCO: SCO5399(SC8F4.03)
 SMA: SAV1384(fadA5) SAV2856(fadA1)
 ART: Arth_1160 Arth_2986 Arth_3268
 Arth_4073
 NCA: Noca_1371 Noca_1797 Noca_1828
 Noca_2764 Noca_4142
 TFU: Tfu_1520 Tfu_2394
 FRA: Francci3_3687
 FRE: Franean1_1044 Franean1_2711
 Franean1_2726 Franean1_3929
 Franean1_4037 Franean1_4577
 FAL: FRAAL2514 FRAAL2618
 FRAAL5910(atoB)
 ACE: Acel_0626 Acel_0672
 SEN: SACE_1192(mmgA) SACE_2736(fadA6)
 SACE_4011(catF)
 SACE_6236(fadA4)
 STP: Strop_3610
 SAQ: Sare_1316 Sare_3991
 RXY: Rxyl_1582 Rxyl_1842 Rxyl_2389
 Rxyl_2530
 FNU: FN0495
 BGA: BG0110(fadA)
 BAF: BAPKO_0110(fadA)
 LIL: LA0457(thiL1) LA0828(thiL2)
 LA4139(fadA)
 LIC: LIC10396(phbA)
 LBJ: LBJ_2862(paaJ-4)
 LBL: LBL_0209(paaJ-4)
 SYN: slr1993(phaA)
 SRU: SRU_1211(atoB) SRU_1547
 CHU: CHU_1910(atoB)
 GFO: GFO_1507(atoB)
 FJO: Fjoh_4612
 FPS: FP0770 FP1586 FP1725
 RRS: RoseRS_3911 RoseRS_4348
 RCA: Rcas_0702 Rcas_3206
 HAU: Haur_0522
 DRA: DR_1072 DR_1428 DR_1960 DR_2480
 DR_A0053
 DGE: Dgeo_0755 Dgeo_1305 Dgeo_1441
 Dgeo_1883
 TTH: TTC0191 TTC0330
 TTJ: TTHA0559
 TME: Tmel_1134
 FNO: Fnod_0314
 PMO: Pmob_0515
 HMA: rrnAC0896(acaB3) rrnAC2815(aca2)
 rrnAC3497(yqeF)

rrnB0240(aca1) rrnB0242(acaB2)
 rrnB0309(acaB1)
 TAC: Ta0582
 TVO: TVN0649
 PTO: PTO1505
 APE: APE_2108
 SSO: SSO2377(acaB-4)
 STO: ST0514

SAI: Saci_0963 Saci_1361(acaB1)
 MSE: Msed_0656
 PAI: PAE1220
 PIS: Pis1_0029 Pis1_1301
 PCL: Pcal_0781
 PAS: Pars_0309 Pars_1071
 CMA: Cmaq_1941

Exemplary HMG-CoA synthase nucleic acids and polypeptides

HSA: 3157(HMGCS1) 3158(HMGCS2)
 PTR: 457169(HMGCS2) 461892(HMGCS1)
 MCC: 702553(HMGCS1) 713541(HMGCS2)
 MMU: 15360(Hmgcs2) 208715(Hmgcs1)
 RNO: 24450(Hmgcs2) 29637(Hmgcs1)
 CFA: 479344(HMGCS1) 607923(HMGCS2)
 BTA: 407767(HMGCS1)
 SSC: 397673(CH242-38B5.1)
 GGA: 396379(HMGCS1)
 XLA: 380091(hmgcs1) 447204(MGC80816)
 DRE: 394060(hmgcs1)
 SPU: 578259(LOC578259)
 DME: Dmel_CG4311(Hmgs)
 CEL: F25B4.6
 ATH: AT4G11820(BAP1)
 OSA: 4331418 4347614
 CME: CMM189C
 SCE: YML126C(ERG13)
 AGO: AGOS_ADL356C
 PIC: PICST_83020
 CAL: CaO19_7312(CaO19.7312)
 CGR: CAGL0H04081g
 SPO: SPAC4F8.14c(hcs)
 MGR: MGG_01026
 ANI: AN4923.2
 AFM: AFUA_3G10660 AFUA_8G07210
 AOR: AO090003000611 AO090010000487
 CNE: CNC05080 CNG02670
 UMA: UM05362.1
 ECU: ECU10_0510
 DDI: DDBDRAFT_0217522
 DDB_0219924(hgsA)
 TET: TTHERM_00691190
 TBR: Tb927.8.6110
 YPE: YPO1457
 YPK: y2712(pksG)
 YPM: YP_1349(pksG)
 YPA: YPA_0750
 YPN: YPN_2521
 YPP: YPDSF_1517
 YPS: YPTB1475
 CBD: COXBU7E912_1931
 TCX: Tcr_1719
 DNO: DNO_0799

BMA: BMAA1212
 BPS: BPSS1002
 BPM: BURPS1710b_A2613
 BPL: BURPS1106A_A1384
 BPD: BURPS668_A1470
 BTE: BTH_II1670
 MXA: MXAN_3948(tac) MXAN_4267(mvaS)
 BSU: BG10926(pksG)
 OIH: OB2248
 SAU: SA2334(mvaS)
 SAV: SAV2546(mvaS)
 SAM: MW2467(mvaS)
 SAR: SAR2626(mvaS)
 SAS: SAS2432
 SAC: SACOL2561
 SAB: SAB2420(mvaS)
 SAA: SAUSA300_2484
 SAO: SAOUHSC_02860
 SAJ: SaurJH9_2569
 SAH: SaurJH1_2622
 SEP: SE2110
 SER: SERP2122
 SHA: SH0508(mvaS)
 SSP: SSP0324
 LMO: lmo1415
 LMF: LMOF2365_1434(mvaS)
 LIN: lin1454
 LWE: lwe1432(mvaS)
 LLA: L13187(hmcM)
 LLC: LACR_1666
 LLM: limg_0929(hmcM)
 SPY: SPy_0881(mvaS.2)
 SPZ: M5005_Spy_0687(mvaS.1)
 SPM: spyM18_0942(mvaS2)
 SPG: SpyM3_0600(mvaS.2)
 SPS: SPs1253
 SPH: MGAS10270_Spy0745(mvaS1)
 SPI: MGAS10750_Spy0779(mvaS1)
 SPJ: MGAS2096_Spy0759(mvaS1)
 SPK: MGAS9429_Spy0743(mvaS1)
 SPF: SpyM51121(mvaS)
 SPA: M6_Spy0704
 SPB: M28_Spy0667(mvaS.1)
 SPN: SP_1727

SPR: spr1571(mvaS)	LBR: LVIS_1363
SPD: SPD_1537(mvaS)	LCA: LSEL_1785
SAG: SAG1316	LGA: LGAS_1372
SAN: gbs1386	LRE: Lreu_0676
SAK: SAK_1347	PPE: PEPE_0868
SMU: SMU.943c	EFA: EF1363
STC: str0577(mvaS)	OOE: OEOE_0968
STL: stu0577(mvaS)	LME: LEUM_1184
STE: STER_0621	NFA: nfa22120
SSA: SSA_0338(mvaS)	SEN: SACE_4570(pksG)
SSU: SSU05_1641	BBU: BB0683
SSV: SSU98_1652	BGA: BG0706
SGO: SGO_0244	BAF: BAPKO_0727
LPL: lp_2067(mvaS)	FJO: Fjoh_0678
LJO: LJ1607	HAL: VNG1615G(mvaB)
LAC: LBA0628(hmcS)	HMA: rrnAC1740(mvaS)
LSA: LSA1484(mvaS)	HWA: HQ2868A(mvaB)
LSL: LSL_0526	NPH: NP2608A(mvaB_1) NP4836A(mvaB_2)
LDB: Ldb0881(mvaS)	
LBU: LBUL_0806	

Exemplary hydroxymethylglutaryl-CoA reductase nucleic acids and polypeptides

HSA: 3156(HMGCR)	PAT: Patl_0427
PTR: 471516(HMGCR)	CBU: CBU_0030 CBU_0610
MCC: 705479(HMGCR)	CBD: COXBU7E912_0151
MMU: 15357(Hmgcr)	COXBU7E912_0622(hmgA)
RNO: 25675(Hmgcr)	TCX: Tcr_1717
CFA: 479182(HMGCR)	DNO: DNO_0797
BTA: 407159(HMGCR)	CVI: CV_1806
GGA: 395145(RCJMB04_14m24)	SUS: Acid_5728 Acid_6132
SPU: 373355(LOC373355)	SAU: SA2333(mvaA)
DME: Dmel_CG10367(Hmgcr)	SAV: SAV2545(mvaA)
CEL: F08F8.2	SAM: MW2466(mvaA)
OSA: 4347443	SAB: SAB2419c(mvaA)
SCE: YLR450W(HMG2) YML075C(HMG1)	SEP: SE2109
AGO: AGOS_AER152W	LWE: lwe0819(mvaA)
CGR: CAGL0L11506g	LLA: L10433(mvaA)
SPO: SPCC162.09c(hmg1)	LLC: LACR_1664
ANI: AN3817.2	LLM: llmg_0931(mvaA)
AFM: AFUA_1G11230 AFUA_2G03700	SPY: SPy_0880(mvaS.1)
AOR: AO090103000311 AO090120000217	SPM: spyM18_0941(mvaS1)
CNE: CNF04830	SPG: SpyM3_0599(mvaS.1)
UMA: UM03014.1	SPS: SPs1254
ECU: ECU10_1720	SPH: MGAS10270_Spy0744
DDI: DDB_0191125(hmgA)	SPI: MGAS10750_Spy0778
DDB_0215357(hmgB)	SPJ: MGAS2096_Spy0758
TBR: Tb927.6.4540	SPK: MGAS9429_Spy0742
TCR: 506831.40 509167.20	SPA: M6_Spy0703
LMA: LmjF30.3190	SPN: SP_1726
VCH: VCA0723	SAG: SAG1317
VCO: VC0395_0662	SAN: gbs1387
VVU: VV2_0117	STC: str0576(mvaA)
VVY: VVA0625	STL: stu0576(mvaA)
VPA: VPA0968	STE: STER_0620
VFI: VFA0841	SSA: SSA_0337(mvaA)

LPL: lp_0447(mvaA)	AFU: AF1736(mvaA)
LJO: LJ1608	HAL: VNG1875G(mvaA)
LSL: LSL_0224	HMA: rrnAC3412(mvaA)
LBR: LVIS_0450	HWA: HQ3215A(hmgR)
LGA: LGAS_1373	NPH: NP0368A(mvaA_2) NP2422A(mvaA_1)
EFA: EF1364	TAC: Ta0406m
NFA: nfa22110	TVO: TVN1168
BGA: BG0708(mvaA)	PTO: PTO1143
SRU: SRU_2422	PAB: PAB2106(mvaA)
FPS: FP2341	PFU: PF1848
MMP: MMP0087(hmgA)	TKO: TK0914
MMQ: MmarC5_1589	RCI: RCIX1027(hmgA) RCIX376(hmgA)
MAC: MA3073(hmgA)	APE: APE_1869
MBA: Mbar_A1972	IHO: Igni_0476
MMA: MM_0335	HBU: Hbut_1531
MBU: Mbur_1098	SSO: SSO0531
MHU: Mhun_3004	STO: ST1352
MEM: Memar_2365	SAI: Saci_1359
MBN: Mboo_0137	PAI: PAE2182
MTH: MTH562	PIS: Pisl_0814
MST: Msp_0584(hmgA)	PCL: Pcal_1085
MSI: Msm_0227	PAS: Pars_0796
MKA: MK0355(HMG1)	

Exemplary mevalonate kinase nucleic acids and polypeptides

HSA: 4598(MVK)	LPF: lpl2017
MCC: 707645(MVK)	LPP: lpp2022
MMU: 17855(Mvk)	BBA: Bd1027(lmbP) Bd1630(mvk)
RNO: 81727(Mvk)	MXA: MXAN_5019(mvk)
CFA: 486309(MVK)	OIH: OB0225
BTA: 505792(MVK)	SAU: SA0547(mvaK1)
GGA: 768555(MVK)	SAV: SAV0590(mvaK1)
DRE: 492477(zgc:103473)	SAM: MW0545(mvaK1)
SPU: 585785(LOC585785)	SAR: SAR0596(mvaK1)
DME: Dmel_CG33671	SAS: SAS0549
OSA: 4348331	SAC: SACOL0636(mvk)
SCE: YMR208W(ERG12)	SAB: SAB0540(mvaK1)
AGO: AGOS_AER335W	SAA: SAUSA300_0572(mvk)
PIC: PICST_40742(ERG12)	SAO: SAOUHSC_00577
CGR: CAGL0F03861g	SEP: SE0361
SPO: SPAC13G6.11c	SER: SERP0238(mvk)
MGR: MGG_06946	SHA: SH2402(mvaK1)
ANI: AN3869.2	SSP: SSP2122
AFM: AFUA_4G07780	LMO: lmo0010
AOR: AO090023000793	LMF: LMOF2365_0011
CNE: CNK01740	LIN: lin0010
ECU: ECU09_1780	LWE: lwe0011(mvk)
DDI: DDBDRAFT_0168621	LLA: L7866(yeaG)
TET: THERM_00637680	LLC: LACR_0454
TBR: Tb927.4.4070	LLM: llmg_0425(mvk)
TCR: 436521.9 509237.10	SPY: SPy_0876(mvaK1)
LMA: LmjF31.0560	SPZ: M5005_Spy_0682(mvaK1)
CBU: CBU_0608 CBU_0609	SPM: spyM18_0937(mvaK1)
CBD: COXBU7E912_0620(mvk)	SPG: SpyM3_0595(mvaK1)
LPN: lpg2039	SPS: SPs1258

SPH: MGAS10270_Spy0740(mvaK1)
 SPI: MGAS10750_Spy0774(mvaK1)
 SPJ: MGAS2096_Spy0753(mvaK1)
 SPK: MGAS9429_Spy0737(mvaK1)
 SPF: SpyM51126(mvaK1)
 SPA: M6_Spy0699
 SPB: M28_Spy0662(mvaK1)
 SPN: SP_0381
 SPR: spr0338(mvk)
 SPD: SPD_0346(mvk)
 SAG: SAG1326
 SAN: gbs1396
 SAK: SAK_1357(mvk)
 SMU: SMU.181
 STC: str0559(mvaK1)
 STL: stu0559(mvaK1)
 STE: STER_0598
 SSA: SSA_0333(mvaK1)
 SSU: SSU05_0289
 SSV: SSU98_0285
 SGO: SGO_0239(mvk)
 LPL: lp_1735(mvaK1)
 LJO: LJ1205
 LAC: LBA1167(mvaK)
 LSA: LSA0908(mvaK1)
 LSL: LSL_0685(eRG)
 LDB: Ldb0999(mvk)
 LBU: LBUL_0906
 LBR: LVIS_0858
 LCA: LSEL_1491
 LGA: LGAS_1033
 LRE: Lreu_0915
 PPE: PEPE_0927
 EFA: EF0904(mvk)
 OOE: OEOE_1100
 LME: LEUM_1385
 NFA: nfa22070

BGA: BG0711
 BAF: BAPKO_0732
 FPS: FP0313
 MMP: MMP1335
 MAE: Maeo_0775
 MAC: MA0602(mvk)
 MBA: Mbar_A1421
 MMA: MM_1762
 MBU: Mbur_2395
 MHU: Mhun_2890
 MEM: Memar_1812
 MBN: Mboo_2213
 MST: Msp_0858(mvk)
 MSI: Msm_1439
 MKA: MK0993(ERG12)
 HAL: VNG1145G(mvk)
 HMA: rrnAC0077(mvk)
 HWA: HQ2925A(mvk)
 NPH: NP2850A(mvk)
 PTO: PTO1352
 PHO: PH1625
 PAB: PAB0372(mvk)
 PFU: PF1637(mvk)
 TKO: TK1474
 RCI: LRC399(mvk)
 APE: APE_2439
 HBU: Hbut_0877
 SSO: SSO0383
 STO: ST2185
 SAI: Saci_2365(mvk)
 MSE: Msed_1602
 PAI: PAE3108
 PIS: Pisl_0467
 PCL: Pcal_1835

Exemplary phosphomevalonate kinase nucleic acids and polypeptides

HSA: 10654(PMVK)
 PTR: 457350(PMVK)
 MCC: 717014(PMVK)
 MMU: 68603(Pmvk)
 CFA: 612251(PMVK)
 BTA: 513533(PMVK)
 DME: Dmel_CG10268
 ATH: AT1G31910
 OSA: 4332275
 SCE: YMR220W(ERG8)
 AGO: AGOS_AER354W
 PIC: PICST_52257(ERG8)
 CGR: CAGL0F03993g
 SPO: SPAC343.01c
 MGR: MGG_05812
 ANI: AN2311.2

AFM: AFUA_5G10680
 AOR: AO090010000471
 CNE: CNM00100
 UMA: UM00760.1
 DDI: DDBDRAFT_0184512
 TBR: Tb09.160.3690
 TCR: 507913.20 508277.140
 LMA: LmjF15.1460
 MXA: MXAN_5017
 OIH: OB0227
 SAU: SA0549(mvaK2)
 SAV: SAV0592(mvaK2)
 SAM: MW0547(mvaK2)
 SAR: SAR0598(mvaK2)
 SAS: SAS0551
 SAC: SACOL0638

SAB: SAB0542(mvaK2)	SAK: SAK_1355
SAA: SAUSA300_0574	SMU: SMU.938
SAO: SAOUHSC_00579	STC: str0561(mvaK2)
SAJ: SaurJH9_0615	STL: stu0561(mvaK2)
SEP: SE0363	STE: STER_0600
SER: SERP0240	SSA: SSA_0335(mvaK2)
SHA: SH2400(mvaK2)	SSU: SSU05_0291
SSP: SSP2120	SSV: SSU98_0287
LMO: lmo0012	SGO: SGO_0241
LMF: LMOF2365_0013	LPL: lp_1733(mvaK2)
LIN: lin0012	LJO: LJ1207
LWE: lwe0013	LAC: LBA1169
LLA: L10014(yebA)	LSA: LSA0906(mvaK2)
LLC: LACR_0456	LSL: LSL_0683
LLM: llmg_0427	LDB: Ldb0997(mvaK)
SPY: SPY_0878(mvaK2)	LBU: LBUL_0904
SPZ: M5005_Spy_0684(mvaK2)	LBR: LVIS_0860
SPM: spyM18_0939	LCA: LSEL_1092
SPG: SpyM3_0597(mvaK2)	LGA: LGAS_1035
SPS: SPs1256	LRE: Lreu_0913
SPH: MGAS10270_Spy0742(mvaK2)	PPE: PEPE_0925
SPI: MGAS10750_Spy0776(mvaK2)	EFA: EF0902
SPJ: MGAS2096_Spy0755(mvaK2)	NFA: nfa22090
SPK: MGAS9429_Spy0739(mvaK2)	BGA: BG0710
SPF: SpyM51124(mvaK2)	BAF: BAPKO_0731
SPA: M6_Spy0701	NPH: NP2852A
SPB: M28_Spy0664(mvaK2)	SSO: SSO2988
SPN: SP_0383	STO: ST0978
SPR: spr0340(mvaK2)	SAI: Saci_1244
SPD: SPD_0348(mvaK2)	
SAG: SAG1324	
SAN: gbs1394	

Exemplary diphoshomevalonate decarboxylase nucleic acids and polypeptides

HSA: 4597(MVD)	TBR: Tb10.05.0010 Tb10.61.2745
PTR: 468069(MVD)	TCR: 507993.330 511281.40
MCC: 696865(MVD)	LMA: LmjF18.0020
MMU: 192156(Mvd)	CBU: CBU_0607(mvaD)
RNO: 81726(Mvd)	CBD: COXB7E912_0619(mvaD)
CFA: 489663(MVD)	LPN: lpg2040
GGA: 425359(MVD)	LPF: lpl2018
DME: Dmel_CG8239	LPP: lpp2023
SCE: YNR043W(MVD1)	TCX: Tcr_1734
AGO: AGOS_AGL232C	DNO: DNO_0504(mvaD)
PIC: PICST_90752	BBA: Bd1629
CGR: CAGL0C03630g	MXA: MXAN_5018(mvaD)
SPO: SPAC24C9.03	OIH: OB0226
MGR: MGG_09750	SAU: SA0548(mvaD)
ANI: AN4414.2	SAV: SAV0591(mvaD)
AFM: AFUA_4G07130	SAM: MW0546(mvaD)
AOR: AO090023000862	SAR: SAR0597(mvaD)
CNE: CNL04950	SAS: SAS0550
UMA: UM05179.1	SAC: SACOL0637(mvaD)
DDI: DDBDRAFT_0218058	SAB: SAB0541(mvaD)
TET: THERM_00849200	SAA: SAUSA300_0573(mvaD)

SAO: SAOUHSC_00578	SSA: SSA_0334(mvaD)
SAJ: SaurJH9_0614	SSU: SSU05_0290
SAH: SaurJH1_0629	SSV: SSU98_0286
SEP: SE0362	SGO: SGO_0240(mvaD)
SER: SERP0239(mvaD)	LPL: lp_1734(mvaD)
SHA: SH2401(mvaD)	LJO: LJ1206
SSP: SSP2121	LAC: LBA1168(mvaD)
LMO: lmo0011	LSA: LSA0907(mvaD)
LMF: LMOF2365_0012(mvaD)	LSL: LSL_0684
LIN: lin0011	LDB: Ldb0998(mvaD)
LWE: lwe0012(mvaD)	LBU: LBUL_0905
LLA: L9089(yeaH)	LBR: LVIS_0859
LLC: LACR_0455	LCA: LSEL_1492
LLM: llmg_0426(mvaD)	LGA: LGAS_1034
SPY: SPy_0877(mvaD)	LRE: Lreu_0914
SPZ: M5005_Spy_0683(mvaD)	PPE: PEPE_0926
SPM: spyM18_0938(mvd)	EFA: EF0903(mvaD)
SPG: SpyM3_0596(mvaD)	LME: LEUM_1386
SPS: SPs1257	NFA: nfa22080
SPH: MGAS10270_Spy0741(mvaD)	BBU: BB0686
SPI: MGAS10750_Spy0775(mvaD)	BGA: BG0709
SPJ: MGAS2096_Spy0754(mvaD)	BAF: BAPKO_0730
SPK: MGAS9429_Spy0738(mvaD)	GFO: GFO_3632
SPF: SpyM51125(mvaD)	FPS: FP0310(mvaD)
SPA: M6_Spy0700	HAU: Haur_1612
SPB: M28_Spy0663(mvaD)	HAL: VNG0593G(dmd)
SPN: SP_0382	HMA: rrnAC1489(dmd)
SPR: spr0339(mvd1)	HWA: HQ1525A(mvaD)
SPD: SPD_0347(mvaD)	NPH: NP1580A(mvaD)
SAG: SAG1325(mvaD)	PTO: PTO0478 PTO1356
SAN: gbs1395	SSO: SSO2989
SAK: SAK_1356(mvaD)	STO: ST0977
SMU: SMU.937	SAI: Saci_1245(mvd)
STC: str0560(mvaD)	MSE: Msed_1576
STL: stu0560(mvaD)	
STE: STER_0599	

Exemplary isopentenyl phosphate kinases (IPK) nucleic acids and polypeptides

Methanobacterium thermoautotrophicum
gil2621082
Methanococcus jannaschii DSM 2661
gil1590842
Methanocaldococcus jannaschii gil1590842
Methanothermobacter thermautotrophicus
gil2621082

Picrophilus torridus DSM9790 (IG-57)
gil48477569
Pyrococcus abyssi gil14520758
Pyrococcus horikoshii OT3 gil3258052
Archaeoglobus fulgidus DSM4304 gil2648231

Exemplary isopentenyl-diphosphate Delta-isomerase (IDI) nucleic acids and polypeptides

HSA: 3422(IDI1) 91734(IDI2)
PTR: 450262(IDI2) 450263(IDI1)
MCC: 710052(LOC710052)
721730(LOC721730)
MMU: 319554(Idi1)

RNO: 89784(Idi1)
GGA: 420459(IDI1)
XLA: 494671(LOC494671)
XTR: 496783(idi2)
SPU: 586184(LOC586184)

CEL: K06H7.9(idi-1)
 ATH: AT3G02780(IPP2)
 OSA: 4338791 4343523
 CME: CMB062C
 SCE: YPL117C(IDI1)
 AGO: AGOS_ADL268C
 PIC: PICST_68990(IDI1)
 CGR: CAGL0J06952g
 SPO: SPBC106.15(idi1)
 ANI: AN0579.2
 AFM: AFUA_6G11160
 AOR: AO090023000500
 CNE: CNA02550
 UMA: UM04838.1
 ECU: ECU02_0230
 DDI: DDB_0191342(ipi)
 TET: TTHERM_00237280
 TTHERM_00438860
 TBR: Tb09.211.0700
 TCR: 408799.19 510431.10
 LMA: LmjF35.5330
 EHI: 46.t00025
 ECO: b2889(idi)
 ECJ: JW2857(idi)
 ECE: Z4227
 ECS: ECs3761
 ECC: c3467
 ECI: UTI89_C3274
 ECP: ECP_2882
 ECV: APECO1_3638
 ECW: EcE24377A_3215(idi)
 ECX: EcHS_A3048
 STY: STY3195
 STT: t2957
 SPT: SPA2907(idi)
 SEC: SC2979(idi)
 STM: STM3039(idi)
 SFL: SF2875(idi)
 SFX: S3074
 SFV: SFV_2937
 SSN: SSN_3042 SSON_3489(yhfK)
 SBO: SBO_3103
 SDY: SDY_3193
 ECA: ECA2789
 PLU: plu3987
 ENT: Ent638_3307
 SPE: Spro_2201
 VPA: VPA0278
 VFI: VF0403
 PPR: PBPRA0469(mvaD)
 PEN: PSEEN4850
 CBU: CBU_0607(mvaD)
 CBD: COXBU7E912_0619(mvaD)
 LPN: lpg2051
 LPF: lpl2029
 LPP: lpp2034
 TCX: Tcr_1718

HHA: Hhal_1623
 DNO: DNO_0798
 EBA: ebA5678 p2A143
 DVU: DVU1679(idi)
 DDE: Dde_1991
 LIP: LI1134
 BBA: Bd1626
 AFW: Ana109_4082
 MXA: MXAN_5021(fni)
 RPR: RP452
 RTY: RT0439(idi)
 RCO: RC0744
 RFE: RF_0785(fni)
 RBE: RBE_0731(fni)
 RAK: A1C_04190
 RBO: A1I_04755
 RCM: A1E_02555
 RRI: A1G_04195
 MLO: mlr6371
 RET: RHE_PD00245(ypd00046)
 XAU: Xaut_4134
 SIL: SPO0131
 SIT: TM1040_3442
 RSP: RSP_0276
 RSH: Rsph17029_1919
 RSQ: Rsph17025_1019
 JAN: Jann_0168
 RDE: RD1_0147(idi)
 DSH: Dshi_3527
 BSU: BG11440(ypgA)
 BAN: BA1520
 BAR: GBAA1520
 BAA: BA_2041
 BAT: BAS1409
 BCE: BC1499
 BCA: BCE_1626
 BCZ: BCZK1380(fni)
 BCY: Bcer98_1222
 BTK: BT9727_1381(fni)
 BTL: BALH_1354
 BLI: BL02217(fni)
 BLD: BLi02426
 BAY: RBAM_021020(fni)
 BPU: BPUM_2020(fni)
 OIH: OB0537
 SAU: SA2136(fni)
 SAV: SAV2346(fni)
 SAM: MW2267(fni)
 SAR: SAR2431(fni)
 SAS: SAS2237
 SAC: SACOL2341(fni)
 SAB: SAB2225c(fni)
 SAA: SAUSA300_2292(fni)
 SAO: SAOUHSC_02623
 SEP: SE1925
 SER: SERP1937(fni-2)
 SHA: SH0712(fni)

SSP: SSP0556
LMO: lmo1383
LMF: LMOF2365_1402(fni)
LIN: lin1420
LWE: lwe1399(fni)
LLA: L11083(yebB)
LLC: LACR_0457
LLM: llmg_0428(fni)
SPY: SPy_0879
SPZ: M5005_Spy_0685
SPM: spyM18_0940
SPG: SpyM3_0598
SPS: SPs1255
SPH: MGAS10270_Spy0743
SPI: MGAS10750_Spy0777
SPJ: MGAS2096_Spy0756
SPK: MGAS9429_Spy0740
SPF: SpyM51123(fni)
SPA: M6_Spy0702
SPB: M28_Spy0665
SPN: SP_0384
SPR: spr0341(fni)
SPD: SPD_0349(fni)
SAG: SAG1323
SAN: gbs1393
SAK: SAK_1354(fni)
SMU: SMU.939
STC: str0562(idi)
STL: stu0562(idi)
STE: STER_0601
SSA: SSA_0336
SGO: SGO_0242
LPL: lp_1732(idi1)
LJO: LJ1208
LAC: LBA1171
LSA: LSA0905(idi)
LSL: LSL_0682
LDB: Ldb0996(fni)
LBU: LBUL_0903
LBR: LVIS_0861
LCA: LSEL_1493
LGA: LGAS_1036
LRE: Lreu_0912
EFA: EF0901
OOE: OEOE_1103
STH: STH1674
CBE: Cbei_3081
DRM: Dred_0474
SWO: Swol_1341
MTA: Moth_1328
MTU: Rv1745c(idi)
MTC: MT1787(idi)
MBO: Mb1774c(idi)
MBB: BCG_1784c(idi)
MPA: MAP3079c
MAV: MAV_3894(fni)
MSM: MSMEG_1057(fni) MSMEG_2337(fni)

MUL: MUL_0380(idi2)
MVA: Mvan_1582 Mvan_2176
MGI: Mflv_1842 Mflv_4187
MMC: Mmcs_1954
MKM: Mkms_2000
MJL: Mjls_1934
CGL: NCgl2223(cgl2305)
CGB: cg2531(idi)
CEF: CE2207
CDI: DIP1730(idi)
NFA: nfa19790 nfa22100
RHA: RHA1_ro00239
SCO: SCO6750(SC5F2A.33c)
SMA: SAV1663(idi)
LXX: Lxx23810(idi)
CMI: CMM_2889(idiA)
AAU: AAur_0321(idi)
PAC: PPA2115
FRA: Francci3_4188
FRE: Franean1_5570
FAL: FRAAL6504(idi)
KRA: Krad_3991
SEN: SACE_2627(idiB_2) SACE_5210(idi)
STP: Strop_4438
SAQ: Sare_4564 Sare_4928
RXY: Rxyl_0400
BBU: BB0684
BGA: BG0707
SYN: sll1556
SYC: syc2161_c
SYF: Synpcc7942_1933
CYA: CYA_2395(fni)
CYB: CYB_2691(fni)
TEL: tll1403
ANA: all4591
AVA: Ava_2461 Ava_B0346
TER: Tery_1589
SRU: SRU_1900(idi)
CHU: CHU_0674(idi)
GFO: GFO_2363(idi)
FJO: Fjoh_0269
FPS: FP1792(idi)
CTE: CT0257
CCH: Cag_1445
CPH: Cpha266_0385
PVI: Cvib_1545
PLT: Plut_1764
RRS: RoseRS_2437
RCA: Rcas_2215
HAU: Haur_4687
DRA: DR_1087
DGE: Dgeo_1381
TTH: TT_P0067
TTJ: TTHB110
MJA: MJ0862
MMP: MMP0043
MMQ: MmarC5_1637

MMX: MmarC6_0906	NP5124A(idiB_2)
MMZ: MmarC7_1040	TAC: Ta0102
MAE: Maeo_1184	TVO: TVN0179
MVN: Mevan_1058	PTO: PTO0496
MAC: MA0604(idi)	PHO: PH1202
MBA: Mbar_A1419	PAB: PAB1662
MMA: MM_1764	PFU: PF0856
MBU: Mbur_2397	TKO: TK1470
MTP: Mthe_0474	RCI: LRC397(fni)
MHU: Mhun_2888	APE: APE_1765.1
MLA: Mlab_1665	SMR: Smar_0822
MEM: Memar_1814	IHO: Igni_0804
MBN: Mboo_2211	HBU: Hbut_0539
MTH: MTH48	SSO: SSO0063
MST: Msp_0856(fni)	STO: ST2059
MSI: Msm_1441	SAI: Saci_0091
MKA: MK0776(lldD)	MSE: Msed_2136
AFU: AF2287	PAI: PAE0801
HAL: VNG1818G(idi) VNG6081G(crt_1)	PIS: Pisl_1093
VNG6445G(crt_2) VNG7060 VNG7149	PCL: Pcal_0017
HMA: rrnAC3484(idi)	PAS: Pars_0051
HWA: HQ2772A(idiA) HQ2847A(idiB)	TPE: Tpen_0272
NPH: NP0360A(idiB_1) NP4826A(idiA)	

Exemplary isoprene synthase nucleic acids and polypeptides

Genbank Accession Nos.

AY341431
 AY316691
 AY279379
 AJ457070
 AY182241

CLAIMS

WHAT IS CLAIMED IS:

1. A system for producing a copolymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with another non-isoprene molecule to produce a copolymer.
2. The system of claim 1, wherein the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises greater than or about 99.94% isoprene by weight compared to the total weight of all C5 hydrocarbons in the composition.
3. The system of claim 1, wherein the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more compounds selected from the group consisting of ethanol, acetone, C5 prenyl alcohols, and isoprenoid compounds with 10 or more carbon atoms.
4. The system of claim 1, wherein the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises one or more second compounds selected from the group consisting of ethanol, acetone, methanol, acetaldehyde, methacrolein, methyl vinyl ketone, 2-methyl-2-vinyloxirane, *cis*- and *trans*-3-methyl-1,3-pentadiene, a C5 prenyl alcohol, 2-heptanone, 6-methyl-5-hepten-2-one, 2,4,5-trimethylpyridine, 2,3,5-trimethylpyrazine, citronellal, acetaldehyde, methanethiol, methyl acetate, 1-propanol, diacetyl, 2-butanone, 2-methyl-3-buten-2-ol, ethyl acetate, 2-methyl-1-propanol, 3-methyl-1-butanal, 3-methyl-2-butanone, 1-butanol, 2-pentanone, 3-methyl-1-butanol, ethyl isobutyrate, 3-methyl-2-butenal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, and 2,3-cycloheptenolpyridine; wherein the amount of the second compound relative to the amount of the isoprene is greater than or about 0.01 % (w/w).

5. The system of claim 1, wherein the isoprene starting composition derived from renewable resources comprises greater than about 2 mg of isoprene and comprises less than or about 0.5 µg/L per compound for any compound in the composition that inhibits the polymerization of isoprene.
6. The system of claim 1 wherein the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has $d^{13}C$ value of greater than -22‰ or which is within the range of -30‰ to -28.5‰.
7. The system of claim 1 wherein the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}C$ value of greater than -22‰ or which is within the range of -32‰ to -24‰.
8. The system of claim 1 wherein the polymer produced from the isoprene starting material is a polymer which is comprised of repeat units that are derived from isoprene monomer and at least one additional monomer, wherein the polymer includes blocks of repeat units that are derived from isoprene, and wherein the blocks of repeat units that are derived from isoprene have a $d^{13}C$ value of greater than -22‰ or which is within the range of -34‰ to -24‰.
9. The system of claim 8 wherein the polymer is a copolymer selected from the group consisted of (i) copolymers of isoprene and 1,3-butadiene, (ii) copolymers of isoprene and styrene, (iii) copolymers of isoprene, 1,3-butadiene, and styrene, and (iv) copolymers of isoprene and *o*-methyl styrene.
10. The system of claim 1 wherein the polymer produced from the isoprene starting material is a polyisoprene polymer which is comprised of repeat units that are derived from isoprene monomer, wherein the polyisoprene polymer has f_M value which is greater than 0.9.
11. The system of claim 1, further comprising one or more of: (i) a catalyst for polymerizing isoprene, (ii) a polymerization initiator, (iii) an ionic surfactant, (iv) a suitable organic solvent, and (v) a polymerization chain terminator.

12. A system for producing a polymer of isoprene comprising: (a) an isoprene starting composition derived from renewable resources; and (b) a polymer produced from at least a portion of the isoprene starting material; wherein at least a portion of the isoprene starting composition undergoes polymerization with other isoprene molecules to produce a polymer of isoprene with a molecular weight of about 5,000 to about 100,000.
13. A method for producing a copolymer of isoprene derived from renewable resources comprising: (a) culturing cells comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene; (b) producing the isoprene; and (c) polymerizing the isoprene derived from renewable resources with another non-isoprene molecules to produce a copolymer.
14. The method of claim 13, further comprising recovering the isoprene from the isoprene-producing cell culture prior to polymerization.
15. The method of claim 13 further comprising step (d) recovering the polymer produced.
16. A method for producing a polymer of isoprene derived from renewable resources comprising: (a) culturing cells comprising a heterologous nucleic acid encoding an isoprene synthase polypeptide under suitable culture conditions for the production of the isoprene; (b) producing the isoprene; and (c) polymerizing the isoprene derived from renewable resources with other isoprene molecules to produce a polymer of isoprene with a molecular weight of about 5,000 to about 100,000.
17. A polymer of isoprene derived from renewable resources produced by the method according to claim 13.
18. A polymer of isoprene derived from renewable resources produced by the method according to claim 16.