

COMPOSITIONS AND METHODS OF PGL FOR THE INCREASED PRODUCTION OF ISOPRENE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Patent Application No. 61/289,959, filed on December 23, 2009, the disclosure of which is hereby incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

[0002] This disclosure relates to improved compositions and methods for the increased production of biochemicals in *E. coli*, as well as improved compositions and methods for the increased production of isoprene in *E. coli*.

BACKGROUND

[0003] Isoprene (2-methyl-1,3-butadiene) is an important organic compound 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.

[0004] 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 vehicle 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.

[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. There is 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 need to procure a source of isoprene from a low cost, renewable source which is environmentally friendly. The improved methods and compositions described herein provide such a source of isoprene, capable of being derived at low cost and from renewable sources.

[0006] Several recent advancements have been made in the production of isoprene from renewable sources (see, for example, International Patent Application Publication No. WO 2009/076676 A2). Such methods produce isoprene at rates, titers, and purity that may be sufficient to meet the demands of a robust commercial process, however process improvements to reduce the operational costs associated with the production of isoprene derived from biological sources and to increase yields of isoprene are needed, such as the improved compositions and methods for the increased production of isoprene and other heterologous polypeptides capable of biological activity provided herein.

[0007] All patents, patent applications, documents, nucleotide and protein sequence database accession numbers and articles cited herein are incorporated herein by reference in their entirety.

SUMMARY

[0008] Disclosed herein are improved compositions and methods for the increased production of isoprene. Also provided herein are improved compositions and methods for the increased production of heterologous polypeptides capable of biological activity. The invention is based in part on the observation that chromosomal integration of 6-phosphogluconolactonase (PGL) into *E. coli* strains which lack nucleic acids encoding for PGL polypeptide improves the production of different types of products, for example, isoprene or mevalonate.

[0009] Accordingly, in one aspect, the invention provides for recombinant cell(s) of an *Escherichia coli* (*E. coli*) strain, or progeny thereof, capable of producing isoprene, the cell comprising: (a) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid is integrated in the *E. coli* chromosome; and (b) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide, and

wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cells that do not comprise (a) and (b).

[0010] In any of the aspects herein, one or more copies of a heterologous nucleic acid encoding a molybdenum uptake polypeptide is additionally integrated in the *E. coli* chromosome. In any of the aspects herein, the molybdenum uptake polypeptide is selected from the group consisting of *modF*, *modE*, *modA*, *modB* and *modC*. In any of the aspects herein, one or more copies of a heterologous nucleic acid encoding a galactose metabolism polypeptide is additionally integrated in the *E. coli* chromosome. In any of the aspects herein, the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*. In any of the aspects herein, one or more copies of a heterologous nucleic acid encoding a galactose metabolism polypeptide and one or more copies of a heterologous nucleic acid encoding a molybdenum uptake polypeptide are additionally integrated in the *E. coli* chromosome. In any of the aspects herein, (a) the PGL polypeptide is an *E. coli* PGL polypeptide; (b) the molybdenum uptake polypeptide is selected from the group consisting of *modF*, *modE*, *modA*, *modB* and *modC*; and (c) the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*. In any of the aspects herein, nucleic acids encoding the PGL polypeptide, galactose metabolism polypeptide, and molybdenum uptake polypeptide are part a 17,257 base pair piece as shown in Figure 20. In any of the aspects herein, the recombinant cell produces isoprene at a higher specific productivity than that of the same cells that do not contain (a) and (b).

[0011] In any of the aspects herein, the recombinant cell has a specific productivity of at least 15 mg/OD/hr. In any of the aspects herein, the nucleic acids encoding PGL polypeptide, molybdenum uptake polypeptide, and/or galactose metabolism polypeptide are from *E. coli* strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655. In any of the aspects herein, the cell is of *E. coli* strain B. In any of the aspects herein, the cell is of *E. coli* strain BL21. In any of the aspects herein, the cell is of *E. coli* strain BL21(DE3).

[0012] In any of the aspects herein, the recombinant *E. coli* cell further comprises (c) a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide and/or a lower MVA pathway polypeptide.

[0013] In any of the aspects herein, the recombinant *E. coli* cell further comprises (d) a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide and/or a lower MVA pathway polypeptide. In any of the aspects herein, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase

polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In any of the aspects herein, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In any of the aspects herein, (a) the PGL polypeptide is an *E. coli* PGL polypeptide; (b) the molybdenum uptake polypeptide is selected from the group consisting of *modF*, *modE*, *modA*, *modB* and *modC*; and (c) the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*. In any of the aspects herein, the isoprene synthase polypeptide is from *Populus alba*.

[0014] The invention also provides for methods of producing isoprene, the method comprising: (a) culturing a composition comprising any of the recombinant cell described herein under suitable culture conditions for the production of isoprene and (b) producing isoprene. In some aspects, the method comprises further recovering the isoprene. In other aspects, the recombinant cell has a specific productivity greater than about 15 mg/OD/hr of isoprene.

[0015] The invention also provides for methods of producing mevalonate, the method comprising: (a) culturing a composition comprising the recombinant cell of claim 15 under suitable culture conditions for the production of mevalonate and (b) producing mevalonate. In some aspects, the method comprises further recovering the mevalonate.

[0016] The invention also provides for methods of making any of the recombinant cell described herein comprising: (a) transducing a heterologous nucleic acid encoding a PGL polypeptide into an *E. coli* cell, wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide; (b) allowing the nucleic acid encoding a PGL polypeptide to integrate in the *E. coli* chromosome; and (c) introducing one or more heterologous nucleic acid(s) encoding isoprene synthase into *E. coli* cell.

[0017] The invention also provides for compositions comprising any of the recombinant cell described herein.

[0018] In other aspects, provided herein are cells of an *Escherichia coli* strain that does not encode a PGL polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity, and wherein the cells produce the heterologous polypeptide capable of biological activity at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated

expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences is/are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in culture. In some aspects, the cells are of *E. coli* strain B. In some aspects, the cells are of *E. coli* strain BL21. In some aspects, the cells are of *E. coli* strain BL21(DE3). In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less and 1% (w/v) glucose or less. In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0019] In some aspects, the heterologous polypeptide capable of biological activity comprises one or more polypeptides involved in the biosynthesis of terpenoid (isoprenoid) or carotenoid compounds, and the cells produce a terpenoid or carotenoid at a higher specific productivity than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the terpenoid is selected from the group consisting of hemiterpenoids, monoterpenoids, sesquiterpenoids, diterpenoids, sesterterpenoids, triterpenoids, tetraterpenoids, and higher polyterpenoids. In some aspects, the hemiterpenoid is prenol (*i.e.*, 3-methyl-2-buten-1-ol), isoprenol (*i.e.*, 3-methyl-3-buten-1-ol), 2-methyl-3-buten-2-ol, or isovaleric acid. In some aspects, the monoterpenoid is geranyl pyrophosphate, eucalyptol, limonene, or pinene. In some aspects, the sesquiterpenoid is farnesyl pyrophosphate, artemisinin, or bisabolol. In some aspects, the diterpenoid is geranylgeranyl pyrophosphate, retinol, retinal, phytol, taxol, forskolin, or aphidicolin. In some aspects, the triterpenoid is squalene or lanosterol. In some aspects, the tetraterpenoid is lycopene or carotene. In some aspects, the carotenoid is selected from the group consisting of xanthophylls and carotenes. In some aspects, the xanthophyll is lutein or zeaxanthin. In some aspects, the carotene is α -carotene, β -carotene, γ -carotene, β -cryptoxanthin or lycopene.

[0020] In another aspect, provided herein are cells of an *Escherichia coli* strain that does not encode a PGL polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an isoprene synthase

polypeptide, and wherein the cells have a specific productivity of isoprene greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences is/are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in culture. In some aspects, the cells further comprise a heterologous nucleic acid encoding an MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is an upper MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is a lower MVA pathway polypeptide.

[0021] In some aspects, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In some aspects, the upper MVA pathway polypeptide is from the genus *Enterococcus*. In some aspects, the upper MVA pathway polypeptide is from *Enterococcus faecalis*. In some aspects, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In some aspects, the lower MVA pathway polypeptide is an MVK polypeptide. In some aspects, the MVK polypeptide is from the genus *Methanosarcina*. In some aspects, the MVK polypeptide is from *Methanosarcina mazei*.

[0022] In some aspects, the cells are of *E. coli* strain B. In some aspects, the cells are of *E. coli* strain BL21. In some aspects, the cells are of *E. coli* strain BL21(DE3). In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less and 1% (w/v) glucose or less. In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0023] In some aspects, the cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the cells have a specific productivity greater than about 25 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene

synthase polypeptide is operably linked to a promoter and the cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the cells have a specific productivity greater than about 25 mg/OD/hr of isoprene.

[0024] In some aspects, the isoprene synthase polypeptide is a plant isoprene synthase polypeptide. In some aspects, the cells further comprise a heterologous nucleic acid encoding an IDI polypeptide. In some aspects, the cells further comprise a chromosomal copy of an endogenous nucleic acid encoding an IDI polypeptide. In some aspects, the cells further comprise a heterologous nucleic acid encoding a DXS polypeptide. In some aspects, the cells further comprise a chromosomal copy of an endogenous nucleic acid encoding a DXS polypeptide. In some aspects, the cells further comprise one or more nucleic acids encoding an IDI polypeptide and a DXS polypeptide. In some aspects, one nucleic acid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some aspects, one plasmid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide.

[0025] In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Pueraria*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Pueraria montana*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Populus*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Populus alba*.

[0026] In some aspects, the cells comprise (i) an integrated nucleic acid encoding the lower MVA pathway from *S. cerevisiae* comprising a glucose isomerase promoter and a nucleic acid encoding mevalonate kinase (MVK); a nucleic acid encoding phosphomevalonate kinase (PMK); a nucleic acid encoding diphosphomevalonate decarboxylase (MVD); and a nucleic acid encoding isopentenyl diphosphate isomerase (IDI); (ii) a nucleic acid encoding *P. alba* isoprene synthase; (iii) a nucleic acid encoding *M. mazei* mevalonate kinase; and (iv) a nucleic acid encoding the upper MVA pathway from *Enterococcus faecalis*, comprising a nucleic acid encoding an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; a nucleic acid encoding a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and a nucleic acid encoding a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide.

[0027] In another aspect, provided herein are improved methods of producing a heterologous polypeptide capable of biological activity, the method comprising: (a) culturing cells of an *E. coli* strain that does not encode a PGL polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated

expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity; and (b) producing the heterologous polypeptide capable of biological activity, wherein the cells produce the heterologous polypeptide at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the method further comprises the step of recovering the heterologous polypeptide capable of biological activity.

[0028] In some aspects, the cells are of *E. coli* strain B. In some aspects, the cells are of *E. coli* strain BL21. In some aspects, the cells are of *E. coli* strain BL21(DE3). In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less and 1% (w/v) glucose or less. In some aspects, the heterologous polypeptide having PGL activity is from *E. coli* strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous polypeptide having PGL activity is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0029] In some aspects, the heterologous polypeptide capable of biological activity comprises one or more polypeptides involved in the biosynthesis of terpenoid (isoprenoid) or carotenoid compounds, and the cells produce a terpenoid or carotenoid at a higher specific productivity than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the terpenoid is selected from the group consisting of hemiterpenoids, monoterpenoids, sesquiterpenoids, diterpenoids, sesterterpenoids, triterpenoids, tetraterpenoids, and higher polyterpenoids. In some aspects, the hemiterpenoid is prenol (*i.e.*, 3-methyl-2-buten-1-ol), isoprenol (*i.e.*, 3-methyl-3-buten-1-ol), 2-methyl-3-buten-2-ol, or isovaleric acid. In some aspects, the monoterpenoid is geranyl pyrophosphate, eucalyptol, limonene, or pinene. In some aspects, the sesquiterpenoid is farnesyl pyrophosphate, artemisinin, or bisabolol. In some aspects, the diterpenoid is geranylgeranyl pyrophosphate, retinol, retinal, phytol, taxol, forskolin, or aphidicolin. In some aspects, the triterpenoid is squalene or lanosterol. In some aspects, the tetraterpenoid is

lycopene or carotene. In some aspects, the carotenoid is selected from the group consisting of xanthophylls and carotenes. In some aspects, the xanthophyll is lutein or zeaxanthin.

[0030] In another aspect, provided herein are improved methods of producing isoprene, the method comprising: (a) culturing cells of an *E. coli* strain that does not encode a PGL polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an isoprene synthase polypeptide; and (b) producing isoprene, wherein the cells have a specific productivity of isoprene greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the improved method further comprises a step of recovering the isoprene. In some aspects, the cells further comprise a heterologous nucleic acid encoding an MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is an upper MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is a lower MVA pathway polypeptide.

[0031] In some aspects, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In some aspects, the upper MVA pathway polypeptide is from the genus *Enterococcus*. In some aspects, the upper MVA pathway polypeptide is from *Enterococcus faecalis*. In some aspects, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In some aspects, the lower MVA pathway polypeptide is an MVK polypeptide. In some aspects, the MVK polypeptide is from the genus *Methanosarcina*. In some aspects, the MVK polypeptide is from *Methanosarcina mazei*. In some aspects, the cells are of *E. coli* strain B. In some aspects, the cells are of *E. coli* strain BL21. In some aspects, the cells are of *E. coli* strain BL21(DE3). In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less and 1% (w/v) glucose or less. In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli*

strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0032] In some aspects, the cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the cells have a specific productivity greater than about 25 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and wherein the cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and wherein the cells have a specific productivity greater than about 25 mg/L_{broth}/hr of isoprene.

[0033] In some aspects, the isoprene synthase polypeptide is a plant isoprene synthase polypeptide. In some aspects, the cells further comprise a heterologous nucleic acid encoding an IDI polypeptide. In some aspects, the cells further comprise a chromosomal copy of an endogenous nucleic acid encoding an IDI polypeptide. In some aspects, the cells further comprise a heterologous nucleic acid encoding a DXS polypeptide. In some aspects, the cells further comprise a chromosomal copy of an endogenous nucleic acid encoding a DXS polypeptide. In some aspects, the cells further comprise one or more nucleic acids encoding an IDI polypeptide and a DXS polypeptide. In some aspects, one nucleic acid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some aspects, one plasmid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Pueraria*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Pueraria montana*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Populus*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Populus alba*.

[0034] In some aspects, the cells comprise (i) an integrated nucleic acid encoding the lower MVA pathway from *S. cerevisiae* comprising a glucose isomerase promoter and a nucleic acid encoding mevalonate kinase (MVK); a nucleic acid encoding phosphomevalonate kinase (PMK); a nucleic acid encoding diphosphomevalonate decarboxylase (MVD); and a nucleic acid encoding isopentenyl diphosphate isomerase (IDI); (ii) a nucleic acid encoding *P. alba* isoprene synthase; (iii) a nucleic acid encoding *M. mazei* mevalonate kinase; and (iv) a nucleic acid encoding the upper MVA pathway from *Enterococcus faecalis*, comprising a nucleic acid encoding an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; a nucleic

acid encoding a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and a nucleic acid encoding a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide.

BRIEF DESCRIPTION OF THE DRAWINGS

[0035] Figure 1A 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. 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.

[0036] Figure 1B 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. The modified MVA pathway is present, for example, in some archaeal organisms, such as *Methanosarcina mazei*.

[0037] Figure 2 is a map of plasmid pET24 P. alba HGS.

[0038] Figure 3A-B are the nucleotide sequence of plasmid pET24 P. alba HGS (SEQ ID NO:1).

[0039] Figure 4 is a schematic diagram showing restriction sites used for endonuclease digestion to construct plasmid EWL230 and compatible cohesive ends between BspHI and NcoI sites.

[0040] Figure 5 is a map of plasmid EWL230.

[0041] Figures 6A-B are the nucleotide sequence of plasmid EWL230 (SEQ ID NO:2).

[0042] Figure 7 is a schematic diagram showing restriction sites used for endonuclease digestion to construct plasmid EWL244 and compatible cohesive ends between NsiI and PstI sites.

[0043] Figure 8 is a map of plasmid EWL244.

[0044] Figures 9A-B are the nucleotide sequence of plasmid EWL244 (SEQ ID NO:3).

[0045] Figure 10A is a map of the *M. mazei* archaeal Lower Pathway operon.

[0046] Figures 10B-C are the nucleotide sequence of the *M. mazei* archaeal Lower Pathway operon (SEQ ID NO:4).

[0047] Figure 11A is a map of MCM376-MVK from *M. mazei* archaeal Lower in pET200D.

[0048] Figures 11B-C are the nucleotide sequence of MCM376-MVK from *M. mazei* archaeal Lower in pET200D (SEQ ID NO:5).

[0049] Figure 12 is a map of plasmid pBBRCMPGI1.5-pgl.

[0050] Figures 13A-B are the nucleotide sequence of plasmid pBBRCMPGI1.5-pgl (SEQ ID NO:6).

[0051] Figures 14A-F 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 14A shows the time course of optical density within the 15-L bioreactor fed with glucose. Figure 14B 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 14C also shows the time course of isoprene titer within the 15-L bioreactor fed with glucose. Method

for calculating isoprene: $\int (\text{Instantaneous isoprene production rate, g/L/hr}) dt$ from $t = 0$ to 59 hours [=] g/L broth. Figure 14D shows the time course of total isoprene produced from the 15-L bioreactor fed with glucose. Figure 14E shows volumetric productivity within the 15-L bioreactor fed with glucose. Figure 14F shows carbon dioxide evolution rate (CER), or metabolic activity profile, within the 15-L bioreactor fed with glucose.

[0052] Figures 15A-B are graphs showing analysis of off-gas from fermentation in 15L bioreactors. Sample A is strain RM111608-2 sampled at 64.8 hours. Sample B is strain EWL256 was *E. coli* BL21 (DE3), pCL upper, cmR-gi1.2-yKKDyI, pTrcAlba-mMVK sampled at 34.5 hours. Hydrogen is detected above the baseline (0.95×10^{-8} torr) for both samples.

[0053] Figure 16A shows an exemplary isoprene recovery unit.

[0054] Figure 16B shows an exemplary isoprene desorption/condensation setup.

[0055] Figure 17 shows a GC/FID chromatogram of an isoprene product. The material was determined to be 99.7% pure.

[0056] Figures 18A-C show the GC/FID chromatograms of an isoprene sample before (A) and after treatment with alumina (B) or silica (C). The isoprene peak is not shown in these chromatograms.

[0057] Figure 19A shows a map of plasmid pDW34, encoding a truncated version of *P. alba* isoprene synthase (MEA variant) under the control of the PTrc promoter and *M. mazei* MVK. Figure 19B-D shows the complete nucleotide sequence of plasmid pDW34 (SEQ ID NO:7).

[0058] Figure 20 shows the chromosomal organization of *E. coli* K12 strain MG1655 around the *pgl* locus (Graph imported from www.ecocyc.com). The region deleted in *E. coli* BL21(DE3) compared to *E. coli* K12 MG655 and restored in strains CMP215 and CMP258 is shown in brackets. The predicted ORF of the *ybgS* gene is circled. A forward arrow ($\rightarrow$) indicates the annealing site of the *galMF* primer (SEQ ID NO:8). A reverse arrow ($\leftarrow$) indicates the annealing site of the *galMR* primer (SEQ ID NO:9).

[0059] Figure 21 shows optical density (OD) plots from microfermentation experiments conducted with PGL+ (CMP312) and PGL- (CMP323) cultures. Black triangles along the X-axis indicate when offline samples were taken. Other OD values are interpolated.

[0060] Figure 22 shows isoprene specific productivity plots from microfermentation experiments conducted with PGL+ (CMP312) and PGL- (CMP323) cultures. Black triangles along the X-axis indicate when offline samples were taken. Other OD values are interpolated.

[0061] Figure 23 shows a time course of optical density in a 15-L bioreactor fed with glucose.

[0062] Figure 24 shows a time course of isoprene titer in a 15-L bioreactor fed with glucose. Isoprene titer is defined as the amount of isoprene produced per liter of fermentation broth. The equation for calculating isoprene titer is: $\int (\text{Instantaneous isoprene production rate, g/L/hr}) dt$ from $t = 0$ to t hrs [=] g/L broth.

[0063] Figure 25 shows the time course of total isoprene produced from the 15-L bioreactors fed with glucose.

[0064] Figure 26 shows isoprene specific productivity within the 15-L bioreactors fed with glucose. Equation for calculating Specific Productivity levels: $(\text{mg isoprene}_t - \text{mg isoprene}_{t_0}) / [(OD550_t * L \text{ broth}_t - OD550_{t_0} * L \text{ broth}_{t_0}) / (2.7 OD * L / g \text{ cell})] / (t - t_0)$ [=] mg isoprene/g cell/hr.

[0065] Figure 27 shows a time course of optical density within the 15-L bioreactor fed with glucose. The pgl+ sample was a culture of strain CMP312. The pgl- sample was a culture of strain CMP323.

[0066] Figure 28 shows 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. The pgl+ sample was a culture of strain CMP312. The pgl- sample was a culture of strain CMP323. Equation for calculating Isoprene Titer: $\int (\text{Instantaneous isoprene production rate, g/L/hr}) dt$ from $t = 0$ to 20 hrs [=] g/L broth.

[0067] Figure 29 shows isoprene specific productivity within the 15-L bioreactor fed with glucose. The pgl+ sample was a culture of strain CMP312. The pgl- sample was a culture of strain CMP323. Equation for calculating Specific Productivity levels: $(\text{mg isoprene}_t - \text{mg isoprene}_{t_0}) / [(OD550_t * L \text{ broth}_t - OD550_{t_0} * L \text{ broth}_{t_0}) / (2.7 OD * L / g \text{ cell})] / (t - t_0)$ [=] mg isoprene/g cell/hr

[0068] Figure 30 shows a time course of optical density within a 15-L bioreactor containing *E. coli* K12 strain MG1655 fed with glucose.

[0069] Figure 31 shows a time course of isoprene titer within the 15-L bioreactor containing *E. coli* K-12 strain MG1655 fed with glucose. The titer is defined as the amount of isoprene produced per liter of fermentation broth. Equation for calculating Isoprene Titer: $\int (\text{Instantaneous isoprene production rate, g/L/hr}) dt$ from $t = 0$ to t hrs [=] g/L broth.

[0070] Figure 32 shows a time course of total isoprene produced from the 15-L bioreactor containing *E. coli* K-12 strain MG1655 fed with glucose.

[0071] Figure 33 shows a time course of isoprene specific productivity in a 15-L bioreactor containing *E. coli* strain K12 MG1655 fed with glucose. Equation for calculating specific productivity: $(\text{mg isoprene}_t - \text{mg isoprene}_{t_0}) / [(\text{OD}_{550_t} * \text{L broth}_t - \text{OD}_{550_{t_0}} * \text{L broth}_{t_0}) / (2.7 \text{ OD} * \text{L} / \text{g cell})] / (t - t_0) [=] \text{mg isoprene/g cell/hr.}$

[0072] Figure 34A shows a map of plasmid pDW15, expressing the upper MVA pathway polypeptides *mvaE* and *mvaS* from *Enterobacter faecalis*. Figures 34B-D shows the complete nucleotide sequence of plasmid pDW15 (SEQ ID NO:10).

[0073] Figure 35 shows mevalonate specific productivity of bacterial strains in TM3 minimal medium containing 0.1% yeast extract and 1% glucose. Experiments were run in triplicate from unique colonies. Strains are described in more detail in Table 29. BL21 + pCL pTrcUpper = strain MCM870; BL21 pgl + pCL pTrcUpper = strain MCM874; BL21 + pBBR pTrcUpper = strain MCM871; BL21 pgl + pBBR pTrcUpper = strain MCM875; BL21 + pTrcUpper = MCM872; BL21 pgl + pTrcUpper = MCM876.

[0074] Figure 36 shows growth of *E. coli* strains MCM872 and MCM876 in TM3 minimal medium containing 0.02% yeast extract and 1% glucose.

[0075] Figure 37 shows mevalonate production rate of *E. coli* strains MCM872 (BL21 pTrc-Upper) and MCM876 (BL21 pgl pTrc-Upper) in TM3 minimal medium containing 0.02% yeast extract and 1% glucose.

[0076] Figure 38 shows the concentration of MvaS protein per OD in *E. coli* strains MCM872 (BL21 pTrc-Upper) and MCM876 (BL21 pgl pTrc-Upper) in TM3 minimal medium with 0.02% yeast extract, taken at two different timepoints.

[0077] Figure 39 shows the concentration of MvaE per OD in *E. coli* strains MCM872 (BL21 pTrc-Upper) and MCM876 (BL21 pgl pTrc-Upper) grown in TM3 minimal medium with 0.02% yeast extract.

[0078] Figure 40A shows the amino acid sequence of 6-phosphogluconolactonase (PGL) from *E. coli* K12 MG1655 (SEQ ID NO:11). Figure 40B shows the amino acid sequence of PGL from *P. aeruginosa* (SEQ ID NO:12). Figure 40C shows the amino acid sequence of PGL from *S. cerevisiae* (SEQ ID NO:13). Figure 40D shows an alignment of the amino acid sequences of *E. coli* PGL and *P. aeruginosa* PGL. Identical amino acids are shown highlighted in grey. Conservative amino acid substitutions are shown highlighted in black.

[0079] Figure 41A-B shows the growth rate of BL21 (Novagen) and strain CMP258 (example 6), labeled as BL21 pgl. Growth was assessed in M9 minimal medium (6 g/L Na_2HPO_4 , 3 g/L KH_2PO_4 , 0.5 g/L NaCl, 0.5 g/L NH_4Cl , 0.1 mM CaCl_2 , 2 mM MgSO_4) containing 0.4% (w/v) glucose. Growth was measured at OD600. Figure 41A shows the

growth of BL21 and strain CMP258 (labeled as BL21 pgl). Figure 41B shows specific growth rate (μ) of BL21 with and without pgl. Restoring the 17,257 bp deletion comprising pgl in BL21 results in a strain with around 15% increase in specific growth rate.

[0080] Figure 42A shows a time course of isoprene titer in a 15-L bioreactor fed with glucose. Isoprene titer is defined as the amount of isoprene produced per liter of fermentation broth. The equation for calculating isoprene titer is: $\int$ (Instantaneous isoprene production rate, g/L/hr)dt from $t = 0$ to t hrs [=] g/L broth. Figure 42B shows isoprene specific productivity within the 15-L bioreactors fed with glucose. Equation for calculating Specific Productivity levels: $(\text{mg isoprene}_t - \text{mg isoprene}_{t_0}) / [(\text{OD}_{550_t} * \text{L broth}_t - \text{OD}_{550_{t_0}} * \text{L broth}_{t_0}) / (2.7 \text{ OD} * \text{L} / \text{g cell})] / (t - t_0)$ [=] mg isoprene/g cell/hr.

DETAILED DESCRIPTION

[0081] *E. coli* BL21 and BL21(DE3) are widely used hosts for the production of recombinant proteins. They can also be used to produce other products, such as isoprene. Yields of recombinant proteins, biochemicals, and other products in such *E. coli* strains can be improved by increasing activity of the pentose phosphate pathway, a metabolic pathway important for cell growth. Comparison of the genomic sequence of *E. coli* BL21 prepared by Codon Genomics (St. Louis, MO) using an Illumina Genome Analyzer II (GA II) Sequencing System to that of *E. coli* MG1655 (GenBank Accession No. U00096) revealed that the *E. coli* BL21 genome carried a deletion of 17,257 bp in the region encoding genes involved in the utilization of galactose as well as other genes that are described in greater detail herein. Unexpectedly, that deletion also encompassed the *ybhE* gene (Thomason, L., Court, D., Datta, A., Khanna, R. and Rosner, J., "Identification of the Escherichia coli K-12 ybhE gene as pgl, encoding 6-phosphogluconolactonase," *J. Bact.* 186:8248-8253 (2004)), which encodes the enzyme 6-phosphogluconolactonase (PGL), the second enzyme in the pentose phosphate pathway. The deletion was made by UV irradiation of a parent strain of *E. coli* BL21 and passed via P1 transduction (Studier F., Daegelen, P., Lenski, R., Maslov, S., Kim, J.F., "Understanding the differences between genome sequences of *Escherichia coli* B strains REL606 and BL21(DE3) and comparison of the *E. coli* B and K-12 genomes," *J. Mol. Biol.* published ahead of print Sept. 15, 2009). Consequently, *E. coli* BL21 and BL21(DE3) lack both PGL activity and the ability to utilize galactose as a carbon source. (Aon et al., "Suppressing posttranslational gluconoylation of heterologous proteins by metabolic engineering of *Escherichia coli*," *Appl. Environ. Microbiol.* 74:950-958 (2008)).

[0082] Additionally, the deletion also included genes required for high affinity transport of molybdate. While required in only trace amounts, molybdenum plays an important role in several metabolic pathways in all organisms. Molybdate is used as an enzymatic cofactor by bacteria in a number of oxidation/reduction reactions, plays a critical role in nitrogen metabolism, and, particularly in the case of anaerobic respiration, contributes to energy production. (See, e.g., Self et al., *Res Microbiol.* 152:311-321 (2001); Grunden & Shanmugam, *Arch Microbiol.* 168:345-354 (1997)).

[0083] The pentose phosphate pathway (PPP) is used during growth to provide NADPH and pentoses (5-carbon sugars) (Neidhart, F., Ingraham, J., and Schaechter, M., 1990, *Physiology of the bacterial cell: a molecular approach* (Sinauer Associates, Inc. Sunderland, MA)). The PPP has two distinct phases: (1) the oxidative phase, in which NADPH is generated; and (2) the non-oxidative synthesis of 5-carbon sugars. The PPP is an alternative to glycolysis, and while it does involve oxidation of glucose, its primary role is anabolic rather than catabolic. The primary results of the pathway are: (1) the generation of reducing equivalents in the form of NADPH, for use in reductive biosynthesis reactions within cells, such as fatty acid synthesis; (2) production of ribose-5-phosphate (R5P), used in the synthesis of nucleotides and nucleic acids; and (3) production of erythrose-4-phosphate (E4P), used in the synthesis of aromatic amino acids. Aromatic amino acids, in turn, are precursors for many biosynthetic pathways. Dietary pentose sugars derived from the digestion of nucleic acids may be metabolized through the pentose phosphate pathway, and the carbon skeletons of dietary carbohydrates may be converted into glycolytic or gluconeogenic intermediates. In mammals, the PPP occurs exclusively in the cytoplasm, and is one of the three main ways the body creates molecules with reducing power, accounting for approximately 60% of NADPH production in humans.

[0084] Restoring the PGL gene and its associated expression control sequences in *E. coli* BL21 and BL21(DE3) strains conveys a substantial growth benefit, as the pentose phosphate pathway provides reducing equivalents for use in reductive biosynthesis reactions within cells, such as fatty acid synthesis, ribose-5-phosphate (R5P) for use in the synthesis of nucleotides and nucleic acids, and (3) erythrose-4-phosphate (E4P) for use in the synthesis of aromatic amino acids. In addition, it will be useful for industrial purposes to have a homologous strain (e.g., an *E. coli* BL21 or BL21(DE3) strain) able to utilize galactose, in order to extend the range of available carbon sources.

[0085] Furthermore, restoring genes that encode high affinity molybdate transport proteins will provide an additional growth benefit, as the cell will be able to utilize molybdate more

efficiently in those metabolic reactions that require molybdenum as a cofactor. The invention encompasses improved methods and compositions for recombinant bacterial cells expressing a heterologous nucleic acid encoding a PGL polypeptide integrated into the bacterial chromosome. The PGL integration alone or in combination with one or more other heterologous nucleic acids encoding polypeptides for galactose metabolism and/or molybdenum transport can improve a recombinant bacterial cell's ability for the production of isoprene.

[0086] Accordingly in one aspect, the invention encompasses recombinant cell(s) of an *Escherichia coli* (*E. coli*) strain capable of producing isoprene, wherein the cell(s) comprise: (a) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid(s) is/are integrated in the *E. coli* chromosome; and (b) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain (a) nucleic acid(s) that encodes a encoding a PGL polypeptide, and wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cell(s) that do not comprise (a) and (b). In some cases, the recombinant *E. coli* cell can use its own endogenous promoter(s) and/or its other regulatory systems to regulate the transcription and subsequent expression of the integrated PGL nucleic acid. In such cases, the expression of the heterologous nucleic acids (e.g., PGL or isoprene) is not constitutive expression driven by a plasmid or elements on a plasmid. In other cases, the recombinant *E. coli* cell can use promoter(s) and/or other regulatory systems that have been introduced to the *E. coli* cell to regulate the transcription and subsequent expression of the integrated PGL nucleic acid.

[0087] The invention also encompasses cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity. In one aspect, the PGL polypeptide is not encoded by nucleic acids on a plasmid. In some aspects, the *E. coli* cells produce the polypeptide capable of biological activity at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. Also provided herein are improved methods of producing heterologous polypeptides capable of biological activity, comprising the steps of culturing the *E. coli* cells that do not encode a PGL polypeptide in minimal medium, wherein the cells comprise one or more

copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity, and producing the heterologous polypeptide. In some aspects, the cells produce the heterologous polypeptide at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium.

[0088] In another aspect, provided herein are cells of an *Escherichia coli* strain that does not encode a PGL polypeptide, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide, a lower MVA pathway polypeptide, and/or an isoprene synthase polypeptide. In some aspects, the *E. coli* cells have a specific productivity of isoprene greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. Also provided herein are improved methods of producing isoprene, comprising the steps of culturing the *E. coli* cells that do not encode a PGL polypeptide in minimal medium, wherein the cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide, a lower MVA pathway polypeptide, or an isoprene synthase polypeptide, and producing isoprene. In some aspects, the cells have a specific productivity of isoprene greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium.

General Techniques

[0089] The practice of the present invention will employ, unless otherwise indicated, conventional techniques of molecular biology (including recombinant techniques), microbiology, cell biology, biochemistry, and immunology, which are within the skill of the art. Such techniques are explained fully in the literature, “Molecular Cloning: A Laboratory Manual”, second edition (Sambrook et al., 1989); “Oligonucleotide Synthesis” (M. J. Gait, ed., 1984); “Animal Cell Culture” (R. I. Freshney, ed., 1987); “Methods in Enzymology”

(Academic Press, Inc.); "Current Protocols in Molecular Biology" (F. M. Ausubel et al., eds., 1987, and periodic updates); "PCR: The Polymerase Chain Reaction", (Mullis et al., eds., 1994). Singleton et al., Dictionary of Microbiology and Molecular Biology 2nd ed., J. Wiley & Sons (New York, N.Y. 1994), and March, Advanced Organic Chemistry Reactions, Mechanisms and Structure 4th ed., John Wiley & Sons (New York, N.Y. 1992), provide one skilled in the art with a general guide to many of the terms used in the present application.

Definitions

[0090] The term "isoprene" refers to 2-methyl-1,3-butadiene (CAS# 78-79-5). It can be the direct and final volatile C5 hydrocarbon product from the elimination of pyrophosphate from 3,3-dimethylallyl pyrophosphate (DMAPP). It may not involve the linking or polymerization of IPP molecules to DMAPP molecules. The term "isoprene" is not generally intended to be limited to its method of production unless indicated otherwise herein.

[0091] As used herein, the term "6-phosphogluconolactone" refers to 6-phospho-D-glucono-1,5-lactone (CAS# 2641-81-8). As used herein, the term "6-phosphogluconate" refers to 6-phospho-D-gluconate (CAS# 921-62-0).

[0092] As used herein, the term "polypeptides" includes polypeptides, proteins, peptides, fragments of polypeptides, and fusion polypeptides.

[0093] 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. An isolated polypeptide can be a non-naturally occurring polypeptide.

[0094] By "heterologous polypeptide" is meant a polypeptide encoded by a nucleic acid sequence derived from a different organism, species, or strain than the host cell. In some aspects, a heterologous polypeptide is not identical to a wild-type polypeptide that is found in the same host cell in nature.

[0095] As used herein, a "nucleic acid" refers to two or more deoxyribonucleotides and/or ribonucleotides covalently joined together in either single or double-stranded form.

[0096] By "recombinant nucleic acid" is meant 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 some aspects, a recombinant nucleic acid is a nucleic acid that encodes a non-naturally occurring polypeptide.

[0097] By “heterologous nucleic acid” is meant a nucleic acid sequence derived from a different organism, species or strain than the host cell. In some aspects, the heterologous nucleic acid is not identical to a wild-type nucleic acid that is found in the same host cell in nature. For example, a nucleic acid encoding a PGL polypeptide isolated from *E. coli* K12 strain MG1655 or a derivative thereof, integrated into the chromosome of *E. coli* BL21(DE3) by P1 transduction and expressed in the cell is a heterologous nucleic acid. In one aspect, a “heterologous nucleic acid” can mean the introduction of a nucleic acid into a host cell that does not have that nucleic acid. In some cases, a heterologous nucleic acid can be a heterologous gene. One of skill in the art would appreciate the differences and also be able to use the context of the teaching accordingly.

[0098] 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 expression control sequence can be “native” or heterologous. A native expression control sequence is derived from the same organism, species, or strain as the gene being expressed. A heterologous expression control sequence is derived from a different organism, species, or strain as the gene being expressed. 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.

[0099] As used herein, the terms “minimal medium” or “minimal media” refer to growth medium containing the minimum nutrients possible for cell growth, generally without the presence of amino acids. Minimal medium typically contains: (1) a carbon source for bacterial growth; (2) various salts, which may vary among bacterial species and growing conditions; and (3) water. The carbon source can vary significantly, from simple sugars like glucose to more complex hydrolysates of other biomass, such as yeast extract, as discussed in more detail below. The salts generally provide essential elements such as magnesium, nitrogen, phosphorus, and sulfur to allow the cells to synthesize proteins and nucleic acids. Minimal medium can also be supplemented with selective agents, such as antibiotics, to select for the maintenance of certain plasmids and the like. For example, if a microorganism

is resistant to a certain antibiotic, such as ampicillin or tetracycline, then that antibiotic can be added to the medium in order to prevent cells lacking the resistance from growing. Medium can be supplemented with other compounds as necessary to select for desired physiological or biochemical characteristics, such as particular amino acids and the like.

[0100] As used herein, the term “terpenoid” or “isoprenoid” refers to a large and diverse class of naturally-occurring organic chemicals similar to terpenes. Terpenoids are derived from five-carbon isoprene units assembled and modified in a variety of ways, and are classified in groups based on the number of isoprene units used in group members. Hemiterpenoids have one isoprene unit. Monoterpenoids have two isoprene units. Sesquiterpenoids have three isoprene units. Diterpenoids have four isoprene units. Sesterterpenoids have five isoprene units. Triterpenoids have six isoprene units. Tetraterpenoids have eight isoprene units. Polyterpenoids have more than eight isoprene units.

[0101] As used herein, the term “carotenoid” refers to a group of naturally occurring organic pigments produced in the chloroplasts and chromoplasts of plants, of some other photosynthetic organisms, such as algae, in some types of fungus, and in some bacteria. Carotenoids include the oxygen-containing xanthophylls and the non-oxygen-containing carotenes.

[0102] 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.

[0103] As used herein, the singular terms “a,” “an,” and “the” include the plural reference unless the context clearly indicates otherwise.

[0104] 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.

Genes Encoding Polypeptides Restored to *E. coli* BL21 or BL21(DE3)

[0105] The 17,257 bp deletion in the *E. coli* BL21 and BL21(DE3) genomes includes the *yghE* gene (PGL), genes encoding proteins involved in the utilization of galactose as a carbon source, genes encoding proteins involved in molybdenum transport, as well as several other genes of unknown functionality. See, for example, Figure 20. The genes involved in the utilization of galactose are *galM* which encodes galactose-1-epimerase, *galK*, which encodes galactokinase, *galT*, which encodes galactose-1-phosphate uridylyltransferase, and *galE*, which encodes UDP-glucose 4-epimerase. The genes encoding proteins involved in molybdenum transport are *modF*, which encodes the fused molybdate transporter subunits of the ABC superfamily, *modE*, which encodes the repressor of the modABC operon for molybdenum transport, and *modA*, *modB*, and *modC*, which each encode a molybdate transporter subunit protein.

[0106] Accordingly, bacterial (e.g., *E. coli*) cells can be engineered to integrate nucleic acids encoding a PGL polypeptide in the *E. coli* chromosome. Introduction of heterologous nucleic acids encoding for isoprene synthase (e.g., *P. alba* isoprene synthase) can increase the total titer and/or specific activity for isoprene production. Furthermore, in addition to the PGL integration, one or more genes encoding proteins involved in the utilization of galactose as a carbon source or proteins involved in molybdenum transport can also be introduced into the *E. coli* cell to increase the overall fitness of the recombinant cell, which, in turn, can lead to increased production of isoprene.

[0107] Various options of integrated PGL alone or integrated PGL in combination with one or more genes encoding proteins involved in the utilization of galactose as a carbon source or proteins involved in molybdenum transport are contemplated within the scope of the invention. Thus, in some aspects, the gene restored to the BL21 or BL21(DE3) genome is PGL. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL and *galM*. In some aspects, genes restored to the BL21 or BL21(DE3) genome are PGL and *galK*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL and *galT*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL and *galE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *galK*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *galT*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *galE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are

PGL, *galK*, and *galT*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, and *galE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galT*, and *galE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, and *galT*. In some aspects, genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, and *galE*. In some aspects, genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galT*, and *galE*.

[0108] In some aspects, genes restored to the BL21 or BL21(DE3) genome are PGL and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *modF*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *modF*, *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *modE*, *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *modF*, *modE*, *modA*, *modB*, and *modC*.

[0109] In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *modE*. In some aspects, genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galT*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galT*, *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *modA*, *modB*, and *modC*.

[0110] In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, and *modE*. In some aspects, the genes restored to the BL21 or

BL21(DE3) genome are PGL, *galM*, *galK*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galT*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galT*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galE*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galE*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galE*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galT*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galT*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galE*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galE*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galK*, *galE*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galT*, and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galT*, and *modA*, *modB*, and *modC*.

[0111] In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galT* and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galT*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galE* and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galE*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galM*, *galK*, *galE*, and *modA*, *modB*, and *modC*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galK*, *galT* and *modF*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galK*, *galT*, and *modE*. In some aspects, the genes restored to the BL21 or BL21(DE3) genome are PGL, *galE*, *galK*, *galT*, and *modA*, *modB*, and *modC*.

[0112] In some aspects, the one or more copies of one or more genes encoded on the 17,257 bp genomic piece (except for PGL) are restored to *E. coli* BL21 or BL21(DE3) on a plasmid. In some aspects, the one or more copies of one or more genes encoded on the 17,257 bp genomic piece are restored to *E. coli* BL21 or BL21(DE3) on a constitutively expressing plasmid. In some aspects one or more copies of one or more genes encoded on the 17,257 bp genomic piece are restored to *E. coli* BL21 or BL21(DE3) on an inducible plasmid. In some aspects, the entire 17,257 bp genomic piece is a plasmid which is transfected into *E. coli* BL21 or BL21(DE3) cells. In some aspects, the one or more copies of one or more genes encoded on the 17,257 bp genomic piece are restored (e.g., as depicted in Figure 20) to *E. coli* BL21 or BL21(DE3) by chromosomal integration. In some aspects, the entire 17,257 bp genomic piece is restored to *E. coli* BL21 or BL21(DE3) by chromosomal integration.

[0113] Exemplary PGL Polypeptides and Nucleic Acids

[0114] 6-phosphogluconolactonase (PGL) converts 6-phosphogluconolactone to 6-phosphogluconate. Exemplary PGL polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a PGL polypeptide. Exemplary PGL 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 that have at least one activity of a PGL polypeptide.

[0115] Mutant PGL polypeptides include those in which one or more amino acid residues have undergone an amino acid substitution while retaining PGL activity (*i.e.*, the ability to convert 6-phosphogluconolactone to 6-phosphogluconate). The amino acid substitutions may be conservative or non-conservative and such substituted amino acid residues may or may not be one encoded by the genetic code. The standard twenty amino acid “alphabet” has been divided into chemical families based on similarity of their side chains. Those families include amino acids with basic side chains (*e.g.*, lysine, arginine, histidine), acidic side chains (*e.g.*, aspartic acid, glutamic acid), uncharged polar side chains (*e.g.*, glycine, asparagine, glutamine, serine, threonine, tyrosine, cysteine), nonpolar side chains (*e.g.*, alanine, valine, leucine, isoleucine, proline, phenylalanine, methionine, tryptophan), beta-branched side chains (*e.g.*, threonine, valine, isoleucine) and aromatic side chains (*e.g.*, tyrosine, phenylalanine, tryptophan, histidine). A “conservative amino acid substitution” is one in which the amino acid residue is replaced with an amino acid residue having a chemically

similar side chain (*i.e.*, replacing an amino acid having a basic side chain with another amino acid having a basic side chain). A “non-conservative amino acid substitution” is one in which the amino acid residue is replaced with an amino acid residue having a chemically different side chain (*i.e.*, replacing an amino acid having a basic side chain with another amino acid having an aromatic side chain).

[0116] Amino acid substitutions in the PGL polypeptide can be introduced to improve the functionality of the molecule. For example, amino acid substitutions that increase the binding affinity of the PGL polypeptide for its substrate, or that improve its ability to convert 6-phosphogluconolactone to 6-phosphogluconate can be introduced into the PGL polypeptide. In some aspects, the mutant PGL polypeptides contain one or more conservative amino acid substitutions. In some aspects, the mutant PGL polypeptides contain one or more non-conservative amino acid substitutions.

[0117] Standard methods, such as those described by A. Sinha and P.K. Maitra, “Induction of specific enzymes of the oxidative pentose phosphate pathway by glucono-delta-lactone in *Saccharomyces cerevisiae*,” *J. Gen. Microbiol.* 138:1865-1873 (1992), can be used to determine whether a polypeptide has PGL activity, by measuring the ability of a polypeptide to reduce NADP⁺ to NADPH. In an exemplary assay, PGL activity is assayed by pre-incubating a reaction mixture containing 50 μ M glucose-6-phosphate 0.5 mM NADP⁺, and 0.5 units glucose-6-phosphate dehydrogenase in 50 mM MES Buffer, pH=6.5, 25 mM KCl, 10 mM MgCl₂, until the reaction was complete. This was followed by addition of 1 unit of 6-phosphogluconate dehydrogenase which resulted in a slow increase in fluorescence due to spontaneous hydrolysis of the lactone formed during the earlier reaction. Next, cell-free extracts are added, leading to an increased rate of NADP⁺ reduction to NADPH via the lactonase reaction catalyzed by PGL. The actual lactonase rate is calculated by subtracting the previous blank rate from this final rate.

[0118] Alternatively, conversion of 6-phosphogluconolactone to 6-phosphogluconate can be monitored by nuclear magnetic resonance (NMR) spectroscopy. *See, e.g.*, E. Miclet et al., “NMR Spectroscopic Analysis of the First Two Steps of the Pentose-Phosphate Pathway Elucidates the Role of 6-Phosphogluconolactonase,” *J. Biol. Chem.* 276(37):34840-34846 (2001).

[0119] Exemplary PGL 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 PGL 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. Exemplary PGL nucleic acids include, for example, PGL isolated from *E. coli* K12 MG1655 or derivatives thereof (EcoGene Accession No. EG13231; part of *E. coli* K12 MG1655 genomic sequence referenced by GenBank Accession No. U0096; *see also* UniProtKB/Swiss-Prot Accession No. P52697 (PGL polypeptide))(see Figure 40A and SEQ ID NO:11); PGL isolated from *Pseudomonas aeruginosa* strain PAO1 (Locus Tag PA3182 of GenBank Accession No. AE004091); *see also* GenBank Accession No. AAG06570.1 (PGL polypeptide))(see Figure 40B and SEQ ID NO:12); and PGL isolated from *Saccharomyces cerevisiae* (Locus Tag YHR163W of GenBank Accession No. NC_001140; *see also* UNIProtKB/Swiss-Prot Accession No. P38858 (PGL polypeptide))(see Figure 40C and SEQ ID NO:13). Other exemplary PGL nucleic acids can be isolated from any genus in the family *Enterobacteriaceae* including, for example, *Alishewanella*, *Alterococcus*, *Aquamonas*, *Citrobacter*, *Cronobacter*, *Edwardsiella*, *Enterobacter*, *Klebsiella* (e.g., *Klebsiella pneumoniae*), *Pantoea* (e.g., *Pantoea citroea*), *Proteus* (e.g., *Proteus vulgaris*), *Salmonella*, *Serratia* (e.g., *Serratia marcescens*), *Shigella*, and *Yersinia* (e.g., *Yersinia pestis*).

Exemplary Galactose Metabolism Polypeptides and Nucleic Acids

[0120] Galactose-1-epimerase (*galM*) catalyzes the conversion of β -D-galactose to α -D-galactose. Exemplary galactose-1-epimerase polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a galactose-1-epimerase polypeptide. Exemplary galactose-1-epimerase 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 that have at least one activity of a galactose-1-epimerase polypeptide.

[0121] Galactokinase (*galK*) catalyzes the phosphorylation of D-galactose to D-galactose-1-phosphate. Exemplary galactokinase polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a

galactokinase polypeptide. Exemplary galactokinase 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 that have at least one activity of a galactokinase polypeptide.

[0122] Galactose-1-phosphate uridylyltransferase (*galT*) catalyzes the second step of the Leloir pathway of galactose metabolism by converting UDP-glucose and galactose 1-phosphate to glucose 1-phosphate and UDP-galactose. Exemplary galactose-1-phosphate uridylyltransferase polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a galactose-1-phosphate uridylyltransferase polypeptide. Exemplary galactose-1-phosphate uridylyltransferase 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 that have at least one activity of a galactose-1-phosphate uridylyltransferase polypeptide.

[0123] UDP-galactose-4-epimerase (*galE*) catalyzes the reversible conversion of UDP-galactose to UDP-glucose. Exemplary UDP-galactose-4-epimerase polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a UDP-galactose-4-epimerase polypeptide. Exemplary UDP-galactose-4-epimerase 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 that have at least one activity of a UDP-galactose-4-epimerase polypeptide.

[0124] Exemplary galactose metabolic 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 galactose metabolic polypeptide. Exemplary galactose metabolic nucleic acids include, for example, galactose metabolic genes isolated from *E. coli* K12 MG1655 or derivatives thereof; galactose metabolic genes isolated from *Pseudomonas aeruginosa* strain PAO1; and galactose metabolic genes isolated from *Saccharomyces cerevisiae*. Other exemplary galactose metabolic nucleic acids can be isolated from any genus in the family *Enterobacteriaceae* including, for example, *Alishewanella*, *Alterococcus*, *Aquamonas*, *Citrobacter*, *Cronobacter*, *Edwardsiella*, *Enterobacter*, *Klebsiella* (e.g., *Klebsiella*

pneumoniae), *Pantoea* (e.g., *Pantoea citroea*), *Proteus* (e.g., *Proteus vulgaris*), *Salmonella*, *Serratia* (e.g., *Serratia marcescens*), *Shigella*, and *Yersinia* (e.g., *Yersinia pestis*).

Exemplary Molybdenum Transporter Polypeptides and Nucleic Acids

[0125] The polypeptide encoded by the *modF* gene is an uncharacterized member of the fused molybdate transporter subunits of ABC superfamily. Exemplary *modF* encoded polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a *modF* encoded polypeptide. Exemplary *modF* encoded 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 that have at least one activity of a *modF* encoded polypeptide.

[0126] Repressor of the modABC operon for molybdenum transport (*modE*) polypeptide is a regulatory protein that is believed to feedback inhibit the transcription of the modABC operon in the presence of molybdate. Exemplary *modE* encoded polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a *modE* encoded polypeptide. Exemplary *modE* encoded 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 that have at least one activity of a *modE* encoded polypeptide.

[0127] The high affinity trimeric molybdenum transporter protein encoded by *modA*, *modB*, and *modC* is a membrane-associated ABC-type transporter system for the uptake of molybdenum into the cell. When any one of the *modABC* genes are mutated or absent, molybdate transport is accomplished by the ABC-type sulfate transport system or by a non-specific anion transporter, but with about 100 times less efficiency. (Self et al., 2001, *Res. Microbiol.* 152:311-321). Exemplary *modABC* encoded polypeptides include polypeptides, fragments of polypeptides, peptides, and fusion polypeptides that have at least one activity of a *modABC* encoded polypeptide. Exemplary *modABC* encoded 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 that have at least one activity of one of the *modABC* encoded polypeptides.

[0128] Exemplary molybdenum transport 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 molybdenum transport polypeptide. Exemplary molybdenum transport nucleic acids include, for example, molybdenum transport genes isolated from *E. coli* K12 MG1655 or derivatives thereof; molybdenum transport genes isolated from *Pseudomonas aeruginosa* strain PAO1; and galactose metabolic genes isolated from *Saccharomyces cerevisiae*. Other exemplary molybdenum transport nucleic acids can be isolated from any genus in the family *Enterobacteriaceae* including, for example, *Alishewanella*, *Alterococcus*, *Aquamonas*, *Citrobacter*, *Cronobacter*, *Edwardsiella*, *Enterobacter*, *Klebsiella* (e.g., *Klebsiella pneumoniae*), *Pantoea* (e.g., *Pantoea citroea*), *Proteus* (e.g., *Proteus vulgaris*), *Salmonella*, *Serratia* (e.g., *Serratia marcescens*), *Shigella*, and *Yersinia* (e.g., *Yersinia pestis*).

Exemplary Host Cells

[0129] *E. coli* host cells can be used to express isoprene synthase, PGL polypeptide, DXP pathway polypeptides, IDI, and MVA pathway polypeptides in the methods described herein. In one aspect, the host cell is a recombinant cell of an *Escherichia coli* (*E. coli*) strain, or progeny thereof, capable of producing isoprene, the cell comprising: (a) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid is integrated in the *E. coli* chromosome; and (b) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide, and wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cells that do not comprise (a) and (b). In some aspects, the host cells are bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity. In some aspects, the bacterial cells produce the heterologous polypeptide at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences when the cells are cultured in minimal medium. In some aspects, the one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (e.g., integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in culture.

[0130] In some aspects, the heterologous polypeptide capable of biological activity comprises one or more polypeptides involved in the biosynthesis of terpenoid (isoprenoid) or carotenoid compounds, and the cells produce a terpenoid or carotenoid at a higher specific productivity than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences when cultured in minimal medium. In some aspects, the method further comprises a step of recovering the terpenoid or carotenoid.

[0131] In some aspects, the host cells are bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an isoprene synthase polypeptide. In some aspects, the bacterial cells produce isoprene at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium.

[0132] In some aspects, the cells further comprise an MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is an upper MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is a lower MVA pathway polypeptide. In some aspects, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In some aspects, the upper MVA pathway polypeptide is from the genus *Enterococcus*. In some aspects, the upper MVA pathway polypeptide is from *Enterococcus faecalis*. In some aspects, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In some aspects, the lower MVA pathway polypeptide is an MVK polypeptide. In some aspects, the MVK polypeptide is from the genus *Methanosarcina*. In some aspects, the MVK polypeptide is from *Methanosarcina mazei*.

[0133] In some aspects, the one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (e.g., integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in

culture. In some aspects, the bacterial cells are of *E. coli* strain B. In some aspects, the bacterial strains are of *E. coli* strain BL21. In some aspects, the bacterial cells are of *E. coli* strain BL21(DE3).

Exemplary Cell Culture Media

[0134] As used herein, the terms “minimal medium” or “minimal media” refer to growth medium containing the minimum nutrients possible for cell growth, generally, but not always, without the presence of one or more amino acids (*e.g.*, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more amino acids). Minimal medium typically contains: (1) a carbon source for bacterial growth; (2) various salts, which may vary among bacterial species and growing conditions; and (3) water. The carbon source can vary significantly, from simple sugars like glucose to more complex hydrolysates of other biomass, such as yeast extract, as discussed in more detail below. The salts generally provide essential elements such as magnesium, nitrogen, phosphorus, and sulfur to allow the cells to synthesize proteins and nucleic acids. Minimal medium can also be supplemented with selective agents, such as antibiotics, to select for the maintenance of certain plasmids and the like. For example, if a microorganism is resistant to a certain antibiotic, such as ampicillin or tetracycline, then that antibiotic can be added to the medium in order to prevent cells lacking the resistance from growing. Medium can be supplemented with other compounds as necessary to select for desired physiological or biochemical characteristics, such as particular amino acids and the like.

[0135] Any minimal medium formulation can be used to cultivate the host cells. Exemplary minimal medium formulations include, for example, M9 minimal medium and TM3 minimal medium. Each liter of M9 minimal medium contains (1) 200 ml sterile M9 salts (64 g $\text{Na}_2\text{HPO}_4 \cdot 7\text{H}_2\text{O}$, 15 g KH_2PO_4 , 2.5 g NaCl , and 5.0 g NH_4Cl per liter); (2) 2 ml of 1 M MgSO_4 (sterile); (3) 20 ml of 20% (w/v) glucose (or other carbon source); and (4) 100 μl of 1 M CaCl_2 (sterile). Each liter of TM3 minimal medium contains (1) 13.6 g K_2HPO_4 ; (2) 13.6 g KH_2PO_4 ; (3) 2 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$; (4) 2 g Citric Acid Monohydrate; (5) 0.3 g Ferric Ammonium Citrate; (6) 3.2 g $(\text{NH}_4)_2\text{SO}_4$; (7) 0.2 g yeast extract; and (8) 1 ml of 1000X Trace Elements solution; pH is adjusted to ~6.8 and the solution is filter sterilized. Each liter of 1000X Trace Elements contains: (1) 40 g Citric Acid Monohydrate; (2) 30 g $\text{MnSO}_4 \cdot \text{H}_2\text{O}$; (3) 10 g NaCl ; (4) 1 g $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$; (4) 1 g $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$; (5) 1 g $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$; (6) 100 mg $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; (7) 100 mg H_3BO_3 ; and (8) 100 mg $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$; pH is adjusted to ~3.0.

[0136] 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. In some aspects, the carbon source is a carbohydrate (such as monosaccharide, disaccharide, oligosaccharide, or polysaccharides), or invert sugar (*e.g.*, enzymatically treated sucrose syrup).

[0137] 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).

Exemplary Cell Culture Conditions

[0138] Materials and methods suitable for the maintenance and growth of the recombinant cells of the invention are described *infra*, *e.g.*, in the Examples section. Other materials and methods suitable for the maintenance and growth of bacterial cultures are well known in the art. Exemplary techniques may be found in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (U.S. Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, US Publ. No. 2010/0003716, *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. In some aspects, the cells are cultured in a culture medium under conditions permitting the expression of one or more isoprene synthase, DXS, IDI, DXP pathway polypeptides or MVA pathway polypeptides encoded by a nucleic acid inserted into the host cells.

[0139] Standard cell culture conditions can be used to culture the cells (*see*, for example, WO 2004/033646 and references cited therein). In some aspects, cells are grown and maintained at an appropriate temperature, gas mixture, and pH (such as at about 20°C to about 37°C, at about 6% to about 84% CO₂, and at a pH between about 5 to about 9). In some aspects, cells are grown at 35°C in an appropriate cell medium. In some aspects, 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.

[0140] Standard culture conditions and *modEs* of fermentation, such as batch, fed-batch, or continuous fermentation, that can be used are described in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (U.S. Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, US Publ. No. 2010/0003716. 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.

[0141] In some aspects, 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%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20%, or 10%) of the amount of glucose that is consumed by the cells. In particular aspects, 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 aspects, 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 aspects, glucose does not accumulate during the time the cells are cultured. In various aspects, 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 aspects, 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.

[0142] In some aspects, the carbon source includes yeast extract or one or more components of yeast extract. In some aspects, the concentration of yeast extract is 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the carbon source includes both yeast extract (or one or more components thereof) and another carbon source, such as glucose.

[0143] In some aspects, the *E. coli* cells are grown in batch culture. In some aspects, the *E. coli* cells are grown in fed-batch culture. In some aspects, the *E. coli* cells are grown in continuous culture. In some aspects, the *E. coli* cells are cultured in minimal medium. In some aspects, the minimal medium is M9 medium or TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium. In

some aspects, the minimal medium is supplemented with 1.0 % (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose. In certain aspects, the minimal medium is supplemented 0.1% (w/v) or less yeast extract. In some aspects, the minimal medium is supplemented with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less and 0.1% (w/v) or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose and with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0144] The invention encompasses recombinant cell(s) of an *Escherichia coli* (*E. coli*) strain capable of producing isoprene, the cell(s) comprising: (a) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid(s) is/are integrated in the *E. coli* chromosome; and (b) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) that encode(s) a encoding a PGL polypeptide, and wherein the resulting recombinant cell(s) produce(s) isoprene at a greater titer than that of the same cell(s) that does/do not comprise (a) and (b).

[0145] In some aspects, the host cells are bacterial cells of an *Escherichia coli* strain that do not encode a 6-phosphogluconolactonase (PGL) polypeptide, further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an isoprene synthase polypeptide. In some aspects, the host cells are bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, polypeptides transcribed from genes for galactose metabolism (for example, *galM*, *galK*, *galT*, and *galE*), or polypeptides transcribed from genes for molybdate transport (for example, *modF*, *modE*,

modA, *modB*, and *modC*) further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, a heterologous nucleic acid encoding an isoprene synthase polypeptide, a heterologous nucleic acid encoding one or more copies of one or more galactose metabolism polypeptides, and a heterologous nucleic acid encoding one or more copies of one or more molybdate transporter polypeptides. In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the one or more copies of the heterologous gene encoding a PGL polypeptide, the one or more copies of the heterologous gene encoding one or more galactose metabolism polypeptides, and/or the one or more copies of the heterologous gene encoding one or more molybdate transport polypeptides are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome).

[0146] In some aspects, the bacterial cells are of *E. coli* strain B. In some aspects, the bacterial strains are of *E. coli* strain BL21. In some aspects, the bacterial cells are of *E. coli* strain BL21(DE3). In some aspects, the minimal medium is supplemented with 0.1% (w/v) yeast extract or less. In some aspects, the minimal medium is supplemented with 1.0 % (w/v) glucose or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose. In certain aspects, the minimal medium is supplemented 0.1% (w/v) or less yeast extract. In some aspects, the minimal medium is supplemented with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less and 0.1% (w/v) or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose and with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is M9 medium or TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium. In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from a derivative of *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a

PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*.

[0147] In some aspects, the cells further comprise an MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is an upper MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is a lower MVA pathway polypeptide. In some aspects, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In some aspects, the upper MVA pathway polypeptide is from the genus *Enterococcus*. In some aspects, the upper MVA pathway polypeptide is from *Enterococcus faecalis*. In some aspects, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In some aspects, the lower MVA pathway polypeptide is an MVK polypeptide. In some aspects, the MVK polypeptide is from the genus *Methanosarcina*. In some aspects, the MVK polypeptide is from *Methanosarcina mazei*.

[0148] The recombinant bacterial cells described herein have the ability to produce isoprene at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences when cultured in minimal medium. In some cases, the heterologous gene encoding a PGL polypeptide is a heterologous nucleic acid encoding a PGL polypeptide that is integrated into the host cell's chromosome. In some aspects, the bacterial cells produce isoprene at a specific productivity greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, one or more copies of a heterologous gene encoding one or more galactose metabolism polypeptides, and/or one or more copies of a heterologous gene encoding one or more molybdate transport polypeptides when cultured in minimal medium.

[0149] In some aspects, the *E. coli* cells have a specific productivity greater than about 5, 6, 7, 8, 9, 10, 11, 12, 13, or 14 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 15 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 16 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 17 m mg/OD/hr of

isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 18 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 19 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 20 mg/L_{broth}/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 21 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 22 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 23 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 24 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 25 mg/OD/hr of isoprene.

[0150] In other aspects, the *E. coli* cells have an upper limit of specific productivity of about 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, or 5 mg/OD/hr of isoprene. In other aspects, the *E. coli* cells have a lower limit of specific productivity of about 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, or 25 mg/OD/hr of isoprene.

[0151] In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 15 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 16 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 17 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 18 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 19 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 21 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid

encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 22 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 23 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 24 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter, and the cells have a specific productivity greater than about 25 mg/OD/hr of isoprene.

[0152] In some aspects, the *E. coli* cells further comprise a heterologous nucleic acid encoding an IDI polypeptide. In some aspects, the *E. coli* cells further comprise a chromosomal copy of an endogenous nucleic acid encoding an IDI polypeptide. In some aspects, the *E. coli* cells further comprise a heterologous nucleic acid encoding a DXS polypeptide or other DXP pathway polypeptides. In some aspects, the *E. coli* cells further comprise a chromosomal copy of an endogenous nucleic acid encoding a DXS polypeptide or other DXP pathway polypeptides. In some aspects, the *E. coli* cells further comprise one or more nucleic acids encoding an IDI polypeptide and a DXS polypeptide or other DXP pathway polypeptides. In some aspects, one nucleic acid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide or other DXP pathway polypeptides. In some aspects, one plasmid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide or other DXP pathway polypeptides. In some aspects, multiple plasmids encode the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide or other DXP pathway polypeptides.

[0153] In some aspects, the *E. coli* cells further comprise a heterologous nucleic acid encoding an isoprene synthase polypeptide. In some cases, the isoprene synthase polypeptide can be one or more copies of an endogenous isoprene synthase. In some aspects, the isoprene synthase polypeptide is a plant isoprene synthase polypeptide. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Pueraria*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Pueraria montana*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from the genus *Populus*. In some aspects, the isoprene synthase polypeptide is a naturally-occurring polypeptide from *Populus alba*. Other isoprene synthase polypeptides or

isoprene synthase variants that can be used to practice the invention include, but is not limited to, the isoprene synthases, variants thereof and/or isoprene synthase mutants as described in WO 2009/132220 or WO 2010/124146 (the contents of which are incorporated by reference in their entirety, especially with respect to isoprene synthases, variants thereof and/or isoprene synthase mutants).

Methods for the Increased Production of Isoprene

[0154] Genetically engineered cell cultures in bioreactors have produced isoprene more efficiently, in larger quantities, in higher purities and/or with unique impurity profiles, and methods of producing commercially useful quantities of isoprene from renewable resources are described and exemplified, for example, in International Patent Application Publication No. WO2009/076676 A2, U.S. Patent Application Publication Nos. US2009/0203102 A1, US2010/0003716 A1, US2010/0048964 A1, US2010/0086978 A1, US2010/0167370 A1, US2010/0113846 A1, US2010/0184178 A1, US2010/0167371 A1, US2010/0196977 A1, US2010/0196977 A1; U.S. Provisional Patent Application Nos. 61/187,930, 61/187,941 and 61/187,959.

[0155] Also provided herein are improved methods for the production of isoprene. In some aspects, the improved method for producing isoprene comprises: (a) culturing a composition comprising recombinant cell(s) of an *Escherichia coli* (*E. coli*) strain, or progeny thereof, capable of producing isoprene, the cell comprising: (i) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid is integrated in the *E. coli* chromosome; and (ii) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide, and wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cells that do not comprise (i) and (ii) and (b) producing the isoprene. In some aspects, the improved method of producing isoprene comprises the steps of: (a) culturing bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide in minimal medium, wherein the *E. coli* cells comprise one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a heterologous nucleic acid encoding an isoprene synthase polypeptide; and (b) producing isoprene, wherein the *E. coli* cells have a specific productivity of isoprene greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated

expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the improved method of producing isoprene further comprises a step of recovering the isoprene.

[0156] In some aspects, the improved method of producing isoprene comprises the steps of culturing the recombinant cells described herein under conditions suitable for the production of isoprene and allowing the recombinant cells to produce isoprene. In some aspects, the improved method of producing isoprene further comprises a step of recovering the isoprene.

[0157] Without being bound by theory, recombinant cells having chromosomally integrated heterologous nucleic acids encoding PGL polypeptide produce isoprene at a higher titer and a higher specific productivity than cells where a heterologous PGL nucleic acid is on a plasmid. Surprisingly, recombinant cells comprising one or more copies of chromosomally integrated PGL polypeptide, and optionally with one or more copies of one or more polypeptides encoded by chromosomally integrated galactose metabolism genes (for example, *galM*, *galK*, *galT* and *galE*), and/or one or more copies of one or more polypeptides encoded by chromosomally integrated molybdenum transport genes (for example, *modF*, *modE*, *modA*, *modB*, and *modC*) convey a substantial growth benefit to the cells, a higher titer of isoprene production, and/or a higher specific production of isoprene versus cells comprising a heterologous PGL nucleic acid on a plasmid.

[0158] Therefore, in one aspect the improved method of producing isoprene comprises the steps of: (a) culturing bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, one or more polypeptides encoded by genes for galactose metabolism (for example, *galM*, *galK*, *galT* and *galE*), and/or one or more polypeptides encoded by genes for molybdenum transport (for example, *modF*, *modE*, *modA*, *modB*, and *modC*), wherein the *E. coli* cells comprise one or more copies of a chromosomally integrated heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, a heterologous nucleic acid encoding an isoprene synthase polypeptide, one or more copies of a chromosomally integrated heterologous nucleic acid encoding one or more galactose metabolism polypeptides and/or one or more molybdenum transport polypeptides; and (b) producing isoprene, wherein the *E. coli* cells have a higher

specific growth rate, specific productivity of isoprene and/or titer production of isoprene than that of the same cells wherein the heterologous gene encoding PGL is located on a plasmid.

[0159] In some aspects, the cells further comprise an MVA pathway polypeptide. In such cases, the invention contemplates compositions and methods for producing mevalonate as well. The methods for producing mevalonate using a chromosomally integrated PGL host cell system can optionally include recovery of the mevalonate. In some aspects, the MVA pathway polypeptide is an upper MVA pathway polypeptide. In some aspects, the MVA pathway polypeptide is a lower MVA pathway polypeptide.

[0160] In some aspects, the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide. In some aspects, the upper MVA pathway polypeptide is acetoacetyl-Coenzyme A synthase (thiolase). In some aspects, the upper MVA pathway polypeptide is 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide. In some aspects, the upper MVA pathway polypeptide is 3-hydroxy-3-methylglutaryl-Coenzyme A reductase. In some aspects, the upper MVA pathway polypeptide is from a bacterium. In some aspects, the bacterium is from the genus *Enterococcus*. In some aspects, bacterium is from *Enterococcus faecalis*.

[0161] In some aspects, the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI). In some aspects, the lower MVA pathway polypeptide is MVK. In some aspects, the MVK is from the genus *Methanosarcina*. In some aspects, the *Methanosarcina* is *Methanosarcina mazei*. In some aspects, the lower MVA pathway polypeptide is PMK, MVD, or IDI. In some aspects, the PMK, MVD, or IDI is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the lower MVA pathway polypeptide is PMK. In some aspects, the PMK is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the lower MVA pathway polypeptide is MVD.

[0162] In some aspects, the MVD is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the lower MVA pathway

polypeptide is IDI. In some aspects, the lower MVA pathway polypeptide is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*.

[0163] In some aspects, the isoprene synthase polypeptide is from a plant. In some aspects, the plant is kudzu. In some aspects, the plant is poplar (*Populus alba x tremula* CAC35696). In some aspects, the plant is aspen (*Populus tremuloides*). In some aspects, the plant is English oak (*Quercus robur*). In one aspect, the plant is *Populus alba*. Other isoprene synthase polypeptides or isoprene synthase variants that can be used to practice the invention include, but is not limited to, the isoprene synthases, variants thereof and/or isoprene synthase mutants as described in WO 2009/132220 or WO 2010/124146 (the contents of which are incorporated by reference in their entirety, especially with respect to isoprene synthases, variants thereof and/or isoprene synthase mutants).

[0164] In some aspects, the *E. coli* cells further comprise a heterologous nucleic acid encoding an IDI polypeptide. In some aspects, the *E. coli* cells further comprise one or more copies of an endogenous nucleic acid encoding an IDI polypeptide. In some aspects, the *E. coli* cells further comprise a chromosomal copy of an endogenous nucleic acid encoding an IDI polypeptide. In some aspects, the *E. coli* cells further comprise a heterologous nucleic acid encoding a DXS polypeptide or other DXP pathway polypeptides. In some aspects, the *E. coli* cells further comprise a chromosomal copy of an endogenous nucleic acid encoding a DXS polypeptide or other DXP pathway polypeptides. In some aspects, the *E. coli* cells further comprise one or more nucleic acids encoding an IDI polypeptide and a DXS polypeptide or other DXP pathway polypeptides. In some aspects, one nucleic acid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide. In some aspects, one plasmid encodes the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide or other DXP pathway polypeptides. In some aspects, multiple plasmids encode the isoprene synthase polypeptide, IDI polypeptide, and DXS polypeptide or other DXP pathway polypeptides.

[0165] In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from a derivative of *E. coli* strain K12 MG1655. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity is SEQ ID NO:11. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID

NO:11. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:11.

[0166] In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*. In some aspects, the *P. aeruginosa* polypeptide having PGL activity is SEQ ID NO:12. In some aspects, the *P. aeruginosa* polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID NO:12. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:12.

[0167] In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the *S. cerevisiae* polypeptide having PGL activity is SEQ ID NO:13. In some aspects, the *S. cerevisiae* polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID NO:13. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:13.

[0168] In some aspects, the bacterial cells of an *Escherichia coli* strain that does not encode a PGL polypeptide are of *E. coli* strain B. In some aspects, the bacterial cells are of *E. coli* strain BL21. In some aspects, the bacterial cells are of *E. coli* strain BL21(DE3).

[0169] In some aspects, the *E. coli* cells are cultured in minimal medium. In some aspects, the *E. coli* cells of *E. coli* strain B are cultured in minimal medium. In some aspects, the *E. coli* cells of *E. coli* strain BL21 are cultured in minimal medium. In some aspects, the *E. coli* cells of *E. coli* strain BL21(DE3) are cultured in minimal medium. In some aspects, the minimal medium is supplemented with 1% (w/v) or less glucose. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6%

(w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose. In certain aspects, the minimal medium is supplemented 0.1% (w/v) or less yeast extract. In some aspects, the minimal medium is supplemented with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less and 0.1% (w/v) or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose and with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is M9 medium or TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium.

[0170] In some aspects, the *E. coli* cells have a specific productivity greater than about 15 mg/L_{broth}/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 16 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 17 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 18 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 19 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 21 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 22 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 23 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 24 mg/OD/hr of isoprene. In some aspects, the *E. coli* cells have a specific productivity greater than about 25 mg/OD/hr of isoprene.

[0171] In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 15 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 16 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 17

mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 18 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 19 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 20 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 21 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 22 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 23 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 24 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 25 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 25 mg/OD/hr of isoprene to about 100 mg/OD/hr of isoprene. In some aspects, the heterologous nucleic acid encoding an isoprene synthase polypeptide is operably linked to a promoter and the *E. coli* cells have a specific productivity greater than about 15 mg/OD/hr of isoprene to about 100 mg/OD/hr of isoprene.

[0172] The invention also provides for recombinant *E. coli* cells with PGL integration that have been engineered to produce isoprene that also have better growth due to their increased overall fitness. One of skill in the art can appreciate that increased growth rate can lead to enhanced production of isoprene, such as higher specific activity, more isoprene produced over a period of time, or higher isoprene titers. In one aspect, the recombinant *E. coli* cells with PGL integration that have been engineered to produce isoprene has at least 10% increased growth as compared to those cells without PGL integration and/or the restoration of the 17,257 base pair piece as described herein (see, for example, Figure 20). In other aspects,

the recombinant *E. coli* cells with PGL integration that have been engineered to produce isoprene has at least about 11%, 12%, 13%, 14%, 15%, 16%, 17%, 18%, 19%, 20%, 21%, 22%, 23%, 24%, or 25% growth as compared to those cells without PGL integration and/or the restoration of the 17,257 base pair piece as described herein.

Methods for the Increased Production of Other Heterologous Polypeptides Capable of Biological Activity

[0173] Also provided herein are improved methods for the production of other heterologous polypeptides capable of biological activity or other products. One non-limiting example of a product is mevalonate. One of skill in the art can produce mevalonate by: (a) culturing a composition comprising the recombinant cell of an *Escherichia coli* (*E. coli*) strain, or progeny thereof, capable of producing isoprene, the cell comprising: (i) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid is integrated in the *E. coli* chromosome; (ii) one or more heterologous nucleic acid(s) encoding isoprene synthase; and (iii) (c) a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide and/or a lower MVA pathway polypeptide; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide, and wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cells that do not comprise (i) and (ii) under suitable culture conditions for the production of mevalonate and (b) producing mevalonate.

[0174] In some aspects, the improved method of producing heterologous polypeptides capable of biological activity comprises the steps of: (a) culturing cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity; and (b) producing the heterologous polypeptide, wherein the *E. coli* cells have a specific productivity of the heterologous polypeptide greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, when the cells are cultured in minimal medium. In some aspects, the one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in culture. In some aspects, the improved method of producing heterologous

polypeptides capable of biological activity further comprises a step of recovering the polypeptide.

[0175] In some aspects, the bacterial cells of an *Escherichia coli* strain that does not encode a PGL polypeptide are of *E. coli* strain B. In some aspects, the bacterial cells are of *E. coli* strain BL21. In some aspects, the bacterial cells are of *E. coli* strain BL21(DE3).

[0176] In some aspects, the heterologous gene encoding a PGL polypeptide is from *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide is from a derivative of *E. coli* strain K12 MG1655. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity is SEQ ID NO:11. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID NO:11. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:11.

[0177] In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*. In some aspects, the *P. aeruginosa* polypeptide having PGL activity is SEQ ID NO:12. In some aspects, the *P. aeruginosa* polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID NO:12. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *P. aeruginosa* polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:12.

[0178] In some aspects, the heterologous gene encoding a PGL polypeptide is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the *S. cerevisiae* polypeptide having PGL activity is SEQ ID NO:13. In some aspects, the *S. cerevisiae* polypeptide having PGL activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to SEQ ID NO:13. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655

polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to SEQ ID NO:13.

[0179] In some aspects, the bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain B are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain BL21 are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain BL21(DE3) are cultured in minimal medium. In some aspects, the minimal medium is supplemented with 1% (w/v) or less glucose. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose. In certain aspects, the minimal medium is supplemented 0.1% (w/v) or less yeast extract. In some aspects, the minimal medium is supplemented with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less and 0.1% (w/v) or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose and with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is M9 medium or TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium.

[0180] Also provided herein are improved methods for the production of other heterologous polypeptides capable of biological activity. In some aspects, the improved method of producing heterologous polypeptides capable of biological activity comprises the steps of: (a) culturing cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, a gene that encodes one or more galactose metabolism polypeptides (for example, *galM*, *galK*, *galT*, and *galE*), and/or a gene that encodes one or more molybdenum transporter polypeptides (for example, *modF*, *modE*, *modA*, *modB*, and *modC*) further comprising one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences and a nucleic acid encoding a heterologous polypeptide capable of biological activity, one or more copies of a heterologous gene encoding one or more galactose metabolism polypeptides,

and/or one or more copies of a heterologous gene encoding one or more molybdenum transport polypeptides; and (b) producing the heterologous polypeptide, wherein the *E. coli* cells have a specific productivity of the heterologous polypeptide greater than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, one or more copies of a heterologous gene encoding one or more galactose metabolism polypeptides, and/or one or more copies of a heterologous gene encoding one or more molybdenum transport polypeptides when the cells are cultured in minimal medium. In some aspects, the one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences, the one or more copies of a heterologous gene encoding one or more galactose metabolism polypeptides, and/or the one or more copies of a heterologous gene encoding one or more molybdenum transporter polypeptides are chromosomal copies (*e.g.*, integrated into the *E. coli* chromosome). In some aspects, the *E. coli* cells are in culture. In some aspects, the improved method of producing heterologous polypeptides capable of biological activity further comprises a step of recovering the polypeptide.

[0181] In some aspects, the bacterial cells of an *Escherichia coli* strain that does not encode a PGL polypeptide, one or more galactose metabolic genes, and/or one or more molybdenum transport genes are of *E. coli* strain B. In some aspects, the bacterial cells are of *E. coli* strain BL21. In some aspects, the bacterial cells are of *E. coli* strain BL21(DE3).

[0182] In some aspects, the heterologous gene encoding a PGL polypeptide, one or more galactose metabolic genes, and/or one or more molybdenum transport genes is from *E. coli* strain K12 MG1655. In some aspects, the heterologous gene encoding a PGL polypeptide, one or more galactose metabolic genes, and/or one or more molybdenum transport genes is from a derivative of *E. coli* strain K12 MG1655. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity, galactose metabolic activity, and/or molybdenum transport activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to the native *E. coli* K12 strain MG1655 polypeptide. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *E. coli* K12 strain MG1655 polypeptide having PGL activity, galactose metabolic activity, and/or molybdenum transport activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%,

87%, 86%, or 85% amino acid sequence identity to the native *E. coli* K12 strain MG1655 polypeptide.

[0183] In some aspects, the heterologous gene encoding a PGL polypeptide, one or more galactose metabolism polypeptides, and/or one or more molybdenum transport polypeptides is from the genus *Pseudomonas*. In some aspects, the *Pseudomonas* is *Pseudomonas aeruginosa*. In some aspects, the *P. aeruginosa* polypeptide having PGL activity, galactose metabolic activity, and/or molybdenum transport activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to the native *P. aeruginosa* polypeptide. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *P. aeruginosa* polypeptide having PGL activity, galactose metabolic activity, and/or molybdenum transport activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to the native *P. aeruginosa* polypeptide.

[0184] In some aspects, the heterologous gene encoding a PGL polypeptide, one or more galactose metabolism polypeptides, and/or one or more molybdenum transport polypeptides is from the genus *Saccharomyces*. In some aspects, the *Saccharomyces* is *Saccharomyces cerevisiae*. In some aspects, the *S. cerevisiae* polypeptide having PGL activity, galactose metabolic activity, and/or molybdenum transport activity comprises 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more amino acid substitutions compared to the native *Saccharomyces cerevisiae*. In some aspects, the amino acid substitutions are conservative. In some aspects, the amino acid substitutions are non-conservative. In some aspects, the *Saccharomyces cerevisiae* polypeptide having PGL activity has 99%, 98%, 97%, 96%, 95%, 95%, 93%, 92%, 91%, 90%, 89%, 88%, 87%, 86%, or 85% amino acid sequence identity to the native *Saccharomyces cerevisiae* polypeptide.

[0185] In some aspects, the bacterial cells of an *Escherichia coli* strain that does not encode a 6-phosphogluconolactonase (PGL) polypeptide, one or more galactose metabolism polypeptides, and/or one or more molybdenum transport polypeptides are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain B are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain BL21 are cultured in minimal medium. In some aspects, the bacterial cells of *E. coli* strain BL21(DE3) are cultured in minimal medium. In some aspects, the minimal medium is supplemented with 1% (w/v) or

less glucose. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose. In certain aspects, the minimal medium is supplemented 0.1% (w/v) or less yeast extract. In some aspects, the minimal medium is supplemented with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is supplemented with 1% (w/v) glucose or less and 0.1% (w/v) or less. In some aspects, the minimal medium is supplemented with 1% (w/v), 0.9% (w/v), 0.8% (w/v), 0.7% (w/v), 0.6% (w/v), 0.5% (w/v), 0.4% (w/v), 0.3% (w/v), 0.2% (w/v), or 0.1% (w/v) glucose and with 0.1% (w/v), 0.09% (w/v), 0.08% (w/v), 0.07% (w/v), 0.06% (w/v), 0.05% (w/v), 0.04% (w/v), 0.03% (w/v), 0.02% (w/v), or 0.01% (w/v) yeast extract. In some aspects, the minimal medium is M9 medium or TM3 medium. In some aspects, the minimal medium is M9 medium. In some aspects, the minimal medium is TM3 medium.

[0186] In some aspects, the heterologous polypeptide capable of biological activity comprises one or more polypeptides involved in the biosynthesis of terpenoid (isoprenoid) or carotenoid compound(s), and the cells produce a terpenoid or carotenoid at a higher specific productivity than that of the same cells lacking one or more copies of a heterologous gene encoding a PGL polypeptide with one or more associated expression control sequences when cultured in minimal medium. In some aspects, the method further comprises a step of recovering the terpenoid or carotenoid.

[0187] As used herein, the term “terpenoid” or “isoprenoid” refers to a large and diverse class of naturally-occurring organic chemicals similar to terpenes. Terpenoids are derived from five-carbon isoprene units assembled and modified in a variety of ways, and are classified in groups based on the number of isoprene units used in group members. Hemiterpenoids have one isoprene unit. Monoterpenoids have two isoprene units. Sesquiterpenoids have three isoprene units. Diterpenoids have four isoprene units. Sesterterpenoids have five isoprene units. Triterpenoids have six isoprene units. Tetraterpenoids have eight isoprene units. Polyterpenoids have more than eight isoprene units. One of ordinary skill in the art would be able to identify heterologous polypeptides capable of biological activity, *e.g.*, capable of making terpenoids of various classes by assembling the appropriate number of isoprene units and modifying them as appropriate.

[0188] As used herein, the term “carotenoid” refers to a group of naturally-occurring organic pigments produced in the chloroplasts and chromoplasts of plants, of some other photosynthetic organisms, such as algae, in some types of fungus, and in some bacteria. Carotenoids include the oxygen-containing xanthophylls and the non-oxygen-containing carotenes.

[0189] In some aspects, the terpenoids are selected from the group consisting of hemiterpenoids, monoterpenoids, sesquiterpenoids, diterpenoids, sesterterpenoids, triterpenoids, tetraterpenoids, and higher polyterpenoids. In some aspects, the hemiterpenoid is prenol (*i.e.*, 3-methyl-2-buten-1-ol), isoprenol (*i.e.*, 3-methyl-3-buten-1-ol), 2-methyl-3-buten-2-ol, or isovaleric acid. In some aspects, the monoterpenoid is geranyl pyrophosphate, eucalyptol, limonene, or pinene. In some aspects, the sesquiterpenoid is farnesyl pyrophosphate, artemisinin, or bisabolol. In some aspects, the diterpenoid is geranylgeranyl pyrophosphate, retinol, retinal, phytol, taxol, forskolin, or aphidicolin. In some aspects, the triterpenoid is squalene or lanosterol. In some aspects, the tetraterpenoid is lycopene or carotene. In some aspects, the carotenoids are selected from the group consisting of xanthophylls and carotenes. In some aspects, the xanthophyll is lutein or zeaxanthin. In some aspects, the carotene is α -carotene, β -carotene, γ -carotene, β -cryptoxanthin or lycopene.

[0190] In some aspects, the source organism for the heterologous polypeptide capable of biological activity is a fungus. In some aspects, the fungus is a species of *Aspergillus* such as *A. oryzae* and *A. niger*, a species of *Saccharomyces* such as *S. cerevisiae*, a species of *Schizosaccharomyces* such as *S. pombe*, or a species of *Trichoderma* such as *T. reesei*. In some aspects, the source organism for the heterologous polypeptide capable of biological activity is a filamentous fungal cell. In some aspects, the filamentous fungal cell is from *Trichoderma longibrachiatum*, *T. viride*, *T. koningii*, *T. harzianum*, *Penicillium sp.*, *Humicola insolens*, *H. lanuginosa*, *H. grisea*, *Chrysosporium sp.*, *C. lucknowense*, *Gliocladium sp.*, *Aspergillus sp.*, such as *A. oryzae*, *A. niger*, *A. sojae*, *A. japonicus*, *A. nidulans*, or *A. awamori*, *Fusarium sp.*, such as *F. roseum*, *F. gramineum*, *F. cerealis*, *F. oxysporum*, or *F. venenatum*, *Neurospora sp.*, such as *N. crassa*, *Hypocrea sp.*, *Mucor sp.*, such as *M. miehei*, *Rhizopus sp.* or *Emericella sp.* In some aspects, the fungus is *A. nidulans*, *A. awamori*, *A. oryzae*, *A. aculeatus*, *A. niger*, *A. japonicus*, *T. reesei*, *T. viride*, *F. oxysporum*, or *F. solani*. In some aspects, the source organism is a yeast, such as

Saccharomyces sp., *Schizosaccharomyces sp.*, *Pichia sp.*, or *Candida sp.* In some aspects, the *Saccharomyces sp.* is *Saccharomyces cerevisiae*.

[0191] In some aspects, the source organism for the heterologous polypeptide capable of biological activity is a bacterium. In some aspects, the bacterium is of the genus *Bacillus*, such as *B. licheniformis* or *B. subtilis*, the genus *Pantoea*, such as *P. citrea*, the genus *Pseudomonas*, such as *P. alcaligenes*, *P. putida*, or *P. fluorescens*, the genus *Streptomyces*, such as *S. lividans*, *S. coelicolor*, *S. griseus*, or *S. rubiginosus*, the genus *Corynebacterium*, such as *Corynebacterium glutamicum*, the genus *Rhodopseudomonas*, such as *Rhodopseudomonas palustris*, or the genus *Escherichia*, such as *E. coli*. In some aspects, the bacterium is selected from group consisting of *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*.

[0192] In some aspects, the source organism is a plant, such as a plant from the family Fabaceae, such as the Faboideae subfamily. In some aspects, the source organism is kudzu, poplar (such as *Populus alba* or *Populus alba x tremula* CAC35696), aspen (such as *Populus tremuloides*), or *Quercus robur*. In some aspects, the source organism is an algae, such as a green algae, red algae, glaucophytes, chlorarachniophytes, euglenids, chromista, or dinoflagellates. In some aspects, the source organism is a cyanobacterium, such as cyanobacterium classified into any of the following groups based on morphology: *Chlorococcales*, *Pleurocapsales*, *Oscillatoriales*, *Nostocales*, or *Stigonematales*.

Isoprene Compositions Produced from Renewable Resources

[0193] Isoprene compositions produced from renewable resources are distinguished from petro-isoprene compositions in that isoprene produced from renewable resources is produced with other biological byproducts (compounds derived from the biological sources and/or associated the biological processes that are obtained together with isoprene) that are not present or present in much lower levels in petro-isoprene compositions, such as alcohols, aldehydes, ketone and the like. The biological 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, 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-butanal, butyl acetate, 3-methylbutyl acetate, 3-methyl-3-buten-1-yl acetate, 3-methyl-2-buten-1-yl acetate, 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), (E)-3,7-dimethyl-1,3,6-octatriene, (Z)-3,7-dimethyl-1,3,6-octatriene, or a linear isoprene polymer (such as a linear isoprene dimer or a linear isoprene trimer derived from the polymerization of multiple isoprene units). Products derived from isoprene produced from renewable resources contain one or more of the biological byproducts or compounds derived from any of the by-products. In addition, products derived from isoprene produced from renewable resources may contain compounds formed from these by-products during subsequent chemical conversion. Examples of such compounds include those derived from Diels-Alder cycloaddition of dienophiles to isoprene, or the oxidation of isoprene.

[0194] Isoprene compositions produced from renewable resources, including particular byproducts or impurities, are described in more detail in U.S. Provisional Patent Application No. 61/187,959 and WO 2010/14825.

[0195] 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), a DXS polypeptide, other DXP pathway polypeptide, and/or an MVA pathway polypeptide into the cells, *e.g.*, as described in International Patent Application Publication No. WO2009/076676 A2, U.S. Patent Application No. 12/335,071, U.S. Patent Application Nos. 12/429,143, 12/496,573, 12/560,390, 12/560,317, 12/560,370, 12/560,305, and 12/560,366; U.S. Provisional Patent Application Nos. 61/187,930; 61/187,941; 61/187,959; U.S. Publ. No. 2010/0196977 and WO 2010/078457.

[0196] Exemplary isoprene synthase polypeptide (*e.g.*, a plant isoprene synthase polypeptide), a DXS, a DXP pathway, or an 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.

Exemplary Isoprene Synthase Polypeptides and Nucleic Acids

[0197] In some aspects, the *E. coli* cells comprise a heterologous nucleic acid encoding an isoprene synthase polypeptide. In some aspects, the isoprene synthase polypeptide or nucleic

acid is from the family Fabaceae, such as the Faboideae subfamily. In some aspects, 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*, or *Populus alba x tremula* (CAC35696) 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). In some aspects, the isoprene synthase polypeptide or nucleic acid is a naturally-occurring isoprene synthase polypeptide or nucleic acid. In some aspects, the isoprene synthase polypeptide or nucleic acid is not a naturally-occurring isoprene synthase polypeptide or nucleic acid. Exemplary isoprene synthase polypeptides and nucleic acids and methods of measuring isoprene synthase activity are described in more detail in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary DXS Polypeptides and Nucleic Acids

[0198] 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 polypeptides and nucleic acids and methods of measuring DXS activity are described in more detail in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary DXP Pathway Polypeptides and Nucleic Acids

[0199] Exemplary DXP pathways polypeptides include, but are not limited to any of the following polypeptides: DXS polypeptides, DXR polypeptides, MCT polypeptides, CMK polypeptides, MCS polypeptides, HDS polypeptides, HDR polypeptides, IDI polypeptides, and polypeptides (*e.g.*, fusion polypeptides) having an activity of one, two, or more of the DXP pathway polypeptides. In particular, DXP pathway polypeptides include polypeptides, fragments of polypeptides, peptides, and fusions polypeptides that have at least one activity

of a DXP pathway polypeptide. Exemplary DXP 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 a DXP pathway polypeptide. Exemplary DXP 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.

[0200] 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 polypeptides and nucleic acids and methods of measuring DXS activity are described in more detail in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

[0201] In particular, DXS polypeptides convert pyruvate and D-glyceraldehyde 3-phosphate into 1-deoxy-d-xylulose 5-phosphate (DXP). Standard methods 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 *in vitro*, in a cell extract, or *in vivo*.

[0202] DXR polypeptides convert 1-deoxy-d-xylulose 5-phosphate (DXP) into 2-C-methyl-D-erythritol 4-phosphate (MEP). Standard methods can be used to determine whether a polypeptide has DXR polypeptides activity by measuring the ability of the polypeptide to convert DXP *in vitro*, in a cell extract, or *in vivo*.

[0203] MCT polypeptides convert 2-C-methyl-D-erythritol 4-phosphate (MEP) into 4-(cytidine 5'-diphospho)-2-methyl-D-erythritol (CDP-ME). Standard methods can be used to determine whether a polypeptide has MCT polypeptides activity by measuring the ability of the polypeptide to convert MEP *in vitro*, in a cell extract, or *in vivo*.

[0204] CMK polypeptides convert 4-(cytidine 5'-diphospho)-2-C-methyl-D-erythritol (CDP-ME) into 2-phospho-4-(cytidine 5'-diphospho)-2-C-methyl-D-erythritol (CDP-MEP).

Standard methods can be used to determine whether a polypeptide has CMK polypeptides activity by measuring the ability of the polypeptide to convert CDP-ME *in vitro*, in a cell extract, or *in vivo*.

[0205] MCS polypeptides convert 2-phospho-4-(cytidine 5'-diphospho)-2-C-methyl-D-erythritol (CDP-MEP) into 2-C-methyl-D-erythritol 2, 4-cyclodiphosphate (ME-CPP or cMEPP). Standard methods can be used to determine whether a polypeptide has MCS polypeptides activity by measuring the ability of the polypeptide to convert CDP-MEP *in vitro*, in a cell extract, or *in vivo*.

[0206] HDS polypeptides convert 2-C-methyl-D-erythritol 2, 4-cyclodiphosphate into (E)-4-hydroxy-3-methylbut-2-en-1-yl diphosphate (HMBPP or HDMAPP). Standard methods can be used to determine whether a polypeptide has HDS polypeptides activity by measuring the ability of the polypeptide to convert ME-CPP *in vitro*, in a cell extract, or *in vivo*.

[0207] HDR polypeptides convert (E)-4-hydroxy-3-methylbut-2-en-1-yl diphosphate into isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP). Standard methods can be used to determine whether a polypeptide has HDR polypeptides activity by measuring the ability of the polypeptide to convert HMBPP *in vitro*, in a cell extract, or *in vivo*.

[0208] IDI polypeptides convert isopentenyl diphosphate into dimethylallyl diphosphate . Standard methods can be used to determine whether a polypeptide has IDI polypeptides activity by measuring the ability of the polypeptide to convert isopentenyl diphosphate *in vitro*, in a cell extract, or *in vivo*.

Exemplary IDI Polypeptides and Nucleic Acids

[0209] Isopentenyl diphosphate isomerase polypeptides (isopentenyl-diphosphate delta-isomerase or IDI) catalyses the interconversion of isopentenyl diphosphate (IPP) and dimethyl allyl 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 polypeptides and nucleic acids and methods of measuring IDI activity are described in more detail in International Publication No. WO 2009/076676, U.S. Patent Application No.

12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary MVA Pathway Polypeptides and Nucleic Acids

[0210] 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 polypeptides and nucleic acids and methods of measuring IDI activity are described in more detail in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

[0211] In some aspects, the cells contain the upper MVA pathway, which includes AA-CoA thiolase, HMG-CoA synthase, and HMG-CoA reductase nucleic acids. In some aspects, the cells contain the lower MVA pathway, which includes MVK, PMK, MVD, and IDI nucleic acids. In some aspects, the cells contain an entire MVA pathway that includes AA-CoA thiolase, HMG-CoA synthase, HMG-CoA reductase, MVK, PMK, MVD, and IDI nucleic acids. In some aspects, 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.

[0212] The *E. coli* cells described herein can also be used for improved methods of producing isoprene and a co-product, such as hydrogen, ethanol, or propanediol (*e.g.*, 1,2-propanediol or 1,3-propanediol). Exemplary hydrogenase polypeptides and nucleic acids, polypeptides and nucleic acids for genes related to production of fermentation side products, and polypeptides and nucleic acids for genes relating to hydrogen reuptake can also be used with the compositions and methods described in. Such polypeptides and nucleic acids are described in U.S. Publ. No. 2010/0196977 and WO 2010/078457.

Exemplary Methods for Isolating Nucleic Acids

[0213] Isoprene synthase, DXS, IDI, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation and/or transcription factor 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). Standard methods of isolating nucleic acids, including PCR amplification of known sequences, synthesis of nucleic acids, screening of genomic libraries, screening of cosmid libraries are described in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary Promoters and Vectors

[0214] Any of the isoprene synthase, DXS, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic, and/or molybdenum transport nucleic acids described herein can be included in one or more vectors. Accordingly, also described herein are vectors with one more nucleic acids encoding any of the isoprene synthase, DXS, IDI, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor polypeptides, galactose metabolic polypeptides, and/or molybdenum transport polypeptides that are described herein. In some aspects, the vector contains a nucleic acid under the control of an expression control sequence. In some aspects, the expression control sequence is a native expression control sequence. In some aspects, the expression control sequence is a non-native expression control sequence. In some aspects, the vector contains a selective marker or selectable marker. In some aspects, an isoprene synthase, DXS, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription regulatory, galactose metabolic, and/or molybdenum transport nucleic acid integrates into a chromosome of the cells without a selectable marker. In some aspects, an isoprene synthase, DXS, IDI, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription regulatory, galactose metabolic, and/or molybdenum transport nucleic acid integrates into a chromosome of the cells with a selectable marker.

[0215] 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. Suitable vectors can be maintained in low,

medium, or high copy number in the host cell. 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). Suitable vectors compatible with the cells and methods described herein are described in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

[0216] 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, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport nucleic acid in the host cell. Initiation control regions or promoters, which are useful to drive expression of isoprene synthase, DXS, IDI, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport 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). Virtually any promoter capable of driving these nucleic acids can be used including a glucose isomerase promoter (*see*, for example, U.S. Patent No. 7,132,527 and references cited therein). Suitable promoters compatible with the cells and methods described herein are described in International Publication No. WO 2009/076676 A2 and U.S. Patent Application Publication No. US2009/0203102 A1.

[0217] In some aspects, 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 aspects, the termination sequence and the promoter sequence are derived from the same source. Suitable termination sequences compatible with the cells and methods described herein are described in International Publication No. WO 2009/076676 A2 and U.S. Patent Application Publication No. US2009/0203102 A1

[0218] An isoprene synthase, DXS, IDI, DXP pathway, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum 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). Suitable techniques compatible with the cells and methods described herein are

described in International Publication No. WO 2009/076676 A2 and U.S. Patent Application Publication No. US2009/0203102 A1.

[0219] In some aspects, it may be desirable to over-express isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport nucleic acids at levels far higher than currently found in naturally-occurring cells. In some aspects, it may be desirable to under-express (*e.g.*, mutate, inactivate, or delete) isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor polypeptide, galactose metabolic polypeptide and/or molybdenum transport polypeptide-encoding nucleic acids at levels far below that those currently found in naturally-occurring cells. Suitable methods for over- or under-expressing the isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport nucleic acids compatible with cells and methods described herein are described in International Publication No. WO 2009/076676 A2 and U.S. Patent Application Publication No. US2009/0203102 A1.

Exemplary Source Organisms

[0220] Isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport nucleic acids (and their encoded polypeptides) can be obtained from any organism that naturally contains isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport 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 (Figures 1A and 1B). Thus, DXP pathway 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. Hydrogenase nucleic acids can be obtained, *e.g.*, from any organism that oxidizes hydrogen or reduces hydrogen ions. Fermentation side product

genes can be obtained or identified, *e.g.*, from any organism that undergoes oxygen-limited or anaerobic respiration, such as glycolysis.

[0221] The nucleic acid sequence of the isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport nucleic acids can be isolated from a bacterium, fungus, plant, algae, or cyanobacterium. Exemplary source organisms include, for example, yeasts, such as species of *Saccharomyces* (*e.g.*, *S. cerevisiae*), bacteria, such as species of *Escherichia* (*e.g.*, *E. coli*), or species of *Methanosarcina* (*e.g.*, *Methanosarcina mazei*), plants, such as kudzu or poplar (*e.g.*, *Populus alba* or *Populus alba x tremula* CAC35696) or aspen (*e.g.*, *Populus tremuloides*). Exemplary host organisms are described in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary Transformation Methods

[0222] Isoprene synthase, DXP pathway, IDI, MVA pathway, PGL, hydrogenase, hydrogenase maturation, transcription factor, galactose metabolic and/or molybdenum transport 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 introduction of a DNA construct or vector into a host cell, 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). The introduced nucleic acids may be integrated into chromosomal DNA or maintained as extrachromosomal replicating sequences. Transformants can be selected by any method known in the art. Suitable methods for selecting transformants are described in International Publication No. WO 2009/076676, U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102), WO 2010/003007, US Publ. No. 2010/0048964, WO 2009/132220, and US Publ. No. 2010/0003716.

Exemplary Purification Methods

[0223] In some aspects, any of the methods described herein further include a step of recovering the compounds produced. In some aspects, any of the methods described herein further include a step of recovering the isoprene. In some aspects, the isoprene is recovered by absorption stripping (*see, e.g.*, U.S. Prov. 61/288,142 or US Appl. No. 12/969,440). In some aspects, any of the methods described herein further include a step of recovering the heterologous polypeptide. In some aspects, any of the methods described herein further include a step of recovering the terpenoid or carotenoid.

[0224] Suitable purification methods are described in more detail in U.S. Patent Application Publication US2010/0196977 A1; and U.S. Provisional Patent Application No. 61/187,959.

Other Techniques

[0225] Additional examples of efficient methods for the production and recovery of isoprene and a coproduct, such as hydrogen, are described in U.S. Patent Application Publication No. US2010/0196977.

[0226] Examples of other techniques (*e.g.*, decoupling isoprene production from cell growth, methods of producing isoprene within safe operating ranges, cell viability at high isoprene titers, efficient methods for the production and recovery of isoprene and a co-product (*e.g.*, hydrogen, ethanol, or 1,3-propanediol)) that can be used with the cells and methods described herein are described in International Patent Publication No. WO 2009/076676 A2; U.S. Patent Application Publication Nos. US2010/0048964 A1, US2010/0086978 A1, US2010/0113846 A1, US2010/0184178 A1 and US2010/0167371 A1, US2010/0196977 A1; U.S. Provisional Patent Application Nos. 61/187,930, 61/187,959, and 61/187,941; and International Patent Application Publication Nos. WO 2004/033646 A2 and WO 1996/035796 A2.

[0227] The invention can be further understood by reference to the following examples, which are provided by way of illustration and are not meant to be limiting.

EXAMPLES

Example 1: Construction of *E. coli* strains expressing the *S. cerevisiae* gi1.2KKDyI operon, *P. alba* isoprene synthase, *M. mazei* mevalonate kinase, pCL Upper MVA (*E. faecalis* mvaE and mvaS) and ybhE (pgl)

(i) Construction of strain EWL201 (BL21, Cm-GI1.2-KKDyI)

[0228] *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.). MCM331 cells contain chromosomal construct gi1.2KKDyI encoding *S. cerevisiae* mevalonate kinase, mevalonate phosphate kinase, mevalonate pyrophosphate decarboxylase, and IPP isomerase (*i.e.*, the gi1.2-KKDyI operon from *S. cerevisiae*; construction of which is described in Example 10 of International Publication No. WO 2009/076676 A2 and U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102)). 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).

[0229] 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 preparations 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 2 ml 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.

[0230] 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 1) 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 1) 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. One was picked and designated as strain EWL201.

(ii) Construction of Strain EWL204 (BL21, loopout-GI1.2-KKDyI)

[0231] 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). 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. 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*)

[0232] 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 2, 3A-B; SEQ ID NO:1).

[0233] 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 Herculanase 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.).

[0234] *P. alba* isoprene synthase PCR product was then digested in a 20 µl reaction containing 1 µl *Bsp*HI endonuclease (New England Biolabs) with 2 µl 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 20 µl reaction containing 1 µl *Pst*I endonuclease (Roche) with 2 µl 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 20 µl reaction containing 1 µl *Nco*I endonuclease (Roche), 1 µl *Pst*I endonuclease, and 2 µl 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 4). Using the compatible cohesive ends of *Bsp*HI and *Nco*I sites, a 20 µl ligation reaction was prepared containing 5 µl *P. alba* isoprene synthase insert, 2 µl pTrc vector, 1 µl T4 DNA ligase (New England Biolabs), 2 µl 10X ligase buffer, and 10 µl ddH₂O. The ligation mixture was incubated at room temperature for 40 minutes. The ligation mixture was desalted by floating a 0.025 µm

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 were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. An aliquot of 50 µl of cell suspension was mixed with 5 µl of desalted pTrc *P. alba* HGS ligation mix. The cell suspension mixture was electroporated in a 2 mm cuvette at 2.5 Volts and 25 µF using a Gene Pulser Electroporator. 1ml of LB was immediately added to the cells, then transferred to a 14 ml polypropylene tube (Sarstedt) with a metal cap. Cells were allowed to recover by growing for 2 hour at 30°C. Transformants were selected on L Agar and 50 µg/µl carbenicillin and 10 mM mevalonic acid and incubated at 30°C. The next day, 6 transformants were picked and grown in 5ml L Broth and 50 µg/µl 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 µl 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 1). DNA sequencing results showed all 6 plasmids were correct. One plasmid was picked designated as plasmid EWL230 (Figures 5, 6A-B; SEQ ID NO:2).

iv) Construction of plasmid pEWL244 (pTrc *P. alba*-mMVK)

[0235] A PCR reaction was performed to amplify the *Methanosarcina mazei* (*M. mazei*) MVK gene using MCM376 as the template, primers MCM165 and MCM177 (see Table 1), 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.).

[0236] The *M. mazei* MVK PCR product was then digested in a 40 µl reaction containing 8 µl PCR product, 2 µl *Pme*I endonuclease (New England Biolabs), 4 µl 10X NEB Buffer 4, 4 µl 10X NEB BSA, and 22 µl 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 47 μ l reaction containing 2 μ l *Nsi*I endonuclease (Roche), 4.7 μ l 10X Buffer H, and 40 μ l of *Pme*I 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 40 μ l reaction containing 10 μ l plasmid, 2 μ l *Pme*I endonuclease, 4 μ l 10X NEB Buffer 4, 4 μ l 10X NEB BSA, and 20 μ l 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 47 μ l reaction containing 2 μ l *Pst*I endonuclease, 4.7 μ l 10X Buffer H, and 40 μ l of *Pme*I 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 7). Using the compatible cohesive ends of *Nsi*I and *Pst*I sites, a 20 μ l ligation reaction was prepared containing 8 μ l *M. mazei* MVK insert, 3 μ l EWL230 plasmid, 1 μ l T4 DNA ligase, 2 μ l 10X ligase buffer, and 6 μ l ddH₂O. The ligation mixture was incubated overnight at 16°C. The next day, the ligation mixture was desalted by floating a 0.025 μ m 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 50 μ l of cell suspension was mixed with 5 μ l of desalted pTrc P.alba-mMVK ligation mix. The cell suspension mixture was electroporated in a 2 mm cuvette at 2.5 Volts and 25 μ Fd using a Gene Pulser Electroporator. 1 ml of LB is immediately added to the cells, then the cells are transferred to a 14 ml 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 50 μ g/ μ l carbenicillin and 5mM mevalonic acid plates and incubated at 30°C. The next day, 6 transformants were picked and grown in 5 ml LB 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. 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. 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 1). DNA sequencing results showed all 3 plasmids were correct. One was picked and designated as plasmid EWL244 (Figures 8 and 9A-B; SEQ ID NO:3).

v) Construction of plasmid MCM376 - MVK from *M. mazei* archaeal Lower in pET200D.

[0237] The MVK ORF from the *M. mazei* archaeal Lower Pathway operon (Figures 10A-C; SEQ ID NO:4) was PCR amplified using primers MCM161 and MCM162 (Table 1) 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 11A-C).

vi) Construction of strain EWL251 (BL21(DE3), Cm-GI1.2-KKDyI, pTrc P.alba-mMVK)

[0238] 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 50 µl of cell suspension with 1µl of plasmid EWL244. The cell suspension mixture was electroporated in a 2mm cuvette at 2.5 Volts and 25 µF using a Gene Pulser Electroporator. 1 ml of LB is immediately added to the cells, and then the cells were transferred to a 14 ml 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 50 µg/µl carbenicillin and 5 mM 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)

[0239] EWL251 cells were grown in LB to midlog phase and then washed three times in ice-cold, sterile water. Mixed 50 µl of cell suspension with 1 µl of plasmid MCM82 (comprising

pCL PtrcUpperPathway (also known as “pCL Upper MVA”), encoding *E. faecalis* mvaE and mvaS). Plasmid pCL Ptrc Upper Pathway was constructed as described in Example 8 of International Publication No. WO 2009/076676 A2 and U.S. Patent Application No. 12/335,071 (US Publ. No. 2009/0203102). The cell suspension mixture was electroporated in a 2 mm cuvette at 2.5 Volts and 25 μ Fd using a Gene Pulser Electroporator. 1 ml of LB was immediately added to the cells. Cells were then transferred to a 14 ml 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 50 μ g/ μ l carbenicillin and 50 μ g/ μ l spectinomycin plates and incubated at 37°C. One colony was picked and designated as strain EWL256.

Table 1: Primer Sequences

Primer name	Primer sequence
MCM130	ACCAATTGCACCCGGCAGA (SEQ ID NO:14)
GB Cm Rev	GCTAAAGCGCATGCTCCAGAC (SEQ ID NO:15)
MVD For	GACTGGCCTCAGATGAAAGC (SEQ ID NO:16)
MVD Rev	CAAACATGTGGCATGGAAAG (SEQ ID NO:17)
MCM182	GGGCCCCGTTTAAACTTTAACTAGACTCTGCAGTTAGCGTTCAAACGGCAGAA (SEQ ID NO:18)
MCM192	CGCATGCATGTCATGAGATGTAGCGTGTCCACCGAAAA (SEQ ID NO:19)
MCM65	ACAATTTACACAGGAAACAGC (SEQ ID NO:20)
MCM66	CCAGGCAAATTCTGTTTTATCAG (SEQ ID NO:21)
EL1000	GCACTGTCTTTCCGTCTGCTGC (SEQ ID NO:22)
MCM165	GCGAACGATGCATAAAGGAGGTAAAAAACATGGTATCCTGTTCTGCGCCGGGTAAGATTACCTG (SEQ ID NO:23)
MCM177	GGGCCCCGTTTAAACTTTAACTAGACTTTAATCTACTTTCAGACCTTGC (SEQ ID NO:24)
EL1003	GATAGTAACGGCTGCGCTGCTACC (SEQ ID NO:25)
EL1006	GACAGCTTATCATCGACTGCACG (SEQ ID NO:26)
MCM161	CACCATGGTATCCTGTTCTGCG (SEQ ID NO:27)
MCM162	TTAATCTACTTTCAGACCTTGC (SEQ ID NO:28)

viii) Construction of strain RM111608-2 (Cm-GI1.2-KKDyI, pTrc P.alba-mMVK, pCL Upper MVA, pBBRCMPGI1.5-pgl)

[0240] The BL21 strain of *E. coli* producing isoprene (EWL256) was constructed with constitutive expression of the *ybhE* gene (encoding *E. coli* 6-phosphogluconolactonase) on a replicating plasmid pBBR1MCS5(Gentamycin) (obtained from Dr. K. Peterson, Louisiana State University).

[0241] 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 (SEQ ID NO:29) and PglGI1.5-R (SEQ ID NO:30) 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).

[0242] 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.

[0243] 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 (SEQ ID NO:31) and 3' primer 3' EcoRV-pglstop (SEQ ID NO:32). 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 µl ligation reaction was prepared containing 5µl CMP-GI1.5-pgl insert, 2 µl pBBR1MCS5 (Gentamycin) vector, 1 µl T4 DNA ligase (New England Biolabs), 2 µl 10X ligase buffer, and 10 µl 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 12, 13A-B and SEQ ID NO:6).

[0244] Plasmid pBBRCMPGI1.5-pgl was electroporated into EWL256, as described herein 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 strain RM111608-2.

Primers:

Pgl-F

5'-

ACCGCCAAAAGCGACTAATTTTAGCTGTTACAGTCAGTTGAATTAACCCTCACTA
AAGGGCGGCCGC-3' (SEQ ID NO:29)

PglGI1.5-R

5'-

GCTGGCGATATAAACTGTTTGCTTCATGAATGCTCCTTTGGGTTACCTCCGGGAA
ACGCGGTTGATTTGTTTAGTGTTGAATTATTTGCTCAGGATGTGGCATAGTCAA
GGGCGTGACGGCTCGCTAATACGACTCACTATAGGGCTCGAG-3' (SEQ ID NO:30)

3' EcoRV-pglstop:

5'-CTT GAT ATC TTA GTG TGC GTT AAC CAC CAC (SEQ ID NO:31)

pgl +49 rev: CGTGAATTTGCTGGCTCTCAG (SEQ ID NO:32)

Bottom Pgb2: GGTTTAGTTCCTCACCTTGTC (SEQ ID NO:33)

Top GB's CMP (946): ACTGAAACGTTTTCATCGCTC (SEQ ID NO:34)

Pglconfirm-F

5'-ACCGCCAAAAGCGACTAATTTTAGCT-3' (SEQ ID NO:35)

Example 2: Improvement of isoprene production by constitutive expression of *ybhE* (pgl) from a plasmid in *E. coli*

[0245] This example shows production of isoprene in a strain constitutively expressing *E. coli ybhE* (pgl) compared to a control strain expressing *ybhE* at wild-type levels (*i.e.*, EWL256). The gene *ybhE* (pgl) encodes *E. coli* 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).

i) Small scale analysis

[0246] Media Recipe (per liter fermentation media): 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 1 g, 1000X Trace Metals Solution 1 ml. All of the components were added together and dissolved in diH₂O. 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.

[0247] 1000X Trace Metal Solution (per liter fermentation media): Citric Acid*H₂O 40g, MnSO₄*H₂O 30g, NaCl 10g, FeSO₄*7H₂O 1g, CoCl₂*6H₂O 1g, ZnSO₄*7H₂O 1g, CuSO₄*5H₂O 100mg, H₃BO₃ 100mg, NaMoO₄*2H₂O 100mg. Each component was dissolved one at a time in diH₂O. The pH was adjusted to 3.0 with HCl/NaOH, and then the solution was brought to volume and filter-sterilized with a 0.22 micron filter.

(a) Experimental procedure

[0248] Isoprene production was analyzed by growing the strains in a Cellerator™ 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.

[0249] 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.

[0250] 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 (µg/L) by the OD reading and the time (hour).

[0251] 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

[0252] 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 Cm-GI1.2-KKDyI, *M. mazei* mevalonate kinase, *P. alba* isoprene synthase, and *ybhE* (*pgl*) (RM111608-2) and grown in fed-batch culture at the 15-L scale

[0253] Medium Recipe (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, 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.

[0254] 1000X Modified trace Metal Solution: 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 was 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

[0255] 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 *E. coli 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.

[0256] 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 µM when the optical density at 550 nm (OD₅₅₀) reached a value of 4. The IPTG concentration was raised to 192 µM when OD₅₅₀ reached 150. The OD₅₅₀ profile within the bioreactor over time is shown in Figure 14A. 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 14B). 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 14C). 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 14D. The time course of volumetric productivity is shown in Figure 14E 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 14F. 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 3: Recovery of Isoprene Produced from Renewable Resources

[0257] Isoprene was recovered from a set of four 14-L scale fermentations in a two-step operation involving stripping of isoprene from the fermentation off-gas stream by adsorption to activated carbon, followed by off-line steam desorption and condensation to give liquid isoprene (Figures 16A and 16B). The total amount of isoprene produced by the four fermentors was 1150 g (16.9 mol), of which 953 g (14 mol, 83%) was adsorbed by the carbon filters. Following the steam desorption/condensation step, the amount of liquid isoprene recovered was 810 g, corresponding to an overall recovery yield of 70%. The recovered isoprene was analyzed for the presence of impurities.

Analysis and Impurity Profile of Isoprene Liquid

[0258] Recovered isoprene liquid was analyzed by GC/MS and gas chromatography/flame ionization detection (GC/FID) to determine the nature and levels of impurities. The product was determined to be >99.5% pure and contained several dominant impurities in addition to many minor components. The GC/FID chromatogram is depicted in Figure 17, and the typical levels of impurities are shown in Table 19. The impurity profile was similar to other isoprene batches produced on this scale.

Table 2: Summary of the nature and levels of impurities seen in several batches of isoprene produced from renewable resources

Compound	Retention Time (min)		Conc. Range
	GC/MS	GC/FID	
Ethanol	1.59	11.89	<50 ppm
Acetone	1.624	12.673	<100 ppm
Methacrolein	1.851	15.369	<200 ppm
Methyl vinyl ketone	1.923	16.333	<20 ppm

Compound	Retention Time (min)		Conc. Range
	GC/MS	GC/FID	
Ethyl acetate	2.037	17.145	100 to 800 ppm
3-Methyl-1,3-pentadiene	2.27	18.875	50 to 500 ppm
Methyl vinyl oxirane	2.548	19.931	<100 ppm
Isoprenol	2.962	21.583	<500 ppm
3-methyl-1-butanol	2.99	21.783	<50 ppm
3-hexen-1-ol	4.019	24.819	<100 ppm
Isopentenyl acetate	4.466	25.733	200 to 1000 ppm
3-hexen-1-yl acetate	5.339	27.223	<400 ppm
limonene	5.715	27.971	< 500 ppm
Other cyclics	5.50 – 6.50	27.5 – 28.0	<200 ppm

Purification of isoprene produced from renewable resources by treatment with adsorbents

[0259] Adsorbents are widely used by industry for the removal of trace impurities from hydrocarbon feedstocks. Suitable adsorbents include zeolite, alumina and silica-based materials. Isoprene produced from renewable resources can be substantially purified by passage over silica gel, and to a lesser extent with alumina. Figure 18 shows the GC/FID chromatograms of an isoprene sample before (A) and after treatment with alumina (B) or silica (C). The Selexsorb™ adsorbent products from BASF is one of the adsorbents of choice for the removal of polar impurities from isoprene produced from renewable resources. Specifically, the Selexsorb™ CD and CDX products are preferred given their proven utility for removal of polar impurities from isoprene and butadiene feedstocks.

Example 4: Construction of Strains MCM518-521 and 528-531: Lambda promoters driving integrated mKKDyI

[0260] P1 transduction enables movement of up to 100 kb of DNA between bacterial strains (Thomason et al. 2007). A 17,257 bp deletion in *E. coli* BL21(DE3) (see Figure 20) was

replaced by moving a piece of the bacterial chromosome from *E. coli* K12 MG1655 to *E. coli* BL21(DE3) using P1 transduction.

[0261] Two strategies were used employing different selectable markers to identify colonies containing the recombined bacterial chromosome. First, an antibiotic marker in a gene close to the 17,257 bp sequence to be transferred, whose deletion was not likely to be detrimental to the strain, was inserted. A strain containing that antibiotic marker would likely have the 17,257 bp piece of bacterial chromosome transduced at the same time as the marker. In this case, a gene encoding kanamycin resistance (“kan^R”) was inserted into the *ybgS* gene, encoding a 126 amino acid protein of unknown function. Second, since it is known that a number of genes involved in utilization of galactose are close to *pgl* in the 17,257 bp piece to be transduced into *E. coli* BL21(DE3), colonies transduced with a P1 lysate obtained from *E. coli* K12 MG1655 (which contains the 17,257 bp sequence deleted in *E. coli* BL21(DE3)) and isolated in M9 medium (6 g/L Na₂HPO₄, 3 g/L KH₂PO₄, 0.5 g/L NaCl, 0.5 g/L NH₄Cl, 0.1 mM CaCl₂, 2 mM MgSO₄) containing 0.4% (w/v) galactose would likely contain the 17,257 bp piece of bacterial chromosome.

[0262] Primers MCM120 (SEQ ID NO:36) and MCM224 (SEQ ID NO:37) were used to amplify the chloramphenicol resistance (“Cm^R”) cassette from the GeneBridges FRT-gb2-Cm-FRT template using the Stratagene Herculase™ II Fusion kit (Agilent Technologies, Stratagene Products Division, La Jolla, California) according to the manufacturer’s protocol. Four 50 µL PCR reactions were cycled as follows: 95°C/2 minutes; 30 cycles of 95°C/20 seconds, 55°C/20 seconds, 72°C/1 minute; and 72°C/3 minutes. Reactions were then cooled to 4°C. The four reactions were pooled, loaded onto a Qiagen PCR column according to the manufacturer’s protocol and eluted with 60 µL elution buffer (“EB”) at 55°C.

[0263] Plasmid pRedET-carbenicillin^R (GeneBridges, Heidelberg, Germany) was electroporated into *E. coli* BL21(DE3) strain MCM446 (Cm^R, gi1.6mKKDyI A1-3) using standard procedures. Transformants were recovered by shaking for one hour in SOC medium at 30°C and then selected on LB + 50 µg/mL carbenicillin (“LB/carb50”) plates at 30°C overnight. A carbenicillin-resistant colony was frozen as strain MCM508.

[0264] Strain MCM508 was grown from a fresh streak in 5 mL LB/carb50 at 30°C to an OD₆₀₀ of ~0.5. At that point, 40 mM L-arabinose was added, and the culture was incubated at 37°C for 1.5 hours. Cells were then harvested by centrifugation, electroporated with 3 µL of

purified amplicons as described above, and then recovered in 500 μ L SOC medium at 37°C for 1.5-3 hours. Transformants were selected on LB+ 10 μ g/mL kanamycin (LB/kan10) plates at 37°C.

[0265] Recombination of the amplicon at the target locus was confirmed by PCR with primers GB-DW (SEQ ID NO:38) and MCM208 (SEQ ID NO:39). The resulting amplicons were sequenced to identify four clones having the sequences listed below. Four carbenicillin-sensitive clones were frozen as strains MCM518-MCM521.

[0266] Strains MCM518-MCM521 were re-streaked onto LB/kan10 and grown overnight at 37°C. Colonies of strains MCM518-MCM521 were picked, cultured in LB/kan10 at 37°C and electrotransformed with plasmid pCP20, which encodes the yeast Flp recombinase, chloramphenicol and ampicillin resistance genes and confers temperature sensitive replication on host cells (Cherepanov, P.P. et al., *Gene* 158(1):9-14 (1995)). Cells were recovered in 500 μ L SOC medium by shaking at 30°C for 1 hour. Transformants were selected on LB/carb50 plates at 30°C overnight. The following morning a colony from each plate was grown at 30°C in LB/carb50 medium until visibly turbid. The culture was then shifted to 37°C for at least 3 hours. Cells were streaked from that culture onto LB plates and grown overnight at 37°C.

[0267] The following day colonies were patched to LB, LB/carb50 and LB/kan10. Clones that were sensitive to both carbenicillin and kanamycin (*i.e.*, which could not grow on carb50 and kan10) were cultured in liquid LB and frozen as strains MCM528-MCM531.

Table 3: *E. coli* strains

Strain	Description	Parent
MCM508	BL21 gi1.6-mKKDyI + predet.-carb	MCM446
MCM518	BL21 neo-PL.6-mKKDyI, clone 10	MCM508
MCM519	BL21 neo-PL.0-mKKDyI, clone 11	MCM508
MCM520	BL21 neo-PL.0-mKKDyI (bad RBS in front of mMVK), clone 13	MCM508
MCM521	BL21 neo-PL.2-mKKDyI, clone 15	MCM508
MCM528	BL21 PL.6-mKKDyI, neo ^R looped out	MCM518
MCM529	BL21 PL.0-mKKDyI, neo ^R looped out	MCM519
MCM530	BL21 PL.0-mKKDyI (bad RBS in front of mMVK), neo ^R looped out	MCM520
MCM531	BL21 PL.2-mKKDyI, neo ^R looped out	MCM521

Table 4: Primer sequences

Primer name	Sequence (5' → 3')
MCM120	aaagtagccgaagatgacggttgcacatggagttggcaggatgttgattaaaagcaattaaccctcactaaaggcg (SEQ ID NO:36)
MCM224	taaatcttaccggcgagaaacaggatgacatgtttttacctccttgcacctcatggtggcagtcgctcctgctgatgtgctcagtatcaccgcc agtgggtatttNgtaacaccgccagagataattatcaccgcagatgggtatctgtatgttttatatgaatttaaacgactcactatagggtcgc (SEQ ID NO:37)(where N can be a, t, c, or g)
GB-DW	aaagaccgaccaagcgacgtctga (SEQ ID NO:38)
MCM208	gctctgaatagtgatagatca (SEQ ID NO:39)

[0268] The assemblies integrated into the chromosomes of strains MCM518-MCM521 include new P_L promoters derived from bacteriophage lambda (λ) and the very beginning of the mMVK ORF, with sequences from the Gene Bridges FRT-gb2-Cm-FRT cassette integrated upstream of the promoter/mMVK assembly, as well as the remainder of the mMVK ORF followed by the rest of the lower MVA pathway integron from strain MCM508.

[0269] Promoter/mMVK sequence integrated into MCM518 (SEQ ID NO:40):

aaagaccgaccaagcgacgtctgagagctccctggcgaattcggtaccaataaaagagctttattttcatgatctgtgtgttggttttgtg
tgcggcgcggaagttcctattctctagaaagtataggaacttcctcgagccctatagtgtgagtcgtattaaattcatataaaaaacatacag
ataacatctgcggtgataaattatctctggcggtgttgacataaataccactggcggtgatactgagcacatcagcaggacgcactga
ccaccatgaaggtgcaaaggaggtaaaaaacatggtatcctgttctgcgccgggtaagatttacctgttcggtgaacacgccgtagtt
tatggcgaaactgcaattgcgtgtgcggtggaactgcgtaccctgttcgcgcggaactcaatgactctatcactattcagagc

[0270] Promoter/mMVK sequence integrated into MCM519 (SEQ ID NO:41):

aaagaccgaccaagcgacgtctgagagctccctggcgaattcggtaccaataaaagagctttattttcatgatctgtgtgttggttttgtg
tgcggcgcggaagttcctattctctagaaagtataggaacttcctcgagccctatagtgtgagtcgtattaaattcatataaaaaacatacag
ataacatctgcggtgataaattatctctggcggtgttgacataaataccactggcggtgatactgagcacatcagcaggacgcactga
ccaccatgaaggtgcaaaggaggtaaaaaacatggtatcctgttctgcgccgggtaagatttacctgttcggtgaacacgccgtagtt
tatggcgaaactgcaattgcgtgtgcggtggaactgcgtaccctgttcgcgcggaactcaatgactctatcactattcagagc

[0271] Promoter/mMVK sequence integrated into MCM520 (SEQ ID NO:42):

aaagaccgaccaagcgacgtctgagagctccctggcgaattcggtaccaataaaagagctttattttcatgatctgtgtgttggttttgtg
tgcggcgcggaagttcctattctctagaaagtataggaacttcctcgagccctatagtgtgagtcgtattaaattcatataaaaaacatacag
ataacatctgcggtgataaattatctctggcggtgttgacataaataccactggcggtgatactgagcacatcagcaggacgcactga

ccaccatgaaggtgcaaaggtaaaaaaacatggtatcctgttctgcgccgggtaagattacctgttcggtgaacacgccgtagtttatg
gcgaaactgcaattgcgtgtgcggtggaactgcgtacccgtgttcgcgcggaactcaatgactctatcactattcagagc

[0272] Promoter/mMVK sequence integrated into MCM521 (SEQ ID NO:43):

aaagaccgaccaagcgacgtctgagagctccctggcgaattcggtagcaataaaagagctttatttcatgatctgtgtgtgtgtgtgtgtg
tgcggcgcggaagtctattctctagaaagtataggaacttcctcgagccctatagtgagtcgtattaaattcatataaaaaacatacag
ataaccatctgcggtgataaattatctctggcggtgttgacgtaaataccactggcggtgatactgagcacatcagcaggacgcactga
ccaccatgaaggtgcaaaggaggtaaaaaacatggtatcctgttctgcgccgggtaagattacctgttcggtgaacacgccgtagtt
tatggcgaaactgcaattgcgtgtgcggtggaactgcgtacccgtgttcgcgcggaactcaatgactctatcactattcagagc

Example 5: Construction of Strains DW199 and DW202

[0273] This example describes the construction of an isoprene-producing *E. coli* strain harboring the truncated version of *P. alba* isoprene synthase (the MEA variant) under control of the PTrc promoter.

[0274] The plasmid harboring truncated *P. alba* isoprene synthase (IspS) was constructed by Quikchange™ (Agilent Technologies, Stratagene Products Division, La Jolla, California) PCR mutagenesis from the template pEWL244 (also referred to as pTrc-P.alba(MEA)-mMVK (described in Example 10 of US Patent Application No. 12/335,071). The PCR reaction contained the following components: 1 µl pEWL244 (encoding pTrc *P.alba*-mMVK), 5 µl 10X PfuUltra High Fidelity buffer, 1 µl 100 mM dNTPs, 1 µl 50 µM QC EWL244 MEA F primer (SEQ ID NO:44), 1 µl 50 µM QC EWL244 MEA R primer (SEQ ID NO:45), 2 µl DMSO, 1 µl PfuUltra High Fidelity polymerase (Agilent Technologies, Stratagene Products Division, La Jolla, California), and 39 µl diH₂O. The PCR reaction was cycled as follows: 95°C/1 minute; and 18 cycles of 95°C/30 seconds, 55°C/1 minute, 68°C/7.3 minutes. The reaction was then cooled to 4°C.

[0275] The PCR product was visualized by gel electrophoresis using an E- gel (Invitrogen, Carlsbad, CA), and then treated with 1 µl DpnI restriction endonuclease (Roche, South San Francisco, CA) for three hours at 37°C. Ten µl of the PCR product were then de-salted using a microdialysis membrane (MilliPore, Billerica, MA) and transformed into electrocompetent *E. coli* strain MCM531 (prepared as described above) using standard molecular biology techniques. Cells were recovered in one ml of LB medium for 1.5 hours at 30°C, plated onto LB-agar plates containing 50 µg/ml carbenicillin and 5 mM mevalonic acid, and then

incubated overnight at 37°C. The next day, positive colonies (of strain DW195, see below) were selected for growth, plasmid purification (Qiagen, Valencia, CA), confirmed by DNA sequencing (Quintara Biosciences, Berkeley, CA) with the primers listed below. The final plasmid, pDW34 (Figure 19A; SEQ ID NO:7), was confirmed to carry the open reading frame that encodes the truncated version of *P. alba* IspS.

[0276] Strain DW199 was generated by transformation of pDW34 and pMCM82 (described in Example 10 of US Patent Application No. 12/335,071) into electrocompetent MCM531 (prepared as described above). Cells were recovered in 1 ml of LB medium for 1 hour at 37°C, plated on LB agar plates containing 50 µg/ml spectinomycin and 50 µg/ml carbenicillin, and then incubated overnight at 37°C. The next day, antibiotic resistant colonies of strain DW199 were chosen for further study.

[0277] Strain DW202 was generated by transformation of pBBRCMPGI1.5-pgl (described in example 1) into electrocompetent DW199 (prepared as described above). Cells were recovered in 1 ml of LB medium for 1 hour at 37°C, plated on LB agar plates containing 50 µg/ml spectinomycin, 50 µg/ml carbenicillin and 5 µg/ml gentamycin, and then incubated overnight at 37°C. The next day, antibiotic resistant colonies of strain DW202 were chosen for further study.

Table 5: Primers

Primer Name	Sequence (5' → 3')
QC EWL244 MEA F	gaggaataaaccatggaagctcgtcgttct (SEQ ID NO:44)
QC EWL244 MEA R	agaacgacgagcttccatggtttattctc (SEQ ID NO:45)
EL-1006	gacagcttatcatcgactgcacg (SEQ ID NO:46)
EL-1000	gcactgtctttccgtctgctgc (SEQ ID NO:47)
A-rev	ctcgtacaggctcaggatag (SEQ ID NO:48)
A-rev-2	ttacgtcccaacgctcaact (SEQ ID NO:49)
QB1493	cttcggcaacgcatggaaat (SEQ ID NO:50)
MCM208	gctctgaatagttagagagtc (SEQ ID NO:39)
MCM66 (aka pTrc Reverse)	ccaggcaaattctgtttatcag (SEQ ID NO:51)

Table 6: Strains

Strain	Background	Plasmid	Resistance	Genotype
DW195	MCM531	pDW34	Carb	BL21 (Novagen) PL.2mKKDyI, pTrc-P. alba(MEA)-mMVK
DW199	MCM531	pDW34 MCM82	Carb / Spec	BL21 (Novagen) PL.2mKKDyI, pTrc-P. alba(MEA)-mMVK, pCL pTrc-Upper
DW02	MCM531	pDW34 MCM82 pBBRCM PGI1.5-pgl	Carb/Spec/Gm	BL21 (Novagen) PL.2mKKDyI, pTrc-P. alba(MEA)-mMVK, pCL pTrc-Upper, pBBRCMPGI1.5-pgl

Example 6: Construction of *E. coli* BL21 strains CMP215, CMP258 and CMP234

[0278] This example describes the construction of *E. coli* strains derived from BL21 transduced with P1 phage containing *E. coli* MG1655 genomic DNA and selected for recombination of a 17,257 bp piece present in MG1655 but absent in BL21 and BL21(DE3).

[0279] A P1 lysate was made of strain JW0736, in which the *ybgS* gene was replaced with a kanamycin resistance gene (“Kan^R”)(*i.e.*, *ybgS*::Kan^R mutation) from the Keio collection (Baba et al. 2006). That lysate was used to infect strain MCM531 (described above), producing strain CMP215. The genotype of CMP215 was confirmed by PCR using primers *galM* R (5'-GTC AGG CTG GAA TAC TCT TCG-3'; SEQ ID NO:8) and *galM* F (5'- GAC GCT TTC GCC AAG TCA GG-3'; SEQ ID NO:9). Those primers anneal to the *galM* gene, as shown on Figure 20, but only produce a PCR product from *E. coli* BL21(DE3) chromosomal DNA having the 17,257 bp deletion.

[0280] Integration of the 17,257 bp fragment following P1 transduction was verified by PCR with the following protocol. One bacterial colony was stirred in 30 µl H₂O and heated to 95°C for 5 minutes. The resulting solution was spun down and 2 µl of the supernatant used as template in the following PCR reaction: 2 µl colony in H₂O, 5 µl Herculase[®] Buffer, 1 µl 100 mM dNTPs, 1 µl 10 µM Forward primer, 1 µl 10 µM Reverse primer, 0.5 µl of Herculase[®] Enhanced DNA Polymerase (Agilent Technologies, Stratagene Products Division, La Jolla, California), and 39.5 µl diH₂O. The PCR reaction was cycled in a PCR Express Thermal Cycler (Thermo Hybaid, Franklin, MA) as follows: 95°C/2 minutes; 30 cycles of 95°C/30 seconds, 52°C/30 seconds, 72°C/60 seconds; and 72°C/7 minutes. The reaction was then cooled to 4°C. The annealing temperature of 52°C was 3°C lower than the lower T^m of

the primer pair. The size of the resulting PCR fragment was determined on a pre-cast 0.8% E-gel[®] (Invitrogen, Carlsbad, CA), using DNA Molecular Weight Marker X (75–12,216 bp) (Roche Diagnostics, Mannheim, Germany) as size marker. Successful transduction was also confirmed by the ability of strain CMP215 to grow on galactose.

[0281] Alternatively, a lysate of *E. coli* MG1655 was used to transduce strain BL21 (as described in Example 1 above). A colony selected on M9 medium supplemented with 0.4% (w/v) galactose was named CMP258. Presence of the 17,257 bp region containing *pgl* was confirmed by PCR using primers *galM* R (SEQ ID NO:9) and *galM* F (SEQ ID NO:8), essentially as described above.

[0282] Strain CMP215 was cotransformed by electroporation with plasmids pCLPtrcUpperPathway expressing *mvaE* and *mvaS* (described in Example 8 of US Patent Application No. 12/335,071) and pDW34 (containing a truncated *P. alba* isoprene synthase and *M. mazei* mevalonate kinase, as described above). Transformants were selected on LB agar plates including 50 µg/ml carbenicillin + 50 µg/ml spectinomycin. One colony was picked and named CMP234.

Example 7: Construction of *E. coli* BL21 strains CMP269 and CMP312

[0283] This example describes the construction of *E. coli* strains derived from BL21 transduced with P1 phage containing *E. coli* MG1655 genomic DNA and selected for recombination of a 17,257 bp piece present in MG1655 but absent in BL21 and BL21(DE3). The marker used for selection has been looped out.

[0284] Strain CMP215 (described above) was transformed with pCP20 (Cherepanov, P.P. et al., 1995, *Gene* 158(1):9-14; Datsenko and Wanner, 2000, *Proc. Nat'l Acad. Sci. USA*, 97(12):6645) and the *kan*^R marker contained in the *ybgS* gene was looped out according to a previously described procedure (Datsenko and Wanner, *Proc. Nat'l Acad. Sci. USA*, 97(12):6645 (2000)). Marker loopout was verified by PCR as described above, but using *ybgS*Amp F primer (5'-CCT GGA ATT AGC AAG AAA AAC GC-3'; SEQ ID NO:52) and *ybgS*Amp R primer (5'-GTG AAA ATT GCA CGG CGA GTA GG-3'; SEQ ID NO:53). That strain was designated CMP269. Strain CMP269 was cotransformed by electroporation with plasmids pCLPtrcUpperPathway (expressing *mvaE* and *mvaS*) and pDW34 (see Figure 19A) containing a truncated *P. alba* IspS and *M. mazei* MVK to produce strain CMP312.

Example 8: Construction of *E. coli* BL21 strains CMP296, CMP315 and CMP323

[0285] This example describes the construction of strains derived from *E. coli* BL21 transduced with P1 phage containing *E. coli* MG1655 genomic DNA and selected for recombination of a 17,257 bp piece present in MG1655 but deleted in BL21 and BL21(DE3), thereby restoring a functional copy of *pgl* to the *E. coli* BL21 and BL21(DE3) derived strains. A strain in which the restored *pgl* gene has been precisely knocked out by inserting a kanamycin cassette which was subsequently looped out was also constructed.

[0286] A PCR product containing a copy of *pgl/ybhE* in which a kan^R gene has been inserted (*pgl/ybhE::kan^R*) was amplified from *E. coli* strain JW0750 from the Keio collection using the primer pair *pglAmpF* (5'-Cagcaaatagcaggtgtatccagc-3'; SEQ ID NO:54) and *pglAmpR* (5'-GCA ACC GAC TGT TGA TAG AAC AAC-3'; SEQ ID NO:55). That primer pair produces a fragment containing *pgl/ybhE::kan^R* plus ~350 bp of flanking sequence from each side of the mutation. PCR template was prepared as follows: one colony of *E. coli* JW0750 carrying *pgl/ybhE::kan^R* was stirred in 30 μl H_2O and heated to 95°C for 5 minutes. The resulting solution was spun down and 2 μl of the supernatant was used as the template in a PCR reaction performed as follows: 2 μl colony in H_2O , 5 μl *Pfu Ultra II* Buffer, 1 μl 100 mM dNTPs, 1 μl 10 μM Forward primer, 1 μl 10 μM Reverse primer, 1 μl of *Pfu Ultra II* polymerase (Agilent Technologies, Stratagene Products Division, La Jolla, California), and 39 μl H_2O . The PCR reaction was cycled in a PCR Express Thermal Cycler (Thermo Hybaid, Franklin, MA) as follows: 95°C/2 minutes; 30 cycles of 95°C/20 seconds, 53.4°C/20 seconds, 72°C/40 seconds; 72°C/3 minutes. The reactions were then cooled to 4°C.

[0287] The size of the resulting PCR fragments was determined on a pre-cast 0.8% E-gel[®] (Invitrogen, Carlsbad, CA), using DNA Molecular Weight Marker X (75–12,216 bp)(Roche Diagnostics, Mannheim, Germany) as size marker. The PCR reaction was purified using the QIAquick[®] PCR Purification Kit (Qiagen, La Jolla, CA).

[0288] Plasmid pRedETamp (GeneBridges GmbH, Heidelberg, Germany) was electroporated into CMP269 to form CMP296. CMP296 was grown and induced with L-arabinose according to the manufacturer's instructions (GeneBridges) and transformed with the *pgl/ybhE::kan^R* PCR product described in this example. Transformants were selected on LB agar including 20 ppm kanamycin. One colony was picked, its genotype checked by PCR

with Herculan[®] polymerase using pglAmpF (5'-cagcaaatagcaggtgtatccagc-3'; SEQ ID NO:54) and pglRecCheck (5'-GGT TAC AAA ATG ATT GGC GTA CGC-3'; SEQ ID NO:56) and named CMP298. The marker was removed as described above in Example 2 to form strain CMP315. Plasmids pCLPtrcUpperPathway and pDW34 (*see* Example 1) were introduced in CMP315 as described above in Examples 4-5 to form strain CMP323.

Table 7: Description of strains

Strain	Description	Parent
MCM531	BL21 PL.2-mKKDyl	
CMP215	BL21 PL.2-mKKDyl t ybgS::Kan	MCM531
CMP258	BL21 t pgl	BL21 (Novagen)
CMP234	BL21 PL.2-mKKDyl t ybgS::Kan, pCLPtrcUpperPathway, pDW34	CMP215
CMP269	BL21 PL.2-mKKDyl t ybgS ML	CMP215
CMP296	BL21 PL.2-mKKDyl t ybgS ML, pRedETamp	CMP269
CMP312	BL21 PL.2-mKKDyl t ybgS ML, pCLPtrcUpperPathway, pDW34	CMP269
CMP315	BL21 PL.2-mKKDyl t ybgS ML r pgl ML	CMP296
CMP323	BL21 PL.2-mKKDyl t ybgS ML r pgl ML, pCLPtrcUpperPathway, pDW34	CMP315

[0289] References cited: Aon et al., 2008, "Suppressing posttranslational gluconoylation of heterologous proteins by metabolic engineering of *Escherichia coli*," *Appl. Environ. Microbiol.* 74:950-958; Baba et al., 2006, "Construction of *Escherichia coli* K-12 in-frame, single-gene knockout mutants: the Keio collection," *Mol. Syst. Biol.* 2: 2006.0008; Cherepanov, P.P. et al., 1995, "Gene disruption in *Escherichia coli*: TcR and KmR cassettes with the option of Flp-catalyzed excision of the antibiotic-resistance determinant," *Gene* 158(1):9-14; Datsenko, K., and Wanner, B., 2000, "One-step inactivation of chromosomal genes in *Escherichia coli* K-12 using PCR products," *Proc. Nat. Acad. Sci. USA* 97:6640-6645; Neidhart, F., Ingraham, J., and Schaechter, M., 1990, *Physiology of the bacterial cell: a molecular approach* (Sinauer Associates, Inc. Sunderland, MA); Thomason, L., Court, D., Datta, A., Khanna, R. and Rosner, J., 2004, "Identification of the *Escherichia coli* K-12 ybhE gene as pgl, encoding 6-phosphogluconolactonase," *J. Bact.* 186:8248-8253; Thomason, L., Costantino, N., Court, D., 2007, "*E. coli* genome manipulation by P1 transduction," *Curr. Protocols Mol. Biol. Chapter 1*, Unit 1.17; Studier F., Daegelen, P., Lenski, R., Maslov, S.,

Kim, J.F., 2009, "Understanding the differences between genome sequences of *Escherichia coli* B strains REL606 and BL21(DE3) and comparison of the *E. coli* B and K-12 genomes," *J. Mol. Biol.* 394(4):653-80, 2009).

Example 9: Isoprene production in a BL21 strain transduced with the 17,257 bp chromosomal fragment encoding *pgl*

[0290] This example demonstrates that high specific productivity of isoprene in 4.5-mL batch mini-fermentations by *E. coli* harboring the mevalonic acid pathway requires the restoration of *pgl* to the bacterial chromosome.

[0291] Medium Recipe (per liter fermentation medium): 13.6 g K₂HPO₄, 13.6 g KH₂PO₄, 2 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 3.2 g (NH₄)₂SO₄, 1 ml 1000X Trace Metals Solution were added together and dissolved in diH₂O. The pH was adjusted to 6.8 with 28% (w/v) ammonium hydroxide and brought up to final volume. The medium was filter-sterilized with a 0.22 micron filter. Glucose (10 g for overnight culture and 5.0 g for main culture) and appropriate antibiotics were added after sterilization and pH adjustment, followed by 1 g of yeast extract from a 100 g/L stock solution and 1 g of MgSO₄ from a 1 M MgSO₄ solution.

[0292] 1000X Trace Metal Solution (per liter fermentation medium): 40 g Citric Acid*H₂O, 30 g MnSO₄*H₂O, 10 g NaCl, 1 g FeSO₄*7H₂O, 1 g CoCl₂*6H₂O, 1 g ZnSO₄*7H₂O, 100 mg CuSO₄*5H₂O, 100 mg H₃BO₃, and 100 mg NaMoO₄*2H₂O were dissolved one at a time in diH₂O. The pH was then adjusted to 3.0 with HCl/NaOH, the solution was brought up to final volume and filter-sterilized with a 0.22 micron filter.

[0293] *E. coli* strains: (1) **CMP312**: *E. coli* BL21 cells engineered to contain the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL2KKDyI), and a plasmid with a truncated *P. alba* IspS (MEA isolate) and mevalonate kinase from *M. mazei* (pTrcAlba(MEA) + mMVK). This strain also includes an integrated copy of the 17,257 bp segment containing genes for galactose utilization and encoding *pgl* that was found to be deleted in *E. coli* BL21(DE3). That segment was derived from *E. coli* K-12 chromosomal DNA. (2) **CMP323**: This strain is identical to strain CMP312 described above, except that *pgl* has been precisely excised from the transduced piece of K-12 DNA and replaced with a gene conferring kanamycin resistance (*pgl/ybhE::kan^R*).

[0294] Experimental procedures: Isoprene production was analyzed by growing the strains in a Cellerator™ from MicroReactor Technologies, Inc. (Mountain View, CA). The working volume in each of the 24 wells was 4.5 mL. The temperature was maintained at 30°C, the pH was not controlled, the oxygen flow setpoint was 10 sccm (“standard cubic centimeters per minute”) and the agitation rate was 550 rpm. The *E. coli* inoculum was obtained from a frozen vial and streaked onto an LB agar plate containing the appropriate antibiotic and incubated at 30°C. A single colony was inoculated into growth medium with antibiotics and grown overnight. The bacteria were diluted into 4.5 mL of medium with the appropriate antibiotics to reach an optical density (“OD”) of 0.05 measured at 550 nm (“OD₅₅₀”). Production of isoprene was induced by the addition of isopropyl-beta-D-1-thiogalactopyranoside (IPTG) to a final concentration of 200 µM at the start of the run.

[0295] Off-gas analysis of isoprene was performed using an online Hiden mass spectrometer (Hiden Analytical, Warrington, UK) with a customized low-flow Proteus valve. The valve sampled one well at a time as it cycled through the 24-well plate. A custom headplate was built to attach capillaries from each of the 24 wells to corresponding ports on the Proteus valve, because offgas flows continuously through the capillaries to the mass spectrometer, but only one port is sampled at a time. The headplate also facilitated external sampling while the plate was rotating.

[0296] OD₅₅₀ measurements were obtained offline using a microplate reader (Spectramax, MDS Analytical Technologies, Sunnyvale, CA) during the course of the run. Microplate ODs were converted to OD (1 cm path length) using an established calibration curve. Specific productivity was obtained by multiplying the isoprene concentration (µg/L) measured by the mass spectrometer by the flow rate of oxygen and dividing that number by the OD reading and the volume remaining in the well. OD samples for the wells of interest were taken at four time points over the course of the mini-fermentations. OD values in between these time points were calculated using linear interpolation between the measured values.

[0297] Results. A representative plot of OD (Figure 21) and specific productivity (Figure 22) is shown for both strains. Specific productivity of isoprene from the pgl⁺ strain (with the pgl gene integrated into the bacterial chromosome) was compared to a pgl⁻ strain. The bacteria were grown under identical conditions in defined medium with glucose as a carbon source in mini-fermentations. Online isoprene measurements over time revealed that the pgl⁺ strain

(CMP312) had higher specific productivity of isoprene (Figure 22) compared to the *pgl*⁻ strain (CMP323), even with fewer cells in the culture (Figure 21).

Example 10: *M. mazei* mevalonate kinase and *P. alba* isoprene synthase overexpression, with and without *pgl* expression

[0298] This example shows isoprene production from *E. coli* BL21 expressing genes from the mevalonic acid pathway and isoprene synthase, grown in fed-batch culture at the 15-L scale.

[0299] Medium Recipe (per liter of fermentation medium): 7.5 g K₂HPO₄, 2 g MgSO₄*7H₂O, 2 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 0.5 g yeast extract, and 1 ml 1000X Modified Trace Metal Solution were added together and dissolved in diH₂O. The solution was heat sterilized at 123°C for 20 minutes, then adjusted to pH = 7.0 with 28% (w/v) ammonium hydroxide and brought up to final volume. Ten grams of glucose, 8 mL Mercury Vitamin Solution, and the appropriate antibiotics were added after sterilization and pH adjustment.

[0300] 1000X Modified Trace Metal Solution (per liter): 40 g citric acid*H₂O, 30 g MnSO₄*H₂O, 10 g NaCl, 1 g FeSO₄*7H₂O, 1 g CoCl₂*6H₂O, 1 g ZnSO₄*7H₂O, 100 mg CuSO₄*5H₂O, 100 mg H₃BO₃, and 100 mg NaMoO₄*2H₂O were dissolved one at a time in diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0301] Mercury Vitamin Solution (per liter): 1 g thiamine hydrochloride, 1 g D-(+)-biotin, 1 g nicotinic acid, 4.8 g D-pantothenic acid, and 4 g pyridoxine hydrochloride were dissolved one at a time in diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0302] Feed solution (per kilogram): 0.57 kg glucose, 0.38 kg diH₂O, 7.5 g K₂HPO₄, and 10 g 100% Foamblast were mixed together and autoclaved. After cooling the sterile solution to 25°C, 3.4 mL Macro Salt Solution, 0.8 ml 1000X Modified Trace Metal Solution, and 6.7 mL Mercury Vitamin Solution were added.

[0303] Macro Salt Solution (per liter): 296 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 296 g citric acid monohydrate, and 49.6 g ferric ammonium citrate were dissolved in diH_2O , brought up to final volume and filter sterilized with a 0.22 micron filter.

[0304] Fermentation was performed in 15-L bioreactors with three different *E. coli* BL21 cell strains: (1) **DW199** expresses the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL.2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) + mMVK (pDW34)) but lacks the *pgl* gene; (2) **CMP312** expresses the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL.2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) + mMVK (pDW34)), and contains a restored chromosomal 17,257 bp segment encoding the *pgl* gene (the *ybgS::kan^R* marker used during strain construction was looped out); and (3) **CMP323** is identical to CMP312 except the *pgl* gene was precisely excised from the restored piece of DNA and replaced with a gene conferring kanamycin resistance (*pgl/ybhE::kan^R*).

[0305] This experiment was carried out to monitor isoprene production from glucose at the desired fermentation pH and temperature (pH=7.0 and 34°C). A frozen vial of each *E. coli* strain was thawed and inoculated into tryptone-yeast extract medium for each bioreactor. After the inoculum grew to $\text{OD}_{550}=1.0$, 500 mL of the culture was used to inoculate a 15-L bioreactor before bringing the initial tank volume to 5 L.

[0306] The feed solution was fed at an exponential rate until a top feed rate of 5.8 g/minute was reached. After this time the glucose feed was added to meet metabolic demands at rates less than or equal to 5.8 g/minute. The total amount of glucose delivered to the bioreactors was 5.8 kg to strain DW199 over 44 hours of fermentation, 3.4 kg to strain CMP312 over 45 hours of fermentation, and 6.3 kg to strain CMP323 over 44 hours of fermentation. Induction of isoprene production was achieved by adding isopropyl-beta-D-1-thiogalactopyranoside ("IPTG") at the levels shown in Table 25. The OD_{550} profiles within the bioreactors over time are shown in Figure 23. The isoprene levels in the offgas from the bioreactors were determined using a Hiden mass spectrometer (Hiden Analytical, Warrington, UK). The isoprene titer increased over the course of the fermentation to a maximum value of 76 g/L at 44 hours for strain DW199, 68 g/L at 45 hours for strain CMP312, and 79 g/L at 44 hours for strain CMP323 (see Figure 24). The total amount of isoprene produced during fermentation was 637 g over 44 hours for strain DW199, 482 g over 45 hours for strain CMP312, and 640

g over 44 hours for strain CMP323 (Figure 25). The time course of specific productivity is shown in Figure 26. The molar and mass yields of isoprene from glucose are shown in Table 9.

Table 8: IPTG addition during the fermentations of strains DW199, CMP312 and CMP323

Strain	Induction	OD ₅₅₀	IPTG concentration, μ M
DW199	1 st	5	105
	2 nd	105	195
CMP312	1 st	5	115
	2 nd	80	225
CMP323	1 st	5	115
	2 nd	115	215

Table 9: Molar and mass yield of isoprene from glucose for strains DW199, CMP312 and CMP323

Strain	Time, hr	Molar yield, %	Mass yield, %
DW199	44	23.9	11.0
CMP312	45	30.3	14.5
CMP323	44	22.0	10.2

Example 11: *M. mazei* mevalonate kinase and *P. alba* isoprene synthase overexpression, and restored K12 DNA including *pgl* (CMP312) compared to the same strain with *pgl* precisely excised (CMP323)

[0307] This example compares isoprene production from *E. coli* strains expressing genes from the mevalonic acid pathway and isoprene synthase with the *pgl* gene restored and with the restored *pgl* gene precisely deleted, grown in fed-batch culture at the 15-L scale.

[0308] Medium Recipe (per liter fermentation medium): 7.5 g K₂HPO₄, 2 g MgSO₄*7H₂O, 2 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 0.5 g yeast extract, 1 ml 1000X Modified Trace Metal Solution were added together and dissolved in diH₂O. This solution was heat sterilized at 123°C for 20 minutes, the pH was then adjusted to 7.0 with 28% (w/v) ammonium hydroxide and brought up to final volume. 10 g glucose, 0.05 g thiamine hydrochloride, and appropriate antibiotics were added after sterilization and pH adjustment.

[0309] 1000X Modified Trace Metal Solution (per liter): 40 g citric acid*H₂O, 30 g MnSO₄*H₂O, 10 g NaCl, 1 g FeSO₄*7H₂O, 1 g CoCl₂*6H₂O, 1 g ZnSO₄*7H₂O, 100 mg

$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 100 mg H_3BO_3 , and 100 mg $\text{NaMoO}_4 \cdot 2\text{H}_2\text{O}$ were dissolved one at a time in diH_2O , pH was adjusted to 3.0 with HCl/NaOH , and then the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0310] Feed solution (per kilogram): 0.57 kg glucose, 0.38 kg diH_2O , and 10 g 100% Foamlab were mixed together and autoclaved.

[0311] This experiment was performed to compare isoprene formation from glucose at the desired fermentation pH and temperature (pH=7.0 and 34°C) in strains with *pgl* restored and with restored *pgl* precisely knocked out. Fermentations were performed in 15-L bioreactors with two *E. coli* strains: (1) **CMP312**, *E. coli* BL21 cells expressing the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) mMVK (pDW34)), and containing a restored 17,259 bp segment of the bacterial chromosome including the *pgl* gene (with the $\text{ybgS}::\text{Kan}^R$ marker looped out); and (2) **CMP323**, an *E. coli* strain with *pgl* precisely excised from the restored piece of DNA, as described above. A frozen vial of each strain was thawed and inoculated into tryptone-yeast extract medium for each bioreactor. After the inoculum grew to $\text{OD}_{550}=1.0$, measured at 550 nm (OD_{550}), 500 mL was used to inoculate a 15-L bioreactor, and the initial tank volume was brought up to 5 L.

[0312] The feed solution was added at an exponential rate until a top feed rate of 5.8 g/minute was reached. After this time the glucose feed was added to meet metabolic demands at rates less than or equal to 5.8 g/minute. The total amount of glucose delivered to the bioreactors during the 20 hour fermentation was 1.6 kg for the *pgl*⁺ strain and 2.0 kg for the *pgl*[−] strain. These strains were fed to avoid glucose accumulation in the medium.

[0313] Isoprene production was induced by adding isopropyl-beta-D-1-thiogalactopyranoside (“IPTG”) to 90 μM when the OD_{550} reached a value of 4. The IPTG concentration was raised to 170 μM when the OD_{550} reached 100.

[0314] Figure 27 shows the OD_{550} profiles in the bioreactors over the course of the fermentation, which were similar for the two tanks. The isoprene level in the off-gas from the bioreactors was determined using a Hiden mass spectrometer (Hiden Analytical, Warrington, UK). The isoprene titer increased over the course of the fermentation to a

maximum value of 17 g/L at the last time point sampled (*see* Figure 28). However, the *pgl*⁺ strain reached this titer faster than the *pgl*⁻ strain. The time course of specific productivity is shown in Figure 29. According to the OD and titer trends, the *pgl*⁺ strain had a higher specific productivity in the run compared to the *pgl*⁻ strain.

Example 12: *M. mazei* mevalonate kinase and *P. alba* isoprene synthase overexpression

[0315] This example show the isoprene production from *E. coli* K12 MG1655 (which contains the 17,257 bp deleted from *E. coli* BL21 (DE3)) expressing genes from the mevalonic acid pathway and isoprene synthase, grown in fed-batch culture at the 15-L scale.

[0316] Medium Recipe (per liter fermentation medium): 7.5 g K₂HPO₄, 2 g MgSO₄*7H₂O, 2 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 0.5 g yeast extract, and 1 ml 1000X Modified Trace Metal Solution were added together and dissolved in diH₂O. This solution was heat sterilized at 123°C for 20 minutes, the pH was adjusted to 7.0 with 28% (w/v) ammonium hydroxide brought up to the final volume. 10 g glucose, 8 mL Mercury Vitamin Solution, and appropriate antibiotics were added after sterilization and pH adjustment.

[0317] 1000X Modified Trace Metal Solution (per liter): 40 g citric acid*H₂O, 30 g MnSO₄*H₂O, 10 g NaCl, 1 g FeSO₄*7H₂O, 1 g CoCl₂*6H₂O, 1 g ZnSO₄*7H₂O, 100 mg CuSO₄*5H₂O, 100 mg H₃BO₃, and 100 mg NaMoO₄*2H₂O were dissolved one at a time in diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, and then the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0318] Mercury Vitamin Solution (per liter): 1 g thiamine hydrochloride, 1 g D-(+)-biotin, 1 g nicotinic acid, and 4.8 g D-pantothenic acid, 4 g pyridoxine hydrochloride were dissolved one at a time in diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, and then the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0319] Feed solution (per kilogram): 0.57 kg glucose, 0.38 kg diH₂O, 7.5 g K₂HPO₄, and 10 g 100% Foamblast were mixed together and autoclaved. 3.4 mL Macro Salt Solution, 0.8 mL 1000X Modified Trace Metal Solution, and 6.7 mL Mercury Vitamin Solution were added after the solution had cooled to 25°C.

[0320] Macro Salt Solution (per liter): 296 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 296 g citric acid monohydrate, and 49.6 g ferric ammonium citrate were dissolved in dH_2O , brought up to final volume and filter sterilized with a 0.22 micron filter.

[0321] This experiment was carried out to monitor isoprene formation from glucose at the desired fermentation pH and temperature (pH=7.0 and 34°C). Fermentation was performed in a 15-L bioreactor with strain MCM769: *E. coli* MG1655 cells expressing the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) + mMVK (pDW34)). A frozen vial of strain MCM769 was thawed and inoculated into tryptone-yeast extract medium for each bioreactor. After the inoculum grew to $\text{OD}_{550}=1.0$, 500 mL was used to inoculate a 15-L bioreactor and the initial tank volume was brought to 5-L.

[0322] The feed solution was added at an exponential rate until a top feed rate of 3.9 g/minute was reached. After this time, the feed solution was added to meet metabolic demands at rates less than or equal to 3.9 g/minute. The total amount of glucose delivered to the bioreactor during the 44 hour fermentation was 2.3 kg. Isoprene production was induced by adding shots of isopropyl-beta-D-1-thiogalactopyranoside ("IPTG") to achieve the levels shown in Table 10 at the measured OD_{550} values. The OD_{550} profiles within the bioreactors over time are shown in Figure 30. The isoprene level in the offgas from the bioreactors was determined using a Hiden mass spectrometer (Hiden Analytical, Warrington, UK). The isoprene titer increased over the course of the fermentation to a maximum value of 30.4 g/L at 44 hours (Figure 31). The total amount of isoprene produced during fermentation was 226.8 g at 44 hours (Figure 32). The time course of specific productivity is shown in Figure 33. The molar yield of utilized carbon that went into producing isoprene during fermentation was 21.1% at 44 hours. The weight percent yield of isoprene from glucose was 9.7% at 44 hours.

Table 10: IPTG additions during the fermentation of strain MCM769

OD_{550}	IPTG concentration after addition, μM
13	41
36	61

OD ₅₅₀	IPTG concentration after addition, uM
70	81
105	100
195	117
115	215

Example 13: The Effect of *pgl* on the Specific Productivity of Mevalonate in *E. coli* BL21

[0323] The mevalonate biosynthetic pathway comprises two parts: (1) the upper mevalonate pathway, containing acetoacetyl-CoA synthase (thiolase), HMG-CoA synthase (HMGS) and HMG-CoA reductase (HMGR); and (2) the lower mevalonate pathway containing mevalonate kinase (MVK), phosphomevalonate kinase (PMK), diphosphomevalonate decarboxylase (MVD) and isopentenyl diphosphate isomerase (IDI). Expression of the upper pathway proteins produces mevalonate, an intermediate in the production of isoprene.

[0324] These experiments were designed to investigate how and by which mechanism *pgl* affects the specific productivity of mevalonate in *E. coli* BL21. The fused thiolase/HMGR (*mvaE*) and the HMGS (*mvaS*) of *Enterococcus faecalis* were constructed on pCL, pBBR, and pTrc plasmids and transformed into both *E. coli* BL21 lacking *pgl* and *E. coli* BL21 containing *pgl* integrated in the bacterial chromosome.

[0325] Strains containing *pgl* had a greater specific productivity than strains lacking *pgl* during growth in minimal medium with high concentrations of yeast extract, growth conditions that mimic the early stages of fed batch fermentation. The presence of *pgl* during growth in minimal medium with low yeast extract concentration also resulted in significantly higher production of mevalonate compared to strains lacking *pgl*. This effect, however, was not due to increased concentration of mevalonate pathway enzymes, demonstrating that the presence of *pgl* under these growth conditions positively influences the flux to or through the mevalonate pathway possibly by affecting central metabolism of *E. coli*. These growth conditions mimic those found late during the exponential part of fed batch fermentation.

[0326] Construction of pDW15 (P_{trc}-upper MVA pathway on pBBR1MCS-5). To insert the upper MVA pathway into the pBBR1MCS-5 vector, the entire expression cassette containing P_{trc}, *mvaE*, *mvaS*, and the *rrn* transcription terminator was amplified by PCR using a plasmid pMCM82 template with the primers Upper5'XhoI (SEQ ID NO:57) and

Upper3'XbaI (SEQ ID NO:58). PCR primer sequences are listed below in Table 28. Each reaction contained 1 µl pMCM82 (~30 ng), 10 µl 5X Herculanase[®] Buffer (Stratagene, La Jolla, California), 0.5 µl dNTPs (100 mM each), 1 µl Upper5'XhoI (20 µM), 1 µl Upper3'XbaI (20 µM), 35.5 µl diH₂O, and 1 µl Herculanase[®] DNA Polymerase (Stratagene, La Jolla, California). Reactions were heated to 95°C for 4 minutes, subject to 5 cycles of 95°C for 20 minutes / 52°C for 20 seconds / 72°C for 4 minutes, to 25 cycles of 95°C for 20 minutes / 55°C for 20 seconds / 72°C for 4 minutes, followed by 10 minutes at 72°C, and finally, cooled to 4°C.

[0327] The size of the PCR product was confirmed by gel electrophoresis using a pre-cast E-gel[®] (Invitrogen, Carlsbad, CA) and the 4.2 kb product was purified using QiaQuick[®] purification columns (Qiagen, Valencia, CA) according to the manufacturer's recommended protocol. Purified PCR product and the pBBR1MCS-5 vector were then digested with XbaI and XhoI restriction endonucleases overnight at 37°C as follows: 6 µl diH₂O, 2 µl 10X SuRE/Cut Buffer H (Roche Applied Science, Indianapolis, Indiana), 10 µl DNA (pBBR1MCS-5 or PCR insert), 1 µl XhoI (Roche Applied Science), and 1 µl XbaI (Roche Applied Science). The next day, the restriction enzymes were heat-inactivated at 65°C for 20 minutes before ligation. Ligation reactions (see below for conditions) included 2 µl diH₂O, 1 µl 10X Ligase buffer (New England Biolabs, Ipswich, Massachusetts), 1 µl T4 DNA ligase (New England Biolabs), 2 µl vector (pBBR1MCS-5), and 4 µl insert (upper MVA expression cassette), and were carried out at 4°C overnight. The ligation reactions were desalted by microdialysis (Millipore, Billerica, Massachusetts) and approximately 5 µl of each reaction was transformed into chemically competent *E. coli* TOP10 cells (Invitrogen, Carlsbad, California) according to the manufacturer's recommended protocol. Electroporated cells were recovered at 37°C in LB for 1 hour, and then plated onto LB plates containing X-gal and 10 µg/ml Gentamicin. Colonies displaying no β-galactosidase activity were selected for further analysis by PCR using primers M13 Reverse and MCM163 to confirm the presence of the insert. Plasmid from one of these colonies was purified (Qiagen), completely sequenced (Quintara Biosciences, see Table 11 for primer sequences) to verify that it contained the complete upper MVA pathway expression cassette in the correct orientation, and designated pDW15 (SEQ ID NO:69). A map of plasmid pDW15 is shown in Figure 34A, and the complete sequence is listed in Figure 34B-C-D.

Table 11: PCR and Sequencing Primers

Primer name	Primer sequence
Upper5'XhoI	atgctcgagctgttgacaattaatcatccggctc (SEQ ID NO:57)
Upper3'XbaI	cgatctagaagggccagctcttcgactgagcc (SEQ ID NO:58)
MCM163	ggattttggccatttccagctt (SEQ ID NO:59)
CF07-58	atgaaaacagtagttattattgatgc (SEQ ID NO:60)
CF07-59	cttaaatcatttaaaatagc (SEQ ID NO:61)
CF07-82	atgacaattgggattgataaaattag (SEQ ID NO:62)
CF07-86	gaaatagccccattagaagtatc (SEQ ID NO:63)
CF07-87	ttgccaatcatatgattgaaaatc (SEQ ID NO:64)
CF07-88	gctatgcttcattagatccttatcg (SEQ ID NO:65)
CF07-89	gaaacctacatccaatctttgccc (SEQ ID NO:66)

[0328] Construction of MVA Producing Strains MCM870-877. Plasmids encoding the *E. faecalis mvaE* and *mvaS* genes were introduced into *E. coli* hosts by electroporation. Host cells were grown in LB medium at 37°C, 250 rpm to OD₆₀₀≈1. Cultures were placed on ice until cold. For each electroporation reaction, 1.5 mL of culture was centrifuged in an Eppendorf microcentrifuge at room temperature for 2-3 minutes at 6000 rpm. After removing the supernatant, the cell pellet was resuspended in 1 mL ice cold sterile, deionized H₂O. The spin and wash procedure was repeated three times, and the pellet was finally resuspended in 100 µL.

[0329] A mixture of plasmids consisting of 1 µL each of pDW15 (SEQ ID NO:67), pTrcHis2AUpperPathway#1 and pCLPtrcUpperPathway (construction of both plasmids is described in Example 8 of U.S. Patent Application No. 12/335,071) was added to 100 µL of cell suspension and electroporated into competent *E. coli* cells in a 2 mm cuvette at 2.5 volts, 25 µFd. Similarly, 1 µL of either pDW15, pTrcHis2AUpperPathway#1 or pCLPtrcUpperPathway was added to 100 µL of cell suspension and electroporated into competent *E. coli* cells in a 2 mm cuvette at 2.5 volts, 25 µFd. Cells were immediately allowed to recover in 500 µL LB medium for one hour at 37°C. Transformants were selected on LB with the appropriate antibiotic(s) as listed in Table 12 below. A single colony from each transformation was grown in LB medium plus the indicated antibiotic(s) at 37°C, 250 rpm to OD₆₀₀≈1 and then 0.5 mL of culture was mixed with 1 mL of 50% sterile glycerol, frozen on dry ice, and stored at -80°C.

Table 12: Bacterial Strains for Measuring Specific Productivity of Mevalonate

Host	Antibiotic Selection	Plasmid(s) Selected	Strain
BL21 (Novagen; MCM98)	Spectinomycin 50 ppm	pCLP _{trc} UpperPathway (pMCM82)	MCM870
BL21 (Novagen; MCM98)	Gentamycin 10 ppm	P _{trc} -upper MVA pathway on pBBR1MCS-5 (pDW15)	MCM871
BL21 (Novagen; MCM98)	Carbenicillin 50 ppm	pTrcHis2AUpperPathway#1 (pCF449)	MCM872
BL21 (Novagen; MCM98)	Spectinomycin 50 ppm, Gentamycin 10 ppm, Carbenicillin 50 ppm	pCLP _{trc} UpperPathway (pMCM82), P _{trc} -upper MVA pathway on pBBR1MCS-5 (pDW15), pTrcHis2AUpperPathway#1 (pCF449)	MCM873
BL21 t pgl+ (CMP258)	Spectinomycin 50 ppm	pCLP _{trc} UpperPathway (pMCM82)	MCM874
BL21 t pgl+ (CMP258)	Gentamycin 10 ppm	P _{trc} -upper MVA pathway on pBBR1MCS-5 (pDW15)	MCM875
BL21 t pgl+ (CMP258)	Carbenicillin 50 ppm	pTrcHis2AUpperPathway#1 (pCF449)	MCM876
BL21 t pgl+ (CMP258)	Spectinomycin 50 ppm, Gentamycin 10 ppm, Carbenicillin 50 ppm	pCLP _{trc} UpperPathway (pMCM82), P _{trc} -upper MVA pathway on pBBR1MCS-5 (pDW15), pTrcHis2AUpperPathway#1 (pCF449)	MCM877

[0330] Construction of strains CMP215, CMP258 and CMP234 is described in Example 6, above. To assay mevalonate specific productivity, all strains were grown in triplicate overnight at 30°C in TM3 medium containing 0.1% (w/v) yeast extract, 1% (w/v) glucose, and the appropriate antibiotic. The overnight cultures were diluted to an OD₆₀₀ of 0.05 in fresh TM3 medium containing 1% (w/v) glucose and either 0.1% (w/v) or 0.02% (w/v) yeast extract. The cultures were incubated at 34°C until reaching OD₆₀₀ of 0.5-1.0, at which point protein expression was induced with 400 µM IPTG. Samples were collected 1 hour and 2 hours post-induction to measure OD, mevalonate concentration and concentrations of MvaS and MvaE proteins. The specific productivity of mevalonate was determined by dividing the difference in mevalonate concentration over the 1 hour time period by the average OD (calculated from the 1 hour and 2 hour ODs) over the 1 hour time period.

[0331] To measure mevalonate concentration, 300 μ L of broth was centrifuged at 14,000 $\times$ g for 5 minutes. Next, 250 μ L of supernatant was added to 7.5 μ L of 70% (w/v) perchloric acid and incubated on ice for 5 minutes. The mixture was then centrifuged for 5 minutes at 14,000 $\times$ g and the supernatant collected for HPLC analysis run under the following conditions: (1) BioRad - Aminex HPX-87H Ion Exclusion Column (300 mm x 7.8 mm)(Catalog # 125-0140)(BioRad, Hercules, California); (2) column temperature = 50°C; (3) BioRad - Microguard Cation H guard column refill (30 mm x 4.6 mm)(Catalog # 125-0129)(BioRad); (4) running buffer = 0.01N H₂SO₄; (5) running buffer flow rate = 0.6 ml / min; (6) approximate running pressure = ~950 psi; (7) injection volume = 100 microliters; (8) runtime = 26 minutes.

[0332] Results. *Strains grown in TM3 media containing 0.1% (w/v) yeast extract and 1% (w/v) glucose.* Six strains were constructed to test the effect of *pgl* expressed from the bacterial chromosome on mevalonate production (Table 13). Strains were cultured as described above. Strains expressing *pgl* from the bacterial chromosome had greater mevalonate specific productivities than strains that were isogenic except for the deletion of the *pgl* region (*see* Figure 35), demonstrating that chromosomal expression of *pgl* improves the specific productivity of mevalonate in *E. coli* BL21. Mevalonate is the substrate for the lower mevalonate pathway. Therefore, strains that have a greater mevalonate specific productivity may also have a greater isoprene specific productivity in the presence of a complementary lower pathway and isoprene synthase.

Table 13: Strains used to measure specific production of mevalonate

Strain Name	Plasmid Type	Pgl
BL21 pCL	pCL	no
BL21+pgl pCL	pCL	yes
BL21 pBBR	pBBR	no
BL21+pgl pBBR	pBBR	yes
BL21 pTrc	pTrc	no
BL21+pgl pTrc	pTrc	yes

[0333] *Strains grown in TM3 media containing 0.02% yeast extract and 1% glucose.* To further investigate the role of chromosomal expression of *pgl* in the production of mevalonate under conditions with low concentrations of yeast extract in minimal medium, the two strains MCM872 and MCM876 were grown in TM3 medium containing 0.02% yeast extract as

described above. This growth medium mimics the conditions found late during the exponential part of fed batch fermentation. The two strains are isogenic except for the functional chromosomal copy of *pgl* present in MCM876. Although the strains grew similarly in the minimal medium, it was clear from the present experiment that MCM876 grew faster than MCM872 as shown in Figure 36, indicating that chromosomal expression of *pgl* positively influences growth of *E. coli* in minimal medium with low concentrations of yeast extract.

[0334] The rate of mevalonate accumulation per cell was significantly higher (2.7-fold) for MCM876 compared to MCM872, as shown in Figure 37, demonstrating that the presence of *pgl* on the bacterial chromosome significantly increases mevalonate production during growth in minimal medium containing limiting levels of yeast extract.

[0335] To investigate if the increased mevalonate production rate in the MCM876 strain resulted from higher protein production in medium with low yeast extract concentration, the concentration of the upper pathway enzymes, MvaS and MvaE was measured and normalized to the optical density of the respective cultures (Figures 38 and 39). The presence of *pgl* on the bacterial chromosome did not significantly change the concentrations of mevalonate pathway enzymes under the specific growth conditions tested. However, since the mevalonate production rate increased 2.7-fold under those growth conditions, chromosomal expression of *pgl* must increase the mevalonate production rate by mechanism other than by increasing concentrations of mevalonate pathway enzymes. One such mechanism could be the production of reducing equivalents through the pentose phosphate pathway. This was not further tested in the present experiments.

[0336] A functional chromosomal copy of *pgl* in *E. coli* increases the production of mevalonate and therefore likely also the production of isoprene not only through the increased production of pathway proteins under nutrient rich growth conditions (early in the fermentation), but also through factors that control carbon flux through the MVA pathway during growth in minimal medium with low yeast extract concentrations late in the fermentation. Surprisingly, this increase is greater than that observed in strains constitutively expressing PGL from a plasmid, suggesting that the chromosomal context or the ability of the bacteria to regulate PGL expression from its natural chromosomal context plays a role in increased production of biochemicals such as isoprene.

Example 14: Comparison of PGL enzyme activity in isoprene-producing strains

[0337] The PGL enzyme activity is measured in three strains: RHM111608-2 (production of this *E. coli* strain is described in Example 13 of International Publication No. WO 2009/076676 A2 and U.S. Patent Application No. 12/335,071), DW199, CMP312 and CMP323 (described in other examples). The enzyme activity can be determined by NMR methods as described (*see, e.g.,* E. Miclet et al., *J. Biol. Chem.* 276(37):34840-34846 (2001)). RHM111608-2 contains the *ybhE* gene (encoding PGL) under control of a constitutive promoter, DW199 lacks any gene expressing PGL, CMP312 and CMP323 are isogenic, CMP312 has *ybhE* restored by transduction and is the parent of CMP323 which has *ybhE* deleted.

[0338] The PGL enzyme activity was measured as follows: Briefly, a mixture of δ -D-6-Phospho-glucono-1,5-lactone and γ -D-6-Phospho-glucono-1,4-lactone was prepared by incubation of 5 mM glucose-6-phosphate, 7.5 mM NADP⁺, and 100 mM BES pH 7.4 with glucose-6-phosphate dehydrogenase (**Sigma-Aldrich, St. Louis, MO**) for about 3 minutes. Following incubation, the solution was allowed to equilibrate at room temperature for about 15-30 minutes. Subsequently, 400 μ L of lactone solution was added into the NMR cuvette and an initial spectrum was taken (**Varian 500 mHz, Palo Alto, CA**). Subsequently, 50 μ L of crude cell lysate was added to the lactone solution and NMR spectra was read at 2 and 8 minute time points. Sigma and delta lactone signals were normalized to their respective starting peak intensity. Normalized peak intensities for the runs are shown in shown in Table 14.

Table 14

Lactonase Activity				
extract	time (min.)	6-P-gluconate (umol product formed)	delta lactone (umol consumed)	gamma lactone (umol consumed)
chromosomal pgl	2	0.49	0.41	0.08
plasmid pgl	2	0.67	0.50	0.16
no pgl	2	0.00	0.00	0.01

[0339] The strains were run in the microfermentor and in 15-L fed batch fermentation (as described in Examples 9 and 10 above). PGL activity was measured in all strains over the course of the small scale run or the fermentation. DW199 is the negative control and demonstrates little to no activity (trace activity may be observed, because the reaction can proceed by chemical catalysis at a slow rate). RHM111608-2 has similar activity over the entire run. CMP323 shows activity levels similar to those of DW199. CMP312 shows varied activity over the course of the fermentation, higher activity is seen during the early time points of the fermentation when the strain shows an increase in specific productivity, and less activity over later times in the fermentation. The ability of the cell to regulate the activity contributes to the overall improvement of isoprene production.

[0340] The expression of the *ybhE* gene in CMP312 can be determined by using transcription arrays (NimbleGen/Agilent Technologies). RNA samples are isolated from 15-L fermentations (as above) over the course of the entire fermentation by harvesting samples into RNeasy Lysing Matrix (Qiagen). The RNA samples are prepared using RNeasy Minikit (Qiagen) according to manufacturer's specifications. Further processing of samples and hybridization to the custom arrays are done by Agilent Technologies. Expression of the *ybhE* gene is analyzed using software such as GeneSpring GX (Agilent Technologies).

Example 15: *pgl* expressed on the plasmid vs *pgl* integrated on the chromosome

[0341] This example shows isoprene production from *E. coli* BL21 expressing genes from the mevalonic acid pathway and isoprene synthase, grown in fed-batch culture at the 15-L scale.

[0342] Medium Recipe (per liter of fermentation medium): 7.5 g K_2HPO_4 , 2 g $MgSO_4 \cdot 7H_2O$, 2 g citric acid monohydrate, 0.3 g ferric ammonium citrate, 0.5 g yeast extract, and 1 ml 1000X Modified Trace Metal Solution were added together and dissolved in dH_2O . The solution was heat sterilized at 123°C for 20 minutes, then adjusted to pH = 7.0 with 28% (w/v) ammonium hydroxide and brought up to final volume. Ten grams of glucose, 8 mL Mercury Vitamin Solution, and the appropriate antibiotics were added after sterilization and pH adjustment.

[0343] 1000X Modified Trace Metal Solution (per liter): 40 g citric acid* H_2O , 30 g $MnSO_4 \cdot H_2O$, 10 g NaCl, 1 g $FeSO_4 \cdot 7H_2O$, 1 g $CoCl_2 \cdot 6H_2O$, 1 g $ZnSO_4 \cdot 7H_2O$, 100 mg $CuSO_4 \cdot 5H_2O$, 100 mg H_3BO_3 , and 100 mg $NaMoO_4 \cdot 2H_2O$ were dissolved one at a time in

diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0344] Mercury Vitamin Solution (per liter): 1 g thiamine hydrochloride, 1 g D-(+)-biotin, 1 g nicotinic acid, 4.8 g D-pantothenic acid, and 4 g pyridoxine hydrochloride were dissolved one at a time in diH₂O, the pH was adjusted to 3.0 with HCl/NaOH, the solution was brought up to final volume and filter sterilized with a 0.22 micron filter.

[0345] Feed solution (per kilogram): 0.57 kg glucose, 0.38 kg diH₂O, 7.5 g K₂HPO₄, and 10 g 100% Foamblast were mixed together and autoclaved. After cooling the sterile solution to 25°C, 3.4 mL Macro Salt Solution, 0.8 ml 1000X Modified Trace Metal Solution, and 6.7 mL Mercury Vitamin Solution were added.

[0346] Macro Salt Solution (per liter): 296 g MgSO₄*7H₂O, 296 g citric acid monohydrate, and 49.6 g ferric ammonium citrate were dissolved in diH₂O, brought up to final volume and filter sterilized with a 0.22 micron filter.

[0347] Fermentation was performed in 15-L bioreactors with two different *E. coli* BL21 cell strains: (1) **DW202** expresses the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL.2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) + mMVK (pDW34)) and *pgl* expressed in the plasmid pBBRCMPGI1.5-*pgl* (see example 1) ; (2) **CMP234** expresses the upper mevalonic acid (MVA) pathway (pCL Upper), the integrated lower MVA pathway (PL.2 mKKDyI), mevalonate kinase from *M. mazei* and truncated isoprene synthase from *P. alba* (pTrcAlba(MEA) + mMVK (pDW34)), and contains a restored chromosomal 17,257 bp segment encoding the *pgl* gene (the *ybgS::kan^R* marker used during strain construction was looped out).

[0348] This experiment was carried out to monitor isoprene production from glucose at the desired fermentation pH and temperature (pH=7.0 and 34°C). A frozen vial of each *E. coli* strain was thawed and inoculated into tryptone-yeast extract medium for each bioreactor. After the inoculum grew to OD₅₅₀=1.0, 500 mL of the culture was used to inoculate a 15-L bioreactor before bringing the initial tank volume to 5 L.

[0349] The feed solution was fed at an exponential rate until a top feed rate of 5.8 g/minute was reached. After this time the glucose feed was added to meet metabolic demands at rates

less than or equal to 5.8 g/minute. The total amount of glucose delivered to the bioreactors was 5.5 kg to strain DW202 over 59 hours of fermentation, and 7.8 kg to strain CMP234 over 72 hours of fermentation. Induction of isoprene production was achieved by adding isopropyl-beta-D-1-thiogalactopyranoside (“IPTG”) at the levels shown in Table 15. The isoprene levels in the offgas from the bioreactors were determined using a Hiden mass spectrometer (Hiden Analytical, Warrington, UK). The isoprene titer increased over the course of the fermentation to a maximum value of 56 g/L at 59 hours for strain DW202 and 81 g/L at 70 hours for strain CMP234 (*see* Figure 42A). The time course of specific productivity is shown in Figure 42B

Table 15: IPTG addition during the fermentations of strains DW202 and CMP234

Strain	Induction	OD ₅₅₀	IPTG concentration, μ M
DW202	1 st	5	100
	2 nd	140	184
CMP234	1 st	5	110
	2 nd	110	197

[0350] The headings provided herein are not limitations of the various aspects or aspects of the invention which can be had by reference to the specification as a whole.

[0351] 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.

CLAIMS

What is claimed is:

1. A recombinant cell of an *Escherichia coli* (*E. coli*) strain, or progeny thereof, capable of producing isoprene, the cell comprising: (a) one or more copies of a heterologous nucleic acid(s) encoding a PGL polypeptide wherein the nucleic acid is integrated in the *E. coli* chromosome; and (b) one or more heterologous nucleic acid(s) encoding isoprene synthase; wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide, and

wherein the resulting recombinant cell produces isoprene at a greater titer than that of the same cells that do not comprise (a) and (b).
2. The recombinant *E. coli* cell of claim 1, wherein one or more copies of a heterologous nucleic acid encoding a molybdenum uptake polypeptide is additionally integrated in the *E. coli* chromosome.
3. The recombinant *E. coli* cell of claim 2, wherein the molybdenum uptake polypeptide is selected from the group consisting of *modF*, *modE*, *modA*, *modB* and *modC*.
4. The recombinant *E. coli* cell of claim 1, wherein one or more copies of a heterologous nucleic acid encoding a galactose metabolism polypeptide is additionally integrated in the *E. coli* chromosome.
5. The recombinant *E. coli* cell of claim 4, wherein the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*.
6. The recombinant *E. coli* cell of claim 1, wherein one or more copies of a heterologous nucleic acid encoding a galactose metabolism polypeptide and one or more copies of a heterologous nucleic acid encoding a molybdenum uptake polypeptide are additionally integrated in the *E. coli* chromosome.
7. The recombinant *E. coli* cell of claim 6, wherein (a) the PGL polypeptide is an *E. coli* PGL polypeptide; (b) the molybdenum uptake polypeptide is selected from the group consisting of *modF*, *modE*, *modA*, *modB* and *modC*; and (c) the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*.

8. The recombinant *E. coli* cell of claim 7, wherein nucleic acids encoding the PGL polypeptide, galactose metabolism polypeptide, and molybdenum uptake polypeptide are part a 17,257 base pair piece as shown in Figure 20.
9. The recombinant *E. coli* cell of claim 1, wherein the cell produces isoprene at a higher specific productivity than that of the same cells that do not contain (a) and (b).
10. The recombinant *E. coli* cell of claim 1, wherein the specific productivity is at least 15 mg/OD/hr.
11. The recombinant *E. coli* cell of claim 7, wherein the nucleic acids encoding PGL polypeptide, molybdenum uptake polypeptide, and/or galactose metabolism polypeptide are from *E. coli* strain K12 MG1655 or a derivative of *E. coli* strain K12 MG1655.
12. The recombinant *E. coli* cell of claim 1, wherein the cell is of *E. coli* strain B.
13. The recombinant *E. coli* cell of claim 12, wherein the cell is of *E. coli* strain BL21.
14. The recombinant *E. coli* cell of claim 12, wherein the cell is of *E. coli* strain BL21(DE3).
15. The recombinant *E. coli* cell of claim 1, further comprising (c) a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide and/or a lower MVA pathway polypeptide.
16. The recombinant *E. coli* cell of claim 7, further comprising (d) a heterologous nucleic acid encoding an upper mevalonate (MVA) pathway polypeptide and/or a lower MVA pathway polypeptide.
17. The recombinant *E. coli* cell of claim 15 or 16, wherein the upper MVA pathway polypeptide is selected from the group consisting of: (i) an acetoacetyl-Coenzyme A synthase (thiolase) polypeptide; (ii) a 3-hydroxy-3-methylglutaryl-Coenzyme A synthase polypeptide; and (iii) a 3-hydroxy-3-methylglutaryl-Coenzyme A reductase polypeptide.
18. The recombinant *E. coli* cell of claim 15 or 16, wherein the lower MVA pathway polypeptide is selected from the group consisting of: (i) mevalonate kinase (MVK); (ii) phosphomevalonate kinase (PMK); (iii) diphosphomevalonate decarboxylase (MVD); and (iv) isopentenyl diphosphate isomerase (IDI).
19. The recombinant *E. coli* cell of claim 16, wherein (a) the PGL polypeptide is an *E. coli* PGL polypeptide; (b) the molybdenum uptake polypeptide is selected from the group

consisting of *modF*, *modE*, *modA*, *modB* and *modC*; and (c) the galactose metabolism polypeptide is selected from the group consisting of *galM*, *galK*, *galT* and *galE*.

20. The recombinant *E. coli* cell of claim 1, wherein the isoprene synthase polypeptide is from *Populus alba*.

21. A method of producing isoprene, the method comprising:

(a) culturing a composition comprising the recombinant cell of claim 1 or 7 under suitable culture conditions for the production of isoprene and

(b) producing isoprene.

22. The method of claim 21 comprising further recovering the isoprene.

23. The method of claim 21, wherein the recombinant cell has a specific productivity greater than about 15 mg/OD/hr of isoprene.

24. A method of producing mevalonate, the method comprising:

(a) culturing a composition comprising the recombinant cell of claim 15 under suitable culture conditions for the production of mevalonate and

(b) producing mevalonate.

25. A method of making the recombinant cell of claim 1 comprising:

(a) transducing a heterologous nucleic acid encoding a PGL polypeptide into an *E. coli* cell, wherein prior to the integration, the *E. coli* cell does not contain nucleic acid(s) encoding a PGL polypeptide;

(b) allowing the nucleic acid encoding a PGL polypeptide to integrate in the *E. coli* chromosome; and

(c) introducing one or more heterologous nucleic acid(s) encoding isoprene synthase into *E. coli* cell.

26. A composition comprising the recombinant cell of claims 1 or 7.