

BIOSYNTHESIS OF ROSE AROMAS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of Singapore application No. 10202251656V, filed 7 November 2022 and Singapore application No. 10202202455U, filed 10 March 2022, the contents of it being hereby incorporated by reference in its entirety for all purposes.

FIELD OF THE INVENTION

[0002] The invention relates to biosynthesis of terpenoids, in particular rose aroma molecules.

BACKGROUND OF THE INVENTION

[0003] Rose oils are rich in volatile molecules, among them, monoterpenes play critical roles in characterizing rose scents. Geraniol, a monoterpene alcohol with rose-like odor and taste, is an important commercial flavor and fragrance molecule. Geraniol and its ester derivative, geranyl acetate, are the two most important monoterpenes in rose oils. Geraniol is widely used in deodorants, perfumes and cosmetic creams and is also an effective plant-based mosquito repellent and insecticide with low mammalian toxicity and biodegradability. Geranyl acetate, the ester derivative of geraniol, is also widely used in the cosmetic industry due to its floral and fruity scent.

[0004] However, these molecules are only produced in low concentrations in plants. Currently, geraniol and geranyl acetate are predominantly produced by chemical synthesis which is unsustainable and not environmentally friendly. In addition, there is an increasing demand among consumers for natural ingredients or bioingredients. Hence, there is growing interest in the development of biotechnological routes for the production of geraniol and geranyl acetate and in recent years, biotechnological routes for geraniol production have been developed. Most of these use plant geraniol synthases (GESs) which have inadequate solubility and/or activity in microbes that limit the yield of geraniol. Therefore, there is a need to provide a method and system for the biosynthesis of geraniol and geranyl acetate that overcomes, or at least ameliorates, one or more of the disadvantages described above.

SUMMARY

[0005] In one aspect, provided herein is a host cell comprising one or more vectors comprising a polynucleotide sequence encoding: one or more genes of the mevalonate pathway; and one or more genes of the Nudix pathway.

[0006] In another aspect, provided herein is an engineered fusion protein comprising a diphosphate synthase or prenyltransferase of the mevalonate pathway and a nudix hydrolase; or a diphosphate synthase or prenyltransferase of the mevalonate pathway, a nudix hydrolase and a geranyl synthase enzyme (GES) of the terpene synthase pathway; or a diphosphate synthase or prenyltransferase of the mevalonate pathway and a GES of the terpene synthase pathway.

[0007] In another aspect, provided herein is a method of geraniol, geranyl acetate, or geraniol and geranyl acetate production comprising culturing the host cell as described herein in a culture medium, wherein the culture medium comprises an inducer and at least one carbon substrate.

[0008] In another aspect, provided herein is a kit for producing geraniol, geranyl acetate, or geraniol and geranyl acetate, wherein the kit comprises the host cell as described herein with instructions for use.

DEFINITIONS

[0009] As used herein, the term “isoprenoid” refers to a large and diverse class of naturally-occurring class of organic compounds composed of two or more units of hydrocarbons, with each unit consisting of five carbon atoms arranged in a specific pattern.

[0010] As used herein, the term “monoterpene” or “monoterpenoids” are a class of isoprenoids produced from geranyl diphosphate by various monoterpene synthases. Monoterpenoids have two isoprenoid units. Monoterpenes are secondary metabolites in plants and the main constituents of essential oils, cosmetics, food flavorings, cleaning products and drugs. They contribute to the specific smell characters of plants. Monoterpenes are industrially used as flavour, fragrant, and cosmetic constituents. Moreover, they are precursors of several flavour compounds such as citronellol, geraniol, menthol, and verbenol.

[0011] As used herein, the term “mevalonate pathway” refers to a cellular metabolic pathway that plays a key role in multiple cellular processes by synthesizing sterol isoprenoids, such as cholesterol, and non-sterol isoprenoids, such as dolichol, heme-A,

isopentenyl tRNA and ubiquinone. The mevalonate pathway is the first recognized pathway for biosynthesis of isopentenyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP), which involves a series of six enzymatic steps that convert acetyl-CoA to IPP. Three molecules of acetyl-CoA are condensed to synthesize mevalonate in the first two steps of the mevalonate pathway. The enzymes acetoacetyl-CoA thiolase and HMG-CoA synthase (HMGS) catalyze the condensation reactions to form hydroxymethylglutaryl-CoA (HMG-CoA). Furthermore, reduction of HMG-CoA into mevalonate is catalyzed by HMG-CoA reductase (HMGR). The mevalonate thus synthesized is phosphorylated and decarboxylated to form IPP. The phosphorylation is first catalyzed by mevalonate kinase followed by the action of phosphomevalonate kinase (PMK) to form mevalonate-5-pyrophosphate. Decarboxylation is the last step, in which phosphomevalonate decarboxylase catalyzes the ATP-dependent decarboxylation of mevalonate-5-pyrophosphate to form IPP. IPP may interact with DHNA to form AQ or isomerases to form DMAPP by IPP isomerase (IDI). Genes of the mevalonate pathway refer to genes that encode enzymes of the mevalonate pathway.

[0012] As used herein, the term “nudix hydrolase” refers to a superfamily of hydrolytic enzymes and are found in all classes of organism. Nudix hydrolases hydrolyse a wide range of organic pyrophosphates, including nucleoside di- and triphosphates, dinucleoside and diphosphoinositol polyphosphates, nucleotide sugars and RNA caps, with varying degrees of substrate specificity.

[0013] As used herein, the term “Nudix pathway” refers to a metabolic pathway that involves a diphosphohydrolase belonging to the Nudix enzyme family. The cytosolic Nudix hydrolase (such as AtNUDX1, NudI, RhNUDX1) converts geranyl diphosphate (GPP) into geranyl monophosphate (GP), which is then hydrolyzed to geraniol by phosphatase activity. Genes of the Nudix pathway refer to genes that encode enzymes of the Nudix pathway.

[0014] As used herein, the term “geraniol” refers to an acyclic monoterpene alcohol with the formula $C_{10}H_{18}O$, 3,7-dimethyl-2,6-octadien-1-ol. Geraniol can be produced by aromatic plants. Geraniol can also be biosynthesized in engineered strains, including *Saccharomyces cerevisiae*.

[0015] As used herein, the term “geranyl acetate” is a monoterpene that is the acetate ester derivative of geraniol.

[0016] As used herein, the term “polypeptides” includes polypeptides, proteins, peptides, fragments of polypeptides, and fusion polypeptides.

[0017] 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.

[0018] As used herein, the term “operably linked” refers to a functional linkage between a nucleic acid expression control sequence (such as a promoter) and a second nucleic acid sequence, wherein the expression control sequence regulates the transcription of the nucleic acid corresponding to the second sequence.

[0019] As used herein, the term “variant” refers to a modification in the DNA sequence. The modification in the DNA sequence includes mutation, truncation, translocation, substitution, deletion and insertion, resulting in the alteration of the activity of the gene.

[0020] The term “promoter” as used herein refers to a region of the DNA that initiates transcription of a gene. The region of the DNA is typically located near the transcription start site of a gene and upstream on the DNA. A promoter may be inducible or non-inducible. The term “inducible promoter” as used herein refers to a promoter that can be regulated in the response to specific stimuli, also known as inducers. The promoter system may be modified to be inducible. Examples of inducible promoter systems include the Tet-on system, Tet-off system, T7 system, Trp system, Tac system, lambda cI857-PL system, bacterial EL222 system and Lac system. A promoter may also be a constitutive promoter which is a promoter that is always active.

[0021] The term “ribosomal binding site” as used herein in the context of the application refers to a site of an mRNA molecule which recruits and binds the ribosome, allowing the selection of the proper initiation codon during the initiation of translation. The ribosomal binding site controls the accuracy and efficiency of the initiation of mRNA translation.

[0022] As used herein, the term “linker” refers to short amino acid sequences that separate multiple domains in a recombinant or fusion protein. Linkers function to prohibit unwanted interactions between the discrete domains. However, there are flexible Gly-rich linkers that connect various domains in a single protein without interfering with the function of each domain. Gly-rich linkers can also help create a covalent link between proteins to form a stable protein-protein complex. The lengths of linkers vary from 2 to 31 amino acids, optimized for each condition so that the linker does not impose any constraints on the conformation or interactions of the linked partners.

[0023] As used herein, the term “deficient” in the context of the expression of a gene or protein refers to a reduction in expression level of a gene or protein relative to a baseline level of expression of the gene or protein. Deficient in the context of the expression of a gene or protein may also refer to non-expression of a gene or protein in a scenario where the gene or protein would otherwise be expressed. The baseline expression of a gene or a protein would be understood to mean the expression level of an unmutated gene or a wild type gene, or in the context where the gene or protein would otherwise be expressed, the expression level of the gene or protein.

[0024] As used herein, the term “co-expressed” refers to transcription and/or translation of two or more genes as a single unit. The transcription and/or translation of two or more genes as a single unit may occur via fusion of two or more genes. Alternatively, co-expression in the context of the expression of genes and/or proteins may also refer to the transcription and/or translation of two or more genes as separate units.

[0025] As used herein, the term “about”, is used in the context of, but not limited to, concentrations of components and percentages of compounds, typically refers to +/- 10% of the stated value, to +/- 9% of the stated value, to +/- 8% of the stated value, to +/- 7% of the stated value, to +/- 6% of the stated value, to +/- 5% of the stated value, +/- 4% of the stated value, more typically +/- 3% of the stated value, more typically, +/- 2% of the stated value, even more typically +/- 1% of the stated value, and even more typically +/- 0.5% of the stated value. Throughout this disclosure, certain embodiments may be disclosed in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed ranges. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] The invention will be better understood with reference to the detailed description when considered in conjunction with the non-limiting examples and the accompanying drawings, in which:

[0027] **Fig. 1** depicts the biosynthetic pathway of geraniol and geranyl acetate. The biosynthetic pathway consists of 1) mevalonate pathway genes, including *atoB*, *hmgS* and *thmgR*, *mevk*, *pmk*, *pmd* and *idi*; 2) monoterpene pathway genes, including *GPPS*, *RhNUDX1*, phosphatase and *RhAAT1*; 3) other genes: *yjgB*. Abbreviation for the compounds: MVA, mevalonate; IPP, isopentenyl pyrophosphate; DMAPP, dimethylallyl pyrophosphate; GPP, geranyl pyrophosphate; GP, geranyl phosphate. Dashed arrow indicates multiple enzymatic steps. The genes expressed encode the following enzymes: *GPPS*, GPP synthase; *RhNUDX1*, the Nudix hydrolase from *Rosa hybrida*; *RhAAT1*, alcohol acyltransferase from *Rosa hybrida* that catalyze geraniol into geranyl acetate; *yjgB*, an alcohol dehydrogenase that converts geraniol into geranial.

[0028] **Fig. 2** shows the *in vitro* characterization and *in vivo* application of RhNUDX1. **Fig. 2A** shows the characterization of purified RhNUDX1 (calculated K_m and k_{cat} in Table 5). **Fig. 2B** depicts the study of pH effect on RhNUDX1. **Fig. 2C** shows the *in vivo* application of RhNUDX1 to produce geraniol. **Fig. 2D** shows the OD₆₀₀ of different strains. Error bars, mean $\pm$ s.d., n = 4-7.

[0029] **Fig. 3** depicts the enhancing GPP supply and pathway balancing. **Fig. 3A** shows the monoterpene titres and **Fig. 3B** displays the OD₆₀₀ of strains constructed by combining RBS engineering and GPPS screening method. **Fig. 3C** shows the geraniol titre and **Fig. 3D** depicts the OD₆₀₀ of strains constructed by pathway balancing. Error bars, mean $\pm$ s.d., n = 3-6.

[0030] **Fig. 4** shows the fusion of GPPS and RhNUDX1. (A) The monoterpene titres and (B) OD₆₀₀ in strains with fused and free forms of GPPS and RhNUDX1.

[0031] **Fig. 5** depicts YjgB deletion. (A) The monoterpene titres and (B) OD₆₀₀ in wildtype (WT) and mutant ($\Delta yjgB$) strains.

[0032] **Fig. 6** refers to abiotic strategies to minimize the by-product formation. **Fig. 6A** shows the GC chromatograms of chemical standards and our optimized (40 mM lactose) and control (20 mM lactose) condition. **Fig. 6B** depicts the monoterpene production and OD₆₀₀ in auto-induction defined media with lactose dosage tuning. **Fig. 6C** shows the monoterpene

production and OD₆₀₀ in manually induced defined media with IPTG dosage tuning. Error bars, mean $\pm$ s.d., n = 2-3.

[0033] **Fig. 7** shows the comparison of GES, RhNUDX1, NudI and their combination with ispA and AgGPPS. **Fig. 7A** shows the geraniol production and **Fig. 7B** shows the OD₆₀₀ in the strains using various enzymes. **Fig. 7C** shows geraniol production and **Fig. 7D** shows the OD₆₀₀ in the strains using combinations of GES/Nudix enzymes and additional GPPSs. Error bars, mean $\pm$ s.d., n = 2.

[0034] **Fig. 8** refers to the optimization of geranyl acetate bioproduction. **Fig. 8A** shows the geraniol titre and OD₆₀₀ of strains constructed by pathway balancing. **Fig. 8B** shows the induction optimization of the two best strains of geranyl acetate. Error bars, mean $\pm$ s.d., n = 3.

[0035] **Fig. 9** refers to the fed-batch fermentation of geraniol and geranyl acetate. **Fig. 9A** shows the time-course profiles of geraniol and OD₆₀₀. **Fig. 9B** shows the time-course profiles of geranyl acetate and OD₆₀₀.

[0036] **Fig. 10** illustrates the deletion of *ackA-pta* on geranyl acetate production. Glycerol concentrations in media were 20 or 30 g/L, respectively. Here, the '-' refers to the strain without the *ackA-pta* deletion. The cells were grown in 10 mL TB medium in 125 mL baffled flasks at 100 rpm, 28°C for 3 days.

[0037] **Fig. 11** depicts the tryptone supplementation on geraniol biosynthesis. Error bars, mean $\pm$ s.d., n = 2. The cells were grown in 1 mL chemically defined medium in tubes at 300 rpm, 28 °C for 3 days.

[0038] **Fig. 12** shows the optimization of dodecane/medium ratio. Error bars, mean $\pm$ s.d., n = 2. The cells were grown in 10 mL chemically defined medium in 125 mL baffled flasks at 100 rpm, 28 °C for 3 days.

[0039] **Fig. 13** illustrates the enzymatic combinations used in this study.

DETAILED DESCRIPTION OF THE PRESENT INVENTION

[0040] In a first aspect, the present invention refers to a host cell comprising one or more vectors comprising a polynucleotide sequence encoding: a) one or more genes of the mevalonate pathway; and b) one or more genes of the Nudix pathway.

[0041] The one or more genes of the mevalonate pathway and the one or more genes of the Nudix pathway may be encoded on one or more vectors within the host cell. For example,

the polynucleotide sequences may be encoded on one vector, two vectors, three vectors, four vectors, five vectors or six vectors. It will be appreciated by a person skilled in the art that the one or more genes of the mevalonate pathway, and the one or more genes of the Nudix pathway can be located in one or more vectors in different combinations. In one example, the one or more genes of the mevalonate pathway may be encoded on one vector and the one or more genes of the Nudix pathway may be encoded on another vector. In another example, the one or more genes of the mevalonate pathway may be encoded on two vectors and the one or more genes of the Nudix pathway may be encoded on another vector. In another example, the one or more genes of the Nudix pathway may be encoded on two vectors and the one or more genes of the mevalonate pathway may be encoded on another vector. It will also be appreciated by a person skilled in the art that where there is more than one gene of a pathway, these can be encoded on separate vectors in combination with one or more genes from another pathway. It will generally be understood that the examples provided in the foregoing are not exhaustive and different combinations would be acceptable.

[0042] The one or more genes of the mevalonate pathway and the one or more genes of the Nudix pathway may in some examples be inserted into the genome of the host cell. A person skilled in the art would understand that the genomic insertion of one or more genes of the mevalonate pathway and one or more genes of the Nudix pathway into the host genome refers to the targeted and stable insertion of an exogenous gene into the host genome, allowing stable gene expression. The one or more genes of the mevalonate pathway and the one or more genes of the Nudix pathway may be inserted into the genome of the host cell using genomic modification methods including but is not limited to CRISPR-Cas9, TALEN-mediated gene knockin.

[0043] In one example, the host cell may comprise two vectors, wherein a) a first vector comprises a polynucleotide sequence encoding one or more genes of the mevalonate pathway; and b) a second vector comprises a polynucleotide sequence encoding one or more genes of the Nudix pathway.

[0044] Genes of the mevalonate pathway include but are not limited to HMG-CoA synthase (*hmgS*), acetoacetyl-CoA thiolase (*atoB*), HMG-CoA reductase (*hmgR*), mevalonate kinase (*mevK*), phosphomevalonate kinase (*pmk*), mevalonate pyrophosphate decarboxylase (*pmd*), (isopentenyl diphosphate) IPP isomerase (*idi*), isopentenyl phosphate kinase, mevalonate 3-phosphate kinase, choline kinase, and acid phosphatase. Genes of the Nudix

pathway include but are not limited to *NUDX1*, *NudI*, *NudA*, *NudB*, *NudC*, *NudH*, *DR2204*, *IalA* and *MJ1149*.

[0045] In some examples, the one or more genes of the mevalonate pathway are isolated from bacterium or yeast. In one example, the one or more genes of the mevalonate pathway may be isolated from a bacterium selected from the group consisting of *Escherichia coli*, *Pantoea agglomerans*, *Pantoea ananatis*, *uncultured marine bacterium HF10_19P19*, *Sulfolobus solfataricus*, *Anabaena variabilis* and *Brevundimonas sp.* In one example, the one or more genes of the mevalonate pathway may be isolated a yeast selected from the group consisting of *Saccharomyces cerevisiae*, *Yarrowia lipolytica*, *Rhodospiridium toruloides*, *Candida* and *Pichia*.

[0046] In one example, the one or more genes of the mevalonate pathway may be selected from the group consisting of HMG-CoA synthase (*hmgS*), acetoacetyl-CoA thiolase (*atoB*), HMG-CoA reductase (*hmgR*), mevalonate kinase (*mevK*), phosphomevalonate kinase (*pmk*), mevalonate pyrophosphate decarboxylase (*pmd*), (isopentenyl diphosphate) IPP isomerase (*idi*) or combinations thereof.

[0047] In some examples, the one or more genes of the Nudix pathway are isolated from prokaryotes or plants. The prokaryote may be a bacterium or an archaea. In one example, the one or more genes of the Nudix pathway may be isolated from a bacterium selected from the group consisting of *Escherichia coli*, *Deinococcus radiodurans*, *Bartonella bacilliformis*. In another example, the one or more genes of the Nudix pathway may be isolated from an archaea such as *Methanocaldococcus jannaschii*. In another example, the one or more genes of the Nudix pathway may be isolated from a plant selected from the group consisting of *Rose hybrida* and *Arabidopsis thaliana*.

[0048] In one example, the one or more genes of the Nudix pathway may be selected from the group consisting of *NUDX1*, *NudI*, *NudA*, *NudB*, *NudC*, *NudH*, *DR2204*, *IalA*, *MJ1149* or combinations thereof.

[0049] In one example, the polynucleotide sequence encoding *atoB* gene is SEQ ID NO: 19. In one example, the polynucleotide sequence encoding *hmgS* gene is SEQ ID NO: 20. In one example, the polynucleotide sequence encoding *mevK* gene is SEQ ID NO: 21. In one example, the polynucleotide sequence encoding *pmk* gene is SEQ ID NO: 22. In one example, the polynucleotide sequence encoding *pmd* gene is SEQ ID NO: 23. In one example, the polynucleotide sequence encoding *idi* gene is SEQ ID NO: 24. In one example,

the polynucleotide sequence encoding *RhNUDX1* gene is SEQ ID NO: 25. In one example, the polynucleotide sequence encoding *NudI* gene is SEQ ID NO: 26. In one example, the polypeptide sequence of hmgR is SEQ ID NO: 66.

[0050] The one or more genes of the mevalonate and Nudix pathway may in some examples be modified. The modification of the one or more genes may comprise mutation, truncation, translocation, substitution, deletion and insertion, or post-translation modification of the translated gene. The genes may be modified to improve the expression levels. post-translational modification of the translated protein or combinations of any of these modifications.

[0051] In one example, the *hmgR* gene is truncated (referred to as “*thmgR*”). It will be appreciated by a person skilled in the art that the term ‘truncation’ refers to elimination of the N- or C-terminal portion of a protein by manipulation of the structural gene, or premature termination of protein elongation due to the presence of a termination codon in its structural gene as a result of a nonsense mutation. In one example, the polypeptide sequence of truncated *hmgR* is SEQ ID NO: 27 and the polynucleotide sequence encoding the truncated *hmgR* gene is SEQ ID NO: 28.

[0052] In some examples, the one or more vectors may comprise a polynucleotide sequence encoding one or more diphosphate synthase genes, prenyltransferase genes, or a combination of diphosphate synthase and prenyltransferase genes. The one or more diphosphate synthase genes, prenyltransferase genes or combination of diphosphate synthase and prenyltransferase genes may be located on the first vector or the second vector or on both first and second vectors. In one example, the polynucleotide encoding the one or more diphosphate synthase genes, prenyltransferase genes or combination of diphosphate synthase and prenyltransferase genes is encoded on the second vector. It will also be appreciated by a person skilled in the art that the polynucleotide sequence on each vector may comprise a combination of diphosphate synthase genes or prenyltransferase genes. For example, the polynucleotide sequence may encode for one diphosphate synthase gene. In another example, the polynucleotide sequence may encode for one prenyltransferase gene. In another example, the polynucleotide sequence may encode for two diphosphate synthase genes. In another example, the polynucleotide sequence may encode for two prenyltransferase genes. In yet another example, the polynucleotide sequence may encode for one diphosphate synthase gene

and one prenyltransferase gene. It will generally be understood that the examples provided in the foregoing are not exhaustive and different combinations would be acceptable.

[0053] The polynucleotide sequences in the one or more vectors would be understood to be operably linked to a promoter. It would generally be understood that any promoter that allows expression of the polynucleotide sequence may be employed. Examples of promoters include but are not limited to the T7 RNA polymerase promoter, the *lac* promoter, araBAD promoter, tac promoter, lambda cI857-PL promoter and the T5 promoter.

[0054] In some examples, the promoter may be an inducible promoter. In one example, the promoter may be naturally inducible. In one example, the promoter may be engineered to be inducible. It will be appreciated that any suitable inducible promoter system may be used. Inducible promoter systems may be induced by an inducer or stimuli including but not limited to chemical inducers, light or heat.

[0055] In one example, the polynucleotide sequence is operably linked to an inducible promoter in one or more vectors and operably linked to an uninducible promoter in the other vectors. For example, the polynucleotide sequence is operably linked to an inducible promoter in each of the vectors. In another example, the polynucleotide sequence is operably linked to an inducible promoter in two vectors and the polynucleotide sequence is operably linked to an uninducible promoter in the other vectors.

[0056] In one example, the polynucleotide sequence in each of the vectors is operably linked to an inducible promoter. In one example, the inducible promoter is a wild-type T7 RNA polymerase promoter or a variant of the wild-type T7 RNA polymerase promoter. The variant of the wild-type T7 RNA polymerase promoter may be generated via mutations to the wild-type promoter. In another example, the T7 RNA polymerase promoter variant is selected from the group consisting of TM1, TM2, TM3, TV1, TV2, TV3 and TV4. In one example, the polynucleotide sequence encoding wild-type T7 RNA polymerase promoter is SEQ ID NO: 29. In one example, the polynucleotide encoding the TM1 promoter is SEQ ID NO: 30. In one example, the polynucleotide encoding the TM2 promoter is SEQ ID NO: 31. In one example, the polynucleotide encoding the TM3 promoter is SEQ ID NO: 32. In one example, the polynucleotide sequence encoding the TV1 promoter is SEQ ID NO: 33. In one example, the polynucleotide sequence encoding the TV2 promoter is SEQ ID NO: 34. In one example, the polynucleotide sequence encoding the TV3 promoter is SEQ ID NO: 35. In one example, the polynucleotide sequence encoding the TV4 promoter is SEQ ID NO: 36.

[0057] The inducible promoter in each of the vectors may be independently selected from the wild-type T7 RNA polymerase promoter or variants. In one example, the inducible promoter in each of the vectors may be the wild-type T7 RNA polymerase promoter. In another example, the inducible promoter in each of the vectors may be the same T7 RNA polymerase promoter variant. In yet another example, the inducible promoter in each of the vectors may be different or combinations of the wild-type T7 RNA polymerase promoter and variants. It will generally be understood that apart from the examples provided herein, different combinations of inducible promoters may be used with each of the vectors of the invention.

[0058] In some examples, different combinations of inducible promoters may be used with each of the vectors to balance the genes of the mevalonate pathway, the Nudix pathway or the mevalonate and Nudix pathways and to optimize the expression level of each of the mevalonate gene or Nudix gene.

[0059] In one example, the first vector may comprise a) a polynucleotide sequence encoding the *hmgS*, *atoB*, *hmgR* genes of the mevalonate pathway operably linked to a first inducible promoter; and b) a polynucleotide sequence encoding the *mevK*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway operably linked to a second inducible promoter.

[0060] In one example, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *atoB*, *hmgS* and truncated *hmgR* genes of the mevalonate pathway in the host cell as described herein is TM1, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *mevK*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway in the host cell as described herein is TM1 and the inducible promoter in the second vector comprising the polynucleotide sequence encoding *NUDX1* gene of the Nudix pathway in the host cell as described herein is TM1. In one example, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *atoB*, *hmgS* and truncated *hmgR* genes of the mevalonate pathway in the host cell as described herein is TM1, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *mevK*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway in the host cell as described herein is TM2 and the inducible promoter in the second vector comprising the polynucleotide sequence encoding *NUDX1* gene of the Nudix pathway in the host cell as described herein is TM1. In one example, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *atoB*, *hmgS* and truncated *hmgR* genes of the mevalonate

pathway in the host cell as described herein is TM2, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *mevk*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway in the host cell as described herein is TM1 and the inducible promoter in the second vector comprising the polynucleotide sequence encoding *NUDX1* gene of the Nudix pathway in the host cell as described herein is TM1. In one preferred example, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *atoB*, *hmgS* and truncated *hmgR* genes of the mevalonate pathway in the host cell as described herein is TM3, the inducible promoter in the first vector comprising the polynucleotide sequence encoding *mevk*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway in the host cell as described herein is TM2 and the inducible promoter in the second vector comprising the polynucleotide sequence encoding *NUDX1* gene of the Nudix pathway in the host cell as described herein is TM1. It will generally be understood that apart from the examples provided herein, different combinations of inducible promoters may be used with each of the vectors of the invention.

[0061] The one or more vectors in the host cell as described herein may further comprise one or more polynucleotide sequences encoding a ribosomal binding site (RBS). Each vector in the host cell may further comprise the polynucleotide sequence encoding the RBS or some of the vectors may further comprise the polynucleotide sequence encoding the RBS while the others do not. For example, each of the first and second vectors may further comprise the polynucleotide sequence encoding the RBS. In another example, the first vector may comprise the polynucleotide sequence encoding the RBS while the second vector does not.

[0062] It will be appreciated by one of skill in the art that the sequence encoding the RBS may be optimized for translational efficiency and the strength of the RBS with respect to the polynucleotide sequence to be translated. Optimization of a RBS would generally be understood to involve modification of the polynucleotide sequence of the RBS. The RBS may be modified by substitution, deletion, insertion or combinations thereof of one or more nucleotide bases. The RBS may be modified using degenerate oligonucleotide bases.

[0063] The polynucleotide sequence encoding the RBS may be synthesized and inserted upstream of one or more genes located in one or more vectors. For example, the RBS may be synthesized and inserted upstream of two genes in two vectors. In another example, the polynucleotide sequence encoding the RBS may be synthesized and inserted upstream of one

gene in one vector. It will generally be understood that the examples provided in the foregoing are not exhaustive and different combinations would be acceptable.

[0064] In one example, the first vector may further comprise a polynucleotide sequence encoding a ribosomal binding site (RBS) upstream of the gene of the mevalonate pathway.

[0065] In some examples, the RBS in the first vector may comprise a polynucleotide sequence of SEQ ID NO: 59, SEQ ID NO: 60, SEQ ID NO: 61, SEQ ID NO: 62, SEQ ID NO: 63, SEQ ID NO: 64, SEQ ID NO: 65 or combinations thereof.

[0066] In one example, the second vector may further comprise a polynucleotide sequence encoding a ribosomal binding site (RBS) upstream of the polynucleotide sequence encoding the diphosphate synthase gene or the prenyltransferase gene.

[0067] In some examples, the RBS in the second vector may comprise a polynucleotide sequence of SEQ ID NO: 1, SEQ ID NO:2, SEQ ID NO:3, SEQ ID NO:4, SEQ ID NO: 5 or combinations thereof. In a preferred example, RBS comprises a polynucleotide sequence of SEQ ID NO: 1 or SEQ ID NO: 4.

[0068] The diphosphate synthase or the prenyltransferase in the host cell may be selected from a geranyl pyrophosphate synthase (GPPS), a farnesyl diphosphate synthase (FPPS) or a geranylgeranyl pyrophosphate synthase.

[0069] In some examples, the diphosphate synthase or the prenyltransferase in the host cell may be modified. The modification of the diphosphate synthase or the prenyltransferase may comprise mutation, truncation, translocation, substitution, deletion and insertion.

[0070] In some examples, the GPPS may be isolated from *Mentha piperita*, *Arabidopsis thaliana*, *Abies grandis*, *Antirrhinum majus*, and *Clarkia breweri*. In a preferred example, the GPPS is isolated from *Abies grandis* (AgGPPS).

[0071] In one example, the AgGPPS is truncated at the N-terminal end.

[0072] In one example, the AgGPPS is truncated between amino acid positions 2 to 85. In one example, the AgGPPS may be truncated from amino acid positions 2 to 30. In another example, the AgGPPS may be truncated from amino acid positions 2 to 50. In another example, the AgGPPS may be truncated from amino acid positions 2 to 80. In another example, the AgGPPS may be truncated from amino acid positions 2 to 84. It will generally be understood that the examples provided in the foregoing are not exhaustive and different combinations would be acceptable. In a preferred example, the AgGPPS is truncated from amino acid positions 2 to 85.

[0073] In one example, the truncated AgGPPS comprises the polypeptide sequence as set forth in SEQ ID NO: 7.

[0074] In some examples, the FPPS may be isolated from *Saccharomyces cerevisiae*, *Escherichia coli*, *Neurospora crassa* and *Gibberella fujikuroi*. In a preferred example, the FPPS is isolated from *Saccharomyces cerevisiae* or *Escherichia coli*.

[0075] In some examples, the FPPS may be modified. The modification of the FPPS may comprise mutation, truncation, translocation, substitution, deletion and insertion to improve the expression levels.

[0076] In one example, the serine residue at amino acid position 80 of the FPPS isolated from *Escherichia coli* is mutated to phenylalanine.

[0077] In one example, the mutated FPPS from *Escherichia coli* comprises the polypeptide sequence as set forth in SEQ ID NO. 9.

[0078] In one example, the FPPS is isolated from *Saccharomyces cerevisiae* and comprises a) a mutation of asparagine at amino acid 127 with tryptophan; or b) a mutation of phenylalanine at amino acid position 96 with tryptophan. A person skilled in the art will understand that the FPPS isolated from *Saccharomyces cerevisiae* comprises a combination of both mutations.

[0079] In one example, the mutated FPPS from *Saccharomyces cerevisiae* comprises the polypeptide sequence as set forth in SEQ ID NO. 11, SEQ ID NO. 12 or SEQ ID NO. 13

[0080] The one or more genes of the Nudix pathway may be isolated from a eukaryote. In one example, the *NUDX1* of the Nudix pathway may be isolated from a plant. The plant may be but is not limited to *Rosa hybrida* and *Arabidopsis thaliana*.

[0081] In one example, the *NUDX1* is isolated from *Rosa hybrida* and has about 70%, 75%, 80%, 85%, 90%, 95% or 100% identity with the polypeptide sequence set forth in SEQ ID NO: 14.

[0082] In another example, the *NUDX1* is isolated from *Arabidopsis thaliana* and has about 70%, 75%, 80%, 85%, 90%, 95% or 100% identity with the polypeptide sequence set forth in SEQ ID NO: 15.

[0083] The one or more genes of the Nudix pathway may also be isolated from a prokaryote. In one example, the *NudI*, *NudA*, *NudB*, *NudC* or *NudH* may be isolated from a prokaryote. The prokaryote may be but is not limited to *Escherichia coli*, *Salmonella typhi*, *Salmonella paratyphi B* and *Cedecea neteri*.

[0084] In some examples, the one or more genes of the Nudix pathway may be co-expressed with the diphosphate synthase or prenyltransferase gene. In one example, the one or more genes of the Nudix pathway may be fused with the diphosphate synthase or prenyltransferase gene. It will generally be understood by a person skilled in the art that the fusion may result from structural rearrangements like translocations and deletions, transcription read-through of neighboring genes, or the trans- and cis-splicing of pre-mRNAs. It will generally be understood that the examples provided in the foregoing are not exhaustive and genetic fusion methods would be acceptable.

[0085] In some examples, the host cell may further comprise a polynucleotide sequence encoding a geranyl synthase enzyme (GES) isolated from a plant. The polynucleotide sequence encoding a geranyl synthase enzyme (GES) isolated from a plant may be located on the first or second vector. In one example, the polynucleotide sequence encoding a geranyl synthase enzyme (GES) isolated from a plant is located on the first vector. In a preferred example, the polynucleotide sequence encoding a geranyl synthase enzyme (GES) isolated from a plant is located on the second vector.

[0086] The plant may be but is not limited to *Ocimum basilicum*, *Valeriana officinalis*, *Phyla dulcis*, *Cinnamomum tenuipile* and *Camptotheca acuminata*.

[0087] In one example, the GES is isolated from *Ocimum basilicum* and comprises the polynucleotide sequence as set forth in SEQ ID NO: 16.

[0088] The polynucleotide sequence encoding the GES may be located upstream or downstream of the polynucleotide sequence encoding the diphosphate synthase or prenyltransferase. The polynucleotide sequence encoding the GES may be located upstream or downstream of the polynucleotide sequence encoding the gene of the Nudix pathway

[0089] The GES may be co-expressed with the diphosphate synthase or prenyltransferase gene, or the gene of the Nudix pathway. The GES may be co-expressed with both the diphosphate synthase gene and gene of the Nudix pathway too. In one example, the GES may be fused with the diphosphate synthase or prenyltransferase gene. It will generally be understood by a person skilled in the art that the fusion may result from structural rearrangements like translocations and deletions, transcription read-through of neighboring genes, or the trans- and cis-splicing of pre-mRNAs. It will generally be understood that the examples provided in the foregoing are not exhaustive and genetic fusion methods would be acceptable.

[0090] In some examples, the host cell may further comprise a polynucleotide sequence encoding a multiple antibiotic resistance protein (MarA). The polynucleotide sequence encoding the MarA may be located on the first vector or second vector, or incorporated into the genome of the host cell. In one example, the polynucleotide sequence encoding the MarA is located on the first vector. In a preferred example, the polynucleotide sequence encoding the MarA is located on the second vector.

[0091] The polynucleotide sequence encoding the MarA may be located upstream or downstream of the polynucleotide sequence encoding the diphosphate synthase or prenyltransferase. The polynucleotide sequence encoding the MarA may be located upstream or downstream of the polynucleotide sequence encoding the gene of the Nudix pathway.

[0092] In some examples, the host cell may further comprise a polynucleotide sequence encoding an alcohol acyltransferase (AAT) enzyme. The polynucleotide sequence encoding an alcohol acyltransferase (AAT) enzyme may be located on the first or second vector. In one example, the polynucleotide sequence encoding an alcohol acyltransferase (AAT) enzyme is located on the second vector.

[0093] The polynucleotide sequence encoding AAT may be located upstream or downstream of the polynucleotide sequence encoding the diphosphate synthase or prenyltransferase. The polynucleotide sequence encoding AAT may be located upstream or downstream of the polynucleotide sequence encoding the gene of the Nudix pathway.

[0094] In one example, the AAT enzyme is isolated from a plant. The plant may be but is not limited to *Rosa hybrida*.

[0095] The host cell of the present invention may be deficient in one or more genes. In some examples, the host cell may be deficient in the *pta* gene, *ackA* gene or both *pta* and *ackA* genes.

[0096] In other examples, the host cell may be deficient in at least one gene involved in amino acid synthesis, oxidation of terpenoids and amino acid degradation. It will be appreciated by a person skilled in the art that where the host cell is deficient in at least one gene, these can be a combination of genes involved in different processes. For example, the host cell may be deficient in one or more genes involved in amino acid synthesis, and one or more genes involved in oxidation of terpenoids. In another example, the host cell may be deficient in one or genes involved in amino acid synthesis, and one or more genes involved in amino acid degradation. In another example, the host cell may be deficient in one or more

genes involved in oxidation of terpenoids, and one or more genes involved in amino acid degradation. It will generally be understood that the examples provided in the foregoing are not exhaustive and different combinations would be acceptable.

[0097] The gene involved in the oxidation of terpenoids may be but is not limited to *yjgB*, *yahK* and *yddN*. It will be appreciated by a person skilled in the art that the host cell may be deficient in a combination of genes involved in the oxidation of terpenoids.

[0098] The gene involved in amino acid synthesis may be but is not limited to *aroA*, *aroB* and *serC*. It will be appreciated by a person skilled in the art that the host cell may be deficient in a combination of genes involved in amino acid synthesis.

[0099] The gene involved in amino acid degradation may be but is not limited to *tnaA*.

[00100] It will generally be understood that the host cell may be deficient in one or more of the *ack* gene, *pta* gene, genes of the amino acid synthesis, oxidation of terpenoids and/or amino acid degradation in various combinations. In one example, the host cell is deficient in *aroA*, *serC*, *yjgB*, *tnaA*, and *ack*. In another example the host cell is deficient in *aroA*, *serC*, *tnaA* and *pta* genes. In a preferred example, the host cell is deficient in *aroA*, *serC*, *yjgB* and *tnaA* genes. In another preferred example, the host cell is deficient in *aroA*, *serC* and *tnaA* genes

[00101] The host cell may be modified to be deficient in *ack* gene, *pta* gene, genes of the amino acid synthesis, oxidation of terpenoids and amino acid degradation by genomic modification methods. Reduction in gene expression levels may be carried out using genomic modification methods including but is not limited to siRNA knockdown and shRNA knockdown. The genes may be deleted from the genome of the host cell using genomic modification methods including but is not limited to CRISPR-Cas9, FRT gene deletion, TALEN-mediated gene knockout.

[00102] As described herein, the host cell of the present invention may be a bacterial cell. The bacterial cell may be but is not limited to *Escherichia*, *Pantoea*, *Bacillus*, *Corynebacterium*, *Paracoccus*, *Streptomyces* and *Synechococcus*. In a preferred example, the bacterial cell is an *Escherichia coli* cell. It will generally be understood that any industrial bacterium or bacterial cell may be used in the present invention.

[00103] The strain of the *Escherichia coli* cell may be but is not limited to BL21 DE3 strain, K-12(RV308), K-12(HMS174), K-12 substr. MG1655, W strain (ATCC 9637),

JM109(DE3), BW25113, JM109 DE3, Mach1 and any strain comprising T7 RNA polymerase gene. In a preferred example, the *Escherichia coli* cell is a BL21 DE3 strain.

[00104] In another aspect, the present invention refers to an engineered fusion protein produced comprising a diphosphate synthase or prenyltransferase of the mevalonate pathway and a nudix hydrolase as described herein, a diphosphate synthase or prenyltransferase of the mevalonate pathway, a nudix hydrolase and a geranyl synthase enzyme (GES) of the terpene synthase pathway as described herein, or a diphosphate synthase or prenyltransferase of the mevalonate pathway and a GES of the terpene synthase pathway as described herein.

[00105] The polynucleotide sequence encoding the GES of the terpene synthase pathway may be located upstream or downstream of the polynucleotide sequence encoding the diphosphate synthase or prenyltransferase. The polynucleotide sequence encoding the GES of the terpene synthase pathway may be located upstream or downstream of the polynucleotide sequence encoding the gene of the Nudix pathway

[00106] In one example, the GES of the terpene synthase pathway is located between the diphosphate synthase or prenyltransferase and the gene of the Nudix pathway.

[00107] The GES of the terpene synthase pathway may be fused with the diphosphate synthase gene, prenyltransferase gene or the gene of the Nudix pathway. The GES of the terpene synthase pathway may be fused with both the diphosphate synthase gene or prenyltransferase gene, and the gene of the Nudix pathway too. It will generally be understood by a person skilled in the art that the fusion may result from structural rearrangements like translocations and deletions, transcription read-through of neighboring genes, or the trans- and cis-splicing of pre-mRNAs. It will generally be understood that the examples provided in the foregoing are not exhaustive and genetic fusion methods would be acceptable.

[00108] The diphosphate synthase or prenyltransferase of the engineered fusion protein may be upstream or downstream of the nudix hydrolase. It will generally be understood by a person skilled in the art each strand of DNA or RNA has a 5' end and a 3' end, named based on the carbon position on the deoxyribose (or ribose) ring. A person skilled in the art will also understand that the terms "upstream" and "downstream" refer to the orientation that reflects the direction of the synthesis of mRNA and its translation from the 5' end to the 3' end. The term "upstream" refers to the 5' end of the coding strand for the gene in question and the region of the coding strand towards the 3' end is referred to as the downstream.

[00109] The engineered fusion protein may further comprise one or more linker sequences.

[00110] In some examples, the linker sequence of the engineered fusion protein may be located between the nudix hydrolase and the diphosphate synthase or prenyltransferase of the fusion protein, wherein the linker is linked to the C-terminal of the nudix hydrolase and the N-terminal of the diphosphate synthase or prenyltransferase. In another example, the linker is linked to the N-terminal of the nudix hydrolase and the C-terminal of the diphosphate synthase or prenyltransferase.

[00111] In some examples, the linker sequence of the engineered fusion protein may comprise at least 70%, 75%, 80%, 85%, 90%, 95% and 100% sequence identity with SEQ ID NO: 17 or SEQ ID NO: 18.

[00112] In another aspect, the present invention refers to a method of geraniol, geranyl acetate, or geraniol and geranyl acetate production comprising culturing the host cell as described herein in a culture medium. The host cell may be cultured in a suitable culture vessel including but not limited to a tube, a flask or a bioreactor.

[00113] The method of geraniol, geranyl acetate, or geraniol and geranyl acetate production may further comprise the step of isolating geraniol, geranyl acetate, or geraniol and geranyl acetate from the culture medium.

[00114] The method comprises the culturing of the host cell as described herein in a culture medium. The culture medium may comprise but not limited to components in the TB medium and the 2XPY medium. Additional components may be added to the culture medium and include antibiotics, inducers and carbon substrates.

[00115] The antibiotics may be supplemented in the culture medium at the beginning of the culturing process. The antibiotics may be added continuously throughout the culturing process. The antibiotics include kanamycin and spectinomycin.

[00116] The culture medium may be further supplemented by one or more inducers capable of inducing the inducible promoter. The inducer may be added in the culture medium at the beginning of the of the culturing process. The culture medium may be supplemented with the inducer when the host cell has grown to an optical density. The culture medium may be supplemented continuously to the culture medium throughout the culturing process. In another example, the host cell may be cultured in conditions suitable for inducing the inducible promoter.

[00117] Examples of inducers include but are not limited to galactose, lactose or isopropyl β -D-1 thiogalactopyranoside (IPTG). In a preferred example, the inducer is lactose or IPTG.

[00118] The concentration of IPTG may be about 0.01 mM to about 0.15 mM. For example, the concentration of IPTG may be about 0.01 mM, about 0.02 mM, about 0.03 mM, about 0.04 mM, about 0.05 mM, about 0.06 mM, about 0.07 mM, about 0.08 mM, about 0.09 mM, about 0.10 mM, about 0.11 mM, about 0.12 mM, about 0.13 mM, about 0.14 mM and about 0.15 mM. In a preferred example, the concentration of IPTG is about 0.05 mM.

[00119] The culture medium may also comprise at least one carbon substrate which may be but is not limited to glucose, glycerol, lactose and sucrose. A person skilled in the art will understand that the culture medium may contain a single type of carbon substrate or combinations of carbon substrates. In a preferred example, the culture medium comprises lactose, glucose and glycerol.

[00120] The concentration of lactose may be about 5 mM to about 50 mM. For example, the concentration of lactose may be about 5 mM, about 10 mM, about 15 mM, about 20 mM, about 25 mM, about 30 mM, about 35 mM, about 40 mM, about 45 mM and about 50 mM. In a preferred example, the concentration of lactose is about 40 mM.

[00121] The concentration of glucose may be about 2 g/L to about 3 g/L. For example, the concentration of glucose may be about 2.0 g/L, about 2.1 g/L, about 2.2 g/L, about 2.3 g/L, about 2.4 g/L, about 2.5 g/L, about 2.6 g/L, about 2.7 g/L, about 2.8 g/L, about 2.9 g/L and about 3.0 g/L.

[00122] The concentration of glycerol may be about 8 g/L to about 30 g/L. For example, the concentration of glycerol may be about 8 g/L, about 9 g/L, about 10 g/L, about 11 g/L, about 12 g/L, about 13 g/L, about 14 g/L, about 15 g/L, about 16 g/L, about 17 g/L, about 18 g/L, about 19 g/L, about 20 g/L, about 21 g/L, about 22 g/L, about 23 g/L, about 24 g/L, about 25 g/L, about 26 g/L, about 27 g/L, about 28 g/L, about 29 g/L and about 30 g/L.

[00123] In some examples, the culture medium may comprise a nitrogen supplement. The nitrogen supplement may be but is not limited to tryptone, nitrates, ammonium, urea and proteose-peptone.

[00124] In a preferred example, the nitrogen supplement is tryptone. The concentration of tryptone may be about 1 g/L to about 10 g/L. For example, the concentration of tryptone may be about 1 g/L, about 2 g/L, about 3 g/L, about 4 g/L, about 5 g/L, about 6 g/L, about 7 g/L, about 8 g/L, about 9 g/L and about 10 g/L.

[00125] In some examples, the culture medium may comprise an organic solvent. The organic solvent may be but is not limited to dodecane, plant oils, undecane, isoamyl laurate and isopropyl myristate.

[00126] The ratio of dodecane to media may be about 0.2 to about 1.0. For example, the ratio of dodecane to media may be about 0.2, about 0.3, about 0.4, about 0.5, about 0.6, about 0.7, about 0.8, about 0.9 and about 1.0.

[00127] The culture medium may be maintained at a pH of about 6.5 to about 7.5. For example, the pH may be about 6.5, about 6.6, about 6.7, about 6.8, about 6.9, about 7.0, about 7.1, about 7.2, about 7.3, about 7.4 and about 7.5. In a preferred example, the pH is about 7.0.

[00128] The method of geraniol, geranyl acetate, or geraniol and geranyl acetate production in some examples, comprise culturing the host cell in the culture medium for about 1 day, about 2 days, about 3 days, about 4 days, about 5 days, about 6 days or about 7 days. In a preferred embodiment, the host cell is cultured in the culture medium for about 3 days or about 4 days.

[00129] In one example, after 3 days of cultivation, the yield of geraniol production in a tube may be between about 292 to about 684 mg/L. For example, the yield of geraniol production in a tube may be about 300 mg/L, about 325 mg/L, about 350 mg/L, about 375 mg/L, about 400 mg/L, about 425 mg/L, about 450 mg/L, about 475 mg/L, about 500 mg/L, about 525 mg/L, about 550 mg/L, about 575 mg/L, about 600 mg/L, about 625 mg/L, about 650 mg/L, about 675 mg/L and about 700 mg/L.

[00130] In one example, after 3 days of cultivation, the yield of geraniol production in a flask may be up to about 907 mg/L. For example, the yield of geraniol production in a flask may be about 50 mg/L, about 100 mg/L, about 150 mg/L, about 200 mg/L, about 250 mg/L, about 300 mg/L, about 350 mg/L, about 400 mg/L, about 450 mg/L, about 500 mg/L, about 550 mg/L, about 600 mg/L, about 650 mg/L, about 700 mg/L, about 750 mg/L, about 800 mg/L, about 850 mg/L and about 900 mg/L.

[00131] In one example, the carbon yield may be at least 24%, at least 30%, at least 35%, at least 40%, at least 45%, at least 50%, at least 55%, at least 60%, at least 65%, at least 70%, at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, and wherein the carbon yield is calculated as a ratio of product obtained and total metabolizable carbon sources used.

[00132] The host cell may be cultured in a batch fermentation culture medium or a fed-batch fermentation culture medium.

[00133] The batch fermentation culture medium or a fed-batch fermentation culture medium may comprise but not limited to components in the TB medium and the 2XPY medium. The components that may be added to the culture medium include one or more antibiotics, one or more inducers, one or more carbon substrates and/or one or more organic solvents.

[00134] The antibiotics may be supplemented in the culture medium at the beginning of the culturing process. The antibiotics may be added continuously throughout the culturing process. The antibiotics include kanamycin and spectinomycin.

[00135] The inducer in the culture medium capable of inducing the inducible promoter may be but is not limited to galactose, lactose or isopropyl β -D-1 thiogalactopyranoside (IPTG). In a preferred example, the inducer is lactose or IPTG.

[00136] The at least one carbon substrate may be but is not limited to glucose, glycerol, lactose and sucrose. In some examples, a person skilled in the art will understand that the culture medium may contain a combination of carbon substrates.

[00137] The organic solvent in the culture medium may be but is not limited to dodecane, plant oils, undecane, isoamyl laurate and isopropyl myristate.

[00138] In some examples, the culture medium may comprise a nitrogen supplement. The nitrogen supplement may be but is not limited to tryptone, nitrates, ammonium, urea and proteose-peptone.

[00139] In one example, the batch fermentation culture medium may comprise glucose, glycerol, lactose and IPTG.

[00140] The concentration of glucose in the batch fermentation culture medium may be about 1 to about 10 g/L. For example, the concentration of glucose may be about 1 g/L, about 2 g/L, about 3 g/L, about 4 g/L, about 5 g/L, about 6 g/L, about 7 g/L, about 8 g/L, about 9 g/L and about 10 g/L. In a preferred example, the concentration of glucose in the batch fermentation culture medium is about 1 to about 2 g/L

[00141] The concentration of glycerol in the batch fermentation culture medium may be about 1 to about 30 g/L. For example, the concentration of glycerol may be about 1 g/L, about 2 g/L, about 3 g/L, about 4 g/L, about 5 g/L, about 6 g/L, about 7 g/L, about 8 g/L, about 9 g/L, about 10 g/L, about 11 g/L, about 12 g/L, about 13 g/L, about 14 g/L, about 15 g/L, about 16 g/L, about 17 g/L, about 18 g/L, about 19 g/L, about 20 g/L, about 21 g/L, about 22 g/L, about 23 g/L, about 24 g/L, about 25 g/L, about 26 g/L, about 27 g/L, about 28

g/L, about 29 g/L and about 30 g/L. In a preferred example, the concentration of glycerol in the batch fermentation culture medium is about 8 to about 10 g/L.

[00142] The concentration of lactose in the batch fermentation culture medium may be about 5 mM to about 50 mM. For example, the concentration of lactose may be about 5 mM, about 10 mM, about 15 mM, about 20 mM, about 25 mM, about 30 mM, about 35 mM, about 40 mM, about 45 mM and about 50 mM. In a preferred example, the concentration of lactose is about 40 mM.

[00143] The concentration of IPTG in the batch fermentation culture medium may be about 0.01 mM to about 0.2 mM. For example, the concentration of IPTG may be about 0.01 mM, about 0.02 mM, about 0.03 mM, about 0.04 mM, about 0.05 mM, about 0.06 mM, about 0.07 mM, about 0.08 mM, about 0.09 mM, about 0.10 mM, about 0.11 mM, about 0.12 mM, about 0.13 mM, about 0.14 mM, about 0.15 mM, about 0.16 mM, about 0.17 mM, about 0.18 mM, about 0.19 mM and about 0.20 mM. In a preferred example, the concentration of IPTG is about 0.10 mM.

[00144] The batch fermentation culture medium may be supplemented with carbon substrates and IPTG when the host cell has grown to an optical density (OD_{600}) of about 0.5 to about 2. The optical density may be about 0.5, about 0.6, about 0.7, about 0.8, about 0.9, about 1.0, about 1.1, about 1.2, about 1.3, about 1.4, about 1.5, about 1.6, about 1.7, about 1.8, about 1.9, and about 2.0. In a preferred example, the OD_{600} is about 1.0.

[00145] In one example, the fed-batch fermentation culture medium may comprise IPTG, magnesium sulphate and glucose or glycerol.

[00146] The concentration of IPTG in the fed-batch fermentation culture medium may be about 0.01 mM to about 0.2 mM. For example, the concentration of IPTG may be about 0.01 mM, about 0.02 mM, about 0.03 mM, about 0.04 mM, about 0.05 mM, about 0.06 mM, about 0.07 mM, about 0.08 mM, about 0.09 mM, about 0.10 mM, about 0.11 mM, about 0.12 mM, about 0.13 mM, about 0.14 mM, about 0.15 mM, about 0.16 mM, about 0.17 mM, about 0.18 mM, about 0.19 mM and about 0.20 mM. In a preferred example, the concentration of IPTG is about 0.1 mM.

[00147] The concentration of glucose or glycerol in the fed-batch fermentation culture medium may be about 200 to about 750 g/L. For example, the concentration of glucose or glycerol may be about 200 g/L, about 225 g/L, about 250 g/L, about 275 g/L, about 300 g/L, about 325 g/L, about 350 g/L, about 375 g/L, about 400 g/L, about 425 g/L, about 450 g/L,

about 475 g/L, about 500 g/L, about 525 g/L, about 550 g/L, about 575 g/L, about 600 g/L, about 625 g/L, about 650 g/L, about 675 g/L, about 700 g/L, about 725 g/L and about 750 g/L. In a preferred example, the concentration of glucose or glycerol in the fed-batch fermentation culture medium may be about 500 g/L.

[00148] The concentration of magnesium sulphate in the fed-batch fermentation culture medium may be about 1 to about 10 g/L. For example, the concentration of magnesium sulphate may be about 1 g/L, about 2 g/L, about 3 g/L, about 4 g/L, about 5 g/L, about 6 g/L, about 7 g/L, about 8 g/L, about 9 g/L and about 10 g/L. In a preferred example, the concentration of magnesium sulphate in the fed-batch fermentation culture medium may be about 5 g/L.

[00149] The fed-batch fermentation culture medium may be supplemented with the carbon substrates and magnesium sulphate continuously throughout the process at a feeding rate of between about 0.6 to about 6 g/L/h/reactor volume. For example, the feeding rate may be about 0.6 g/L/h/reactor volume, about 1.0 g/L/h/reactor volume, about 1.5 g/L/h/reactor volume, about 2.0 g/L/h/reactor volume, about 2.5 g/L/h/reactor volume, about 3.0 g/L/h/reactor volume, about 3.5 g/L/h/reactor volume, about 4.0 g/L/h/reactor volume, about 4.5 g/L/h/reactor volume, about 5.0 g/L/h/reactor volume, about 5.5 g/L/h/reactor volume and about 6.0 g/L/h/reactor volume.

[00150] The fed-batch fermentation culture medium may be further supplemented with IPTG when the host cell has grown to an optical density (OD₆₀₀) of about 10 to about 60. The optical density may be about 10, about 15, about 20, about 25, about 30, about 35, about 40, about 45, about 50, about 55 and about 60. In a preferred example, the OD₆₀₀ is about 30 to about 50.

[00151] The batch fermentation culture medium or a fed-batch fermentation culture medium may be maintained at a pH of about 6.5 to about 7.5. For example, the pH may be about 6.5, about 6.6, about 6.7, about 6.8, about 6.9, about 7.0, about 7.1, about 7.2, about 7.3, about 7.4 and about 7.5. In a preferred example, the pH is about 7.0.

[00152] In one example, the yield of geraniol production in the fed-batch fermentation may be at least 1 g/L. For example, the yield of geraniol production in the fed-batch fermentation may be at least 1 g/L, at least 5 g/L, at least 10 g/L, at least 15 g/L, at least 20 g/L, at least 25 g/L, at least 30 g/L, at least 35 g/L, at least 40 g/L, at least 45 g/L and at least 50 g/L.

[00153] In one example, the yield of geranyl acetate production in the fed-batch fermentation may be about 4 g/L to about 40 g/L. For example, the yield of geranyl acetate production in the fed-batch fermentation is about 4 g/L, about 5 g/L, about 10 g/L, about 15 g/L, about 20 g/L, about 25 g/L, about 30 g/L, about 35 g/L and about 40 g/L. [

[00154] In another aspect, the present invention refers to a kit producing geraniol, geranyl acetate, or geraniol and geranyl acetate, wherein the kit comprises the host cell as described herein with instructions for use.

[00155] In some examples, the host cell in the kit may be dissolved in solution or lyophilized.

[00156] In some examples, the host cell may be preserved by deep freezing.

[00157] The invention illustratively described herein may suitably be practiced in the absence of any element or elements, limitation or limitations, not specifically disclosed herein. Thus, for example, the terms "comprising", "including", "containing", etc. shall be read expansively and without limitation. Additionally, the terms and expressions employed herein have been used as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed. Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments and optional features, modification and variation of the inventions embodied therein herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this invention.

[00158] The invention has been described broadly and generically herein. Each of the narrower species and subgeneric groupings falling within the generic disclosure also form part of the invention. This includes the generic description of the invention with a proviso or negative limitation removing any subject matter from the genus, regardless of whether or not the excised material is specifically recited herein.

[00159] Other embodiments are within the following claims and non-limiting examples. In addition, where features or aspects of the invention are described in terms of Markush groups, those skilled in the art will recognize that the invention is also thereby described in terms of any individual member or subgroup of members of the Markush group.

EXPERIMENTAL SECTION

[00160] Non-limiting examples of the invention and comparative examples will be further described in greater detail by reference to specific Examples, which should not be construed as in any way limiting the scope of the invention.

[00161] *Materials & Methods*

[00162] Strain and plasmid construction

[00163] *E. coli* BL21 DE3 strain was used for monoterpenoid production. Plasmids were constructed by combining the operons *hmgS-atoB-hmgR* and *mevK-pmk-pmd-idi* into the same p15A-spec (L2-8) vector with three different promoters (TM1, TM2 and TM3). The new plasmid set includes 9 plasmids, spk001-spk009 (Table 1). The plasmid carrying RhNUDX1 and various GPPS (AgGPPS, ispA_S80F and ERG20 mutants) was cloned into p15A-kan vector (as spk001-002d, Table 1). The best geraniol strain carried two plasmids sps004 and spk002 (RhNUDX1 and AgGPPS). For geranyl acetate plasmid, the gene *RhAAT1* was inserted into spk002 after AgGPPS, and the resulting plasmid was named spk003. The genes *tnaA*, *YjgB* and *ackA-pta* were deleted with the CRISPR-Cas9 method as previously described using the gRNA listed in Table 2. The plasmids, oligos and strains used in this study were summarized in Tables 1, 2 and 3, respectively.

[00164] **Table 1. Plasmid information**

Serial #	Plasmids ¹	Promoters of modules ²			Remarks ³
		M1 ⁴	M2 ⁵	M3 ⁶	
1	sps001	TM1	TM1		
2	sps002	TM1	TM2		
3	sps003	TM1	TM3		
4	sps004	TM2	TM1		
5	sps005	TM2	TM2		
6	sps006	TM2	TM3		
7	sps007	TM3	TM1		
8	sps008	TM3	TM2		
9	sps009	TM3	TM3		
10	spk01			TM1	Only Nudx1 is in the M3 module
11	spk02			TM1	RBS4-GPPS1
12	spk02_aroA ₂			TM1	RBS5-GPPS1
13	spk02_tGPPS			TM1	RBS1-GPPS2
	spk02_tGPPS2			TM1	RBS2-GPPS2
14	spk02_s1			TM1	small linkers, fusion of NUDX1

					and GPPS1
15	spk02_s2			TM1	small linkers, fusion of NUDX1 and GPPS1
16	spk02_m1			TM1	medium linkers, fusion of NUDX1 and GPPS1
17	spk02_m2			TM1	medium linkers, fusion of NUDX1 and GPPS1
18	spk3			TM1	GPPS3
19	spk3a			TM1	RBS3-GPPS3
20	spk3b			TM1	GPPS3a
21	spk3c			TM1	GPPS3b
22	spk3d			TM1	GPPS3c
23	spk04			TM1	spk02 + marA
24	spk04a			TM1	spk02_tGPPS + marA
25	spk05			TM1	nudI and GPPS1
26	spk06			TM1	ObGES and GPPS1
27	spk06a			TM1	cmR-ObGES and GPPS1
28	spk06b			TM1	cmR-ObGES, GPPS1 and GPPS2
29	spk08			TM1	NUDX1, ObGES, GPPS1 and GPPS2
30	spk09			TM1	NUDX1 and GPPS2
31	spk10			TM1	NUDX1, GPPS1 and GPPS2
32	spk11			TM1	NUDX1, GPPS1 and RhAAT1
33	spk12			TM1	NUDX1, GPPS2 and RhAAT1

¹ sps001-009 expressing two modules M1 and M2.

² The relative strengths for the TM1, TM2, TM3 promoters were about 92%, 37% and 16%, respectively to that of the T7 promoter.

³ GPPSs used in this study. GPPS1 – ispA_S80F from *Escherichia coli*; GPPS2- truncated AgGPPS from *Abies grandis*; GPPS3 – Erg20_N127W from *Saccharomyces cerevisiae*; GPPS3a - Erg20_F96W; GPPS3c - Erg20_F96W_N127W. RBS information is in Table 2.

⁴ The module M1 contains the three genes - HmgS, thmR and atoB

⁵ The module M2 contains the three genes - mevK, pmk, pmd, and idi

⁶ The module M3 have different design, details are shown in Remarks

[00165] **Table 2. Oligo sequence used in this study**

Name	Sequence	
spk2m1-f	GGTAGTGGCGGCGGTGGCAGCGGTGGCCCGGGCAGCatgcatcatcatcaccatcacgag	SEQ ID NO: 37
spk2m1-r	CACCGCCGCCACTACCACCGCCGCCGCTGCCACCGCCACCAGTCGGGAACGGGTTGAAGC	SEQ ID NO: 38
spk2s1-f	GCGGTGGCCCGGGCAGCatgcatcatcatcaccatcacgag	SEQ ID NO: 39
spk2s1-r	GCCCGGGCCACCAGCTGCCACCGCCACCAGTCGGGAACGGGTTGAAGC	SEQ ID NO: 40
yjbB gRNA	TATGCCGCAAAAGAAGCGGG	SEQ ID NO: 41

tnaA gRNA	CACGAATGCGGAACGGTTCA	SEQ ID NO: 42
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[00166] **Table 3. Strain information**

Strain ID	Host	Plasmids	Products
#G1	BL21	sps005 and spk01	geraniol
#G2	BL21	sps005 and spk02	geraniol
#G3	BL21	spk02 and sps01	geraniol
#G4	BL21	spk02 and sps01	geraniol
#G5	BL21	spk02 and sps02	geraniol
#G6	BL21	spk02 and sps02	geraniol
#G7	BL21	spk02 and sps03	geraniol
#G8	BL21	spk02 and sps03	geraniol
#G9	BL21	spk02 and sps04	geraniol
#G10	BL21	spk02 and sps04	geraniol
#G11	BL21	spk02 and sps05	geraniol
#G12	BL21	spk02 and sps05	geraniol
#G13	BL21	spk02 and sps06	geraniol
#G14	BL21	spk02 and sps06	geraniol
#G15	BL21	spk02 and sps07	geraniol
#G16	BL21	spk02 and sps07	geraniol
#G17	BL21	spk02 and sps08	geraniol
#G18	BL21	spk02 and sps09	geraniol
#G19	BL21	spk02 and sps09	geraniol
#G20	BL21	spk02_aroA2 and sps08	geraniol
#G21	BL21	spk02_aroA2 and sps08	geraniol
#G22	BL21	spk02_aroA3 and sps08	geraniol
#G23	BL21	spk02_aroA3 and sps08	geraniol
#G24	BL21	spk02_aroA4 and sps08	geraniol
#G25	BL21	spk02_aroA4 and sps08	geraniol
#G26	BL21	spk02_aroA5 and sps08	geraniol
#G27	BL21	spk02_aroA5 and sps08	geraniol
#G28	BL21	spk02_tGPPS and sps08	geraniol
#G29	BL21	spk02_tGPPS and sps08	geraniol
#G30	BL21	spk02_s1 and sps08	geraniol
#G31	BL21	spk02_s1 and sps08	geraniol
#G32	BL21	spk02_m1 and sps08	geraniol
#G33	BL21	spk02_m1 and sps08	geraniol
#G34	BL21	spk03 and sps08	geraniol
#G35	BL21	spk03 and sps08	geraniol
#G36	BL21	spk03a and sps08	geraniol
#G37	BL21	spk03a and sps08	geraniol
#G38	BL21	spk03b and sps08	geraniol
#G39	BL21	spk03b and sps08	geraniol

#G40	BL21	spk03c and sps08	geraniol
#G41	BL21	spk03c and sps08	geraniol
#G42	BL21	spk03d and sps08	geraniol
#G43	BL21	spk03d and sps08	geraniol
#G44	BL21	spk04 and sps08	geraniol
#G45	BL21	spk04 and sps08	geraniol
#G46	BL21	spk04a and sps08	geraniol
#G47	BL21	spk04a and sps08	geraniol
#G48	BL21	spk05 and sps08	geraniol
#G49	BL21	spk05 and sps08	geraniol
#G50	BL21	spk06 and sps08	geraniol
#G51	BL21	spk06 and sps08	geraniol
#G52	BL21	spk06a and sps08	geraniol
#G53	BL21	spk06a and sps08	geraniol
#G54	BL21	spk06b and sps08	geraniol
#G55	BL21	spk06b and sps08	geraniol
#G56	BL21	spk07 and sps08	geraniol
#G57	BL21	spk07 and sps08	geraniol
#G58	BL21	spk07a and sps08	geraniol
#G59	BL21	spk07a and sps08	geraniol
#G60	BL21	spk08 and sps08	geraniol
#G61	BL21	spk08 and sps08	geraniol
#G62	BL21	spk09 and sps08	geraniol
#G63	BL21	spk09 and sps08	geraniol
#G64	BL21	spk09a and sps08	geraniol
#G65	BL21	spk09a and sps08	geraniol
#G66	BL21	spk10 and sps08	geraniol
#G67	BL21	spk10 and sps08	geraniol
#G68	BL21	sps04 and spk09	geraniol
#G69	BL21	sps04 and spk09	geraniol
#G70	BL21	sps01 and spk09	geraniol
#G71	BL21	sps01 and spk09	geraniol
#G72	BL21 Δ aroA Δ serC	sps08 and spk02	geraniol
#G73	BL21 Δ aroA Δ serC	sps08 and spk02	geraniol
#G74	BL21 Δ aroA Δ serC	sps08 and spk02	geraniol
#G75	BL21 Δ aroA Δ serC Δ yjgB	sps08 and spk02	geraniol
#G76	BL21 Δ aroA Δ serC Δ yjgB	sps08 and spk02	geraniol
#G77	BL21 Δ aroA Δ serC Δ yjgB	sps08 and spk02	geraniol
#G78	BL21 Δ aroA Δ serC	sps04 and spk09	geraniol
#G79	BL21 Δ aroA Δ serC	sps04 and spk09	geraniol
#G80	BL21 Δ aroA Δ serC	sps04 and spk09	geraniol
#G81	BL21 Δ aroA Δ serC Δ yjgB	sps04 and spk09	geraniol
#G82	BL21 Δ aroA Δ serC Δ yjgB	sps04 and spk09	geraniol

#G83	BL21 Δ aroA Δ serC Δ yjgB	sps04 and spk09	geraniol
#G84	BL21 Δ aroA Δ serC	sps01 and spk09	geraniol
#G85	BL21 Δ aroA Δ serC	sps01 and spk09	geraniol
#G86	BL21 Δ aroA Δ serC	sps01 and spk09	geraniol
#G87	BL21 Δ aroA Δ serC Δ yjgB	sps01 and spk09	geraniol
#G88	BL21 Δ aroA Δ serC Δ yjgB	sps01 and spk09	geraniol
#G89	BL21 Δ aroA Δ serC Δ yjgB	sps01 and spk09	geraniol
#G90	BL21	sps08 and spk11	geranyl acetate
#G91	BL21	sps08 and spk11	geranyl acetate
#G92	BL21	sps08 and spk11	geranyl acetate
#G93	BL21	sps01 and spk11	geranyl acetate
#G94	BL21	sps01 and spk11	geranyl acetate
#G95	BL21	sps01 and spk11	geranyl acetate
#G96	BL21	sps04 and spk11	geranyl acetate
#G97	BL21	sps04 and spk11	geranyl acetate
#G98	BL21	sps04 and spk11	geranyl acetate
#G99	MG1655 T7	sps08 and spk02	geraniol
#G100	BL21 Δ tnaA	sps04 and spk02	geraniol
#G101	BL21	sps04 and spk12	geranyl acetate
#G102	BL21 Δ yjgB Δ tnaA	sps04 and spk02	geraniol
#G103	BL21 Δ yjgB Δ tnaA	sps04 and spk11	geranyl acetate

[00167] Under the CRISPR-Cas9 method, different pTarget plasmids with various sgRNAs were obtained by restriction free (RF) cloning methods. The asymmetric homology arm (HA) donor DNA was amplified from the E. coli genome using iProof PCR mix (BioRad) and column purified by Zymoclean Gel DNA Recovery Kit (Zymo Research). Generally, 100–200 ng/ μ l of donor DNA in 30 μ l can be obtained in a 100 μ l PCR reaction. For the primer design, the forward primer is a fusion of the upstream homology arm (40–45 bp) sequence and downstream homology arm (15–20 bp) sequence. The 15–20 bp downstream homology arm is for annealing during initial cycles of PCR, and its length is chosen based on $T_m \sim 50^\circ\text{C}$. The total length of forward primer is kept at 60 bp. The reverse primer is a normal PCR primer about 15–20 bp with $T_m \sim 50^\circ\text{C}$. The length of downstream homology arms can be varied based on the reverse primer chosen. The downstream homology arm length was kept at 500 bp. BL21 chemical competent cells were prepared using the Mix & Go! E. coli Transformation Kit (Zymo Research). For the construction of BL21 cells harbouring the pCas plasmid, 10 μ l of cells were mixed with 50 ng/ μ l of pCas plasmid and heat shocked at 42°C for 45 s. The cell was rescued in 200 μ l of LB broth, at 30°C , 300 rpm for 1 h before spreading onto LB agar containing kanamycin (50 $\mu\text{g/ml}$) and incubated

overnight at 30 °C. A single colony was picked and inoculated into 1 ml LB medium containing kanamycin (50 µg/ml) and incubated at 30 °C, 300 rpm overnight for making electrocompetent cells. For the preparation of electrocompetent cells, OD₆₀₀ 0.1 of the overnight BL21 cell culture harbouring the pCas plasmid was inoculated into 10 ml of LB medium containing kanamycin (50 µg/ml) and cultured at 30 °C, 300 rpm. 20 mM arabinose was added to the culture at OD₆₀₀ 0.2 for the induction of λ-Red recombinase. The bacterial cells were harvested at OD₆₀₀ 0.6 and centrifuged at 3800 rpm for 10 min at 4 °C. The supernatant was discarded and the cells were re-suspended in 10 ml 10% glycerol. The washing step was repeated twice. The electrocompetent cells was then suspended in 100 µl of 10% glycerol. For electroporation, 20 µl of cells were mixed with 100 ng/µl of pTarget plasmid and 100 ng of donor DNA in the 1 mm Gene Pulser cuvette (Bio-Rad) and electroporated at 1.8 kV. The cells were rescued in 500 µl of LB broth, at 30 °C, 300 rpm for 3 h before spreading onto LB agar containing kanamycin (50 µg/ml) and spectinomycin (100 µg/ml) and incubated overnight at 30 °C. Colonies were screened by colony PCR using 2×PCRBIO Ultra Mix (PCR Biosystems) along with an unedited BL21 strain as control. The plasmids, oligos and strains used in this study are summarized in Tables 1, 2 and 3, respectively.

[00168] Enzyme fusion

[00169] The RhNUDX1 was fused with ispA_S80F with the orientation of RhNUDX1-ispA_S80F. Two linkers (short, GGGGSGGPGS (SEQ ID NO: 17); and medium, GGGGSGGGGSGGGGSGGPGS (SEQ ID NO: 18) were used (Table 4). The two fusion proteins were obtained using the primers (spk2m1-f/r and spk2s1-f/r) in Table 2 with the in-house cloning method modified from Agilent QuikChange II method. Specifically, the PCR fragments with 14 bps complementary extensions to the vector ends, are amplified using the iProof™ High-Fidelity DNA Polymerase. A gel check is done to ensure amplified product size is correct. The amplified DNA fragments undergo 3h DpnI treatment. Thereafter the PCR product is purified using Omega PCR Cycle Pure Kits. It is then treated with Takara infusion cloning mix for 15 mins at 50° C. 1µL of the treated product is transformed into 20µL of DH5 α competent cells, rescued for 1h and then plated on LB plate supplemented with 50µg/mL of kanamycin.

[00170] **Table 4. RBS sequence for various GPPS used in this study**

No.	GPPS	RBS ID	RBS	Protein sequence (N-term 35NT)
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1	AgGPPS (GPPS2)	RBS- 1	Gagatataataacgagataaggaaaagacaaa (SEQ ID NO: 43)	Atgttcgatttcaacaaatacatggacagcaaagc catga (SEQ ID NO: 44)
2	AgGPPS (GPPS2)	RBS- 2	gccgagatataataacgagataaggaaaagacaaa (SEQ ID NO: 45)	Atgttcgatttcaacaaatacatggacagcaaagc catga (SEQ ID NO: 46)
3	ERG20_N 127W (GPPS3)	RBS- 3	Tgccaaactttaaagaggcctaaa (SEQ ID NO: 47)	Atggcttcagaaaaagaaattaggagagagagat tcttga (SEQ ID NO: 48)
4	ERG20_N 127W (GPPS3)	RBS- 2	gccgagatataataacgagataaggaaaagacaaa (SEQ ID NO: 49)	Atggcttcagaaaaagaaattaggagagagagat tcttga (SEQ ID NO: 50)
5	ERG20_96 _127 (GPPS3b)	RBS- 3	Tgccaaactttaaagaggcctaaa (SEQ ID NO: 51)	Atggcttcagaaaaagaaattaggagagagagat tcttga (SEQ ID NO: 52)
6	ERG20_96 _127 (GPPS3b)	RBS- 2	gccgagatataataacgagataaggaaaagacaaa (SEQ ID NO: 53)	Atggcttcagaaaaagaaattaggagagagagat tcttga (SEQ ID NO: 54)
7	IspA (GPPS1)	RBS- 4	Tttgtttaactttaagaaggagatatcat (SEQ ID NO: 55)	Atgcatcatcatcaccatcacgagctcgactttcgcg cagc (SEQ ID NO: 56)
8	IspA (GPPS1)	RBS- 5	Tttgtttaactttaacaaggaggagatcat (SEQ ID NO: 57)	Atgcatcatcatcaccatcacgagctcgactttcgcg cagc (SEQ ID NO: 58)

[00171] Media and culture conditions

[00172] Chemically defined medium (or defined medium) contained 10 g/L glucose, 2 g/L (NH₄)₂SO₄, 4.2 g/L KH₂PO₄, 11.24 g/L K₂HPO₄, 1.7 g/L citric acid, 0.5 g/L MgSO₄ and 10 ml/l trace element solution, pH 7.0. The trace element solution (100X) contained 0.25 g/L CoCl₂·6H₂O, 1.5 g/L MnSO₄·4H₂O, 0.15 g/L CuSO₄·2H₂O, 0.3 g/L H₃BO₃, 0.25 g/L Na₂MoO₄·2H₂O, 0.8 g/L Zn(CH₃COO)₂, 5 g/L Fe(III) citrate and 0.84 g/L EDTA, pH 8.0.

[00173] Semi chemically defined medium was the same as defined medium except that 2 g/L tryptone was supplemented for the geraniol production in flasks.

[00174] Auto-induction defined medium (AIDM): 2-3 g/L glucose, 8-30 g/L glycerol and 5-50 mM lactose (as inducer). The rest components were the same as defined medium. Terrific Broth (TB, 12 g/L tryptone, 24 g/L yeast extract, 2.31g/L KH₂PO₄, and 12.54g/L K₂HPO₄) containing 2-3 g/L glucose and 20-30 g/L glycerol was used for geranyl acetate production. For auto-induction of geranyl acetate, 5-50mM lactose was used as inducer.

[00175] For strain and abiotic optimization, the cells were grown in 1 mL of defined or AID medium in 14 ml BD Falcon™ tube at 28 °C/300 rpm for 3 days. In addition, 200 μL of dodecane was used to extract monoterpenes during cell culture. When using the defined media, cells were initially grown at 37 °C/300 rpm until OD₆₀₀ reached 1-2, induced by 0.01~0.15 mM IPTG, and were then grown at 28 °C/300 rpm for 2 days. For AID media, cells were grown at 28 °C/300 rpm for 3 days and automatically induced by lactose. All the cultures were supplemented with the antibiotics (50 μg/ml kanamycin and 100 μg/ml spectinomycin) to maintain the two plasmids.

[00176] Flasks conditions (100, 200 and 300 rpm).

[00177] For geraniol production, cells were inoculated in 10mL of AIDM or semi chemically defined medium in 125mL baffled flasks at 28 °C, 100-300 rpm for 3 days. 10-100% of dodecane/sunflower oil was used as product extractant. On the other hand, TB auto-induction medium was used for geranyl acetate and was supplemented with 20% dodecane/sunflower oil. The rest of the set up were the same as geraniol.

[00178] All the cultures were supplemented with the antibiotics (50 µg/ml kanamycin and 100 µg/ml spectinomycin) to maintain the two plasmids.

[00179] Bioreactor fermentation

[00180] Both 500 ml Mini Bioreactors and 7L Bioreactor (Applikon Biotechnology) were used with the working volume of 200-400 mL and 2-5L, respectively, in this study. The cells (-80°C stock) were grown in 10 ml defined medium for 48h at 37°C. Two modes were tested. The first mode was auto-induced batch fermentation, in which no additional nutrients were fed but the initial media contained 10 g/L glucose, 14-20 g/L lactose, 50 g/L glycerol, 4-6 g/L of ammonium sulphate and 1.5 g/L MgSO₄, other components were kept the same as in the defined media. The second mode was fed-batch fermentation, in which the process was similarly as previously described. Briefly, once OD reached about 5-6, feed solution (500 g/L glucose and 5 g/L MgSO₄) was added into the bioreactor in an exponential manner calculated on the growth rate of 0.6 h⁻¹. The cells were induced by 0.1 mM IPTG when OD reached about 30-50 (16-18h from inoculation). After induction, a constant feeding rate at 7.5 g/L/h of glucose and 0.075 g/L/h of MgSO₄ was maintained. The culture temperature was adjusted to 30°C and 15-20 % (v/v) of dodecane was supplemented into the bioreactor. During the fermentation, dissolved oxygen level was maintained at 30% (800 – 2000 r.p.m) by supplying filtered air at a gas rate of 1.5 vvm. The pH of the culture was controlled at 7.0 with 28% ammonia solution. The fed-batch experiments were performed in the defined media without any antibiotics.

[00181] Theoretic yield of geraniol and geranyl acetate

[00182] The production of isoprene or isopentenyl pyrophosphate (IPP) via the mevalonate pathway under aerobic fermentation requires three acetyl coenzyme A (AcCoA), three ATP and two NAD(P)H. Therefore,

(1) 1.5 Glucose (or 3 glycerol) + 2 O₂ → 3 AcCoA + 3 ATP + 3 CO₂ + 6 NAD(P)H
(glycolysis)

(2) 3 AcCoA + 2 NAD(P)H → MVA

(3) $\text{MVA} + 3 \text{ ATP} \rightarrow \text{IPP} + \text{CO}_2$

(4) $2 \text{ IPP} \rightarrow \text{Geraniol}$

(5) $\text{Geraniol} + \text{AcCoA} \rightarrow \text{Geranyl acetate}$

Overall, $3 \text{ Glucose (or 6 glycerol)} + 4 \text{ O}_2 \rightarrow \text{Geraniol} + 8 \text{ CO}_2 + 10 \text{ H}_2\text{O}$, and $7/2 \text{ Glucose (or 7 glycerol)} + 14/3 \text{ O}_2 \rightarrow \text{geranyl acetate} + 9 \text{ CO}_2 + 10 \text{ H}_2\text{O}$, therefore, geraniol and geranyl acetate mass yields on glucose or glycerol are 28.6% and 31.1%, respectively.

[00183] Quantification of terpenoids

[00184] The terpenoid samples were prepared by diluting 0.5-20 μl of organic layer into 1000 μl hexane. The samples were analyzed on an Agilent 7890 gas chromatography equipped with an Agilent 5977B MSD. Samples were injected into Agilent VF-WAXms column with a split ratio of 40:1 at 240 $^{\circ}\text{C}$. The oven program started at 100 $^{\circ}\text{C}$ for 1 min, was raised up to 150 $^{\circ}\text{C}$ at 50 $^{\circ}\text{C}/\text{min}$, then to 240 $^{\circ}\text{C}$ at 15 $^{\circ}\text{C}/\text{min}$ and maintained at 240 $^{\circ}\text{C}$ for another 2 min. The compound concentrations were calculated by interpolating with a standard curve prepared by authentic terpene standards (MilliporeSigma, Singapore). As the citral standard has two peaks (α - and β -citral), their concentrations were estimated based on the relative ratio of their GC chromatogram peak areas. Mass spectrometer was operated in EI mode with full scan analysis (m/z 30–300, 2 spectra/s).

[00185] *Results*

[00186] In-vitro characterization of RhNUDX1

[00187] Before using RhNUDX1 for in vivo production of geraniol, RhNUDX1 was first expressed in *E. coli* BL21 strain and the enzyme was purified. Based on the characterization, the k_{cat} and K_m values of the purified RhNUDX1 (~65.3% purity, Figure 2A) are $0.36 \pm 0.07 \text{ s}^{-1}$ and $46.4 \pm 4.4 \text{ }\mu\text{M}$, respectively. Here, the k_{cat} and K_m values are higher than previously reported ones (Table 5), which is possibly because that NusA-RhNUDX1 fusion protein was used in previous study, while the present study used the wildtype RhNUDX1 for enzyme characterization. In both cases, the k_{cat}/K_m values are comparable or even better than that of the GES from *Ocimum basilicum* (sweet basil) (Table 5). The optimal pH, and RhNUDX1 has highest *in vitro* activity at pH of 8 and it completely loses activity when pH drops below 6 (Figure 2B).

[00188] **Table 5. Enzymes information.**

Enzymes	RhNUDX1	NudI	ObGES	CtGES	CaGES
UniProt	JQ820249	P52006	AY362553	CAD29734	ALL56347
Accession no.					

Enzyme name	GPP phosphohydrolase	Nucleoside triphosphatase NudI	Geraniol synthase	Geraniol synthase	Geraniol synthase
Organism	Rosa hybrid cultivar	<i>Escherichia coli</i> (strain K12)	Ocimum basilicum (Sweet Basil)	Cinnamomum tenuipile	Camptotheca acuminata (Happy tree)
Kingdom	Plant	Bacteria	Plant	Plant	Plant
K_m (μM)	46.4 $\pm$ 4.4 (0.14)	310 $\pm$ 20	21	55.8	89.5
k_{cat} (s⁻¹)	0.36 $\pm$ 0.07 (0.02)	11	0.8	/	/
k_{cat}/K_m (s⁻¹ M⁻¹)	7747 $\pm$ 1736 (1.4 $\times$ 10 ⁵)	3.6 $\times$ 10 ⁵	3.8 $\times$ 10 ⁴	/	/
Reference	This study (Science 349:81-83(2015))	Protein Sci. 2019;28(8):1494-1500	Plant Physiol. 134:370-379(2004)	Phytochemistry 66:285-293(2005)	J. Ind. Microbiol. Biotechnol. 43, 1281-1292 (2016)
GPPS enzymes	ispA	AgGPPS		ERG20	
UniProt Accession no.	P22939	Q8LKJ2		P08524	
Enzyme name	Farnesyl diphosphate Synthase	Geranyl diphosphate synthase		Farnesyl diphosphate synthase	
Organism	<i>Escherichia coli</i> (strain K12)	<i>Abies grandis</i>		<i>Saccharomyces cerevisiae</i>	
Mutations	S80F	Δ N85 ¹		N127W F96W ²	
Functions of mutations	Convert from a FPPS to a GPPS	Remove signal peptide		Convert from a FPPS to a GPPS	
Reference	Biotechnology and Bioengineering 87, 200–212 (2004).	Metabolic Engineering 19 (2013) 33–41		ACS. Synth. Biol. 2014, 3 (5), 298-306.	

¹N-terminal truncation of the 2nd-85th amino acids

²Both single and double mutants were used: N127W, N127W-F96W

[00189] Using RhNUDX1 to produce geraniol in *E. coli*

[00190] Next, RhNUDX1 was expressed in wildtype *E. coli*. Indeed, it produced low amount of geraniol (~1.0 mg/L), also, 0.3 mg/L of geranial (or α -citral) was detected and trace amount of citronellol as by-products (Figure 2C). The mevalonate pathway genes were then overexpressed (Figure 1), to supply more terpene precursors (isopentenyl diphosphate, or IPP and dimethylallyl pyrophosphate, or DMAPP), which boosted the geraniol yield to ~28.2 mg/L. Interestingly, only about 0.04 mg/L of geraniol in *E. coli* cells was detected expressing the mevalonate pathway genes but not RhNUDX1, which could be the result of

native *E. coli* enzymes (e.g., NudB, AphA). As GPP is the intermediate of farnesyl diphosphate (FPP, C15) synthase (*ispA*) enzyme in *E. coli* and quickly converted into FPP, the truncated GPPS from *Abies grandis* (AgGPPS) was further expressed to increase GPP supply (Figure 1). By combining the overexpression of GPPS and mevalonate pathway enzymes, the geraniol production was increased to 92.0 mg/L, together with about 14.8 mg/L of geranial and 0.4 mg/L of citronellol. For all the strains, cell densities were similar at the range of 9.6-11.6 (Figure 2D), indicating that cells were not severely inhibited by the amount of geraniol produced.

[00191] Enhancing the supply of GPP, the monoterpene precursor

[00192] As the overexpression of GPPS resulted in over 3-fold increase in geraniol production, geraniol production might be still limited by GPP. Hence, various GPPSs were explored: AgGPPS, two mutants of FPP synthase (ERG20) from *Saccharomyces cerevisiae*; the mutant of FPP synthase (IspA_S80F) from *E. coli*. Based on previous study, the two ERG20 mutants with a reduced FPP synthase activity were selected for geraniol production: ERG20_N127W and F96W-N127W (or ERG20_96_127). In addition, the ribosomal binding sites (RBSs) of various GPPSs were perturbed (see details in Table 3). The combination of IspA_S80F and RBS-4 was found to have led to the highest production of geraniol, ~128.2 mg/L (Figure 3A). AgGPPS strain produced more geraniol (61-73 mg/L) than the two yeast ERG20 mutants (19-58 mg/L), but less efficient than IspA_S89F. In addition, for eukaryotic GPPSs, RBS-2 led to higher geraniol production than RBS-1 or RBS-3; for bacterial GPPS (IspA_S80F), RBS-4 was better than RBS-5 (Figure 3A). In addition, the biomass for all the strains was similar (OD₆₀₀ values of 8-10), except that AgGPPS with RBS-1 had slightly higher OD₆₀₀ (Figure 3B). These data indicated that the combination of RBS engineering and selection of suitable GPPSs was an effective strategy.

[00193] Pathway balancing and substrate channelling by fusing GPPS with RhNUDX1

[00194] After optimized the GPP supply, the mevalonate pathway was further fine tuned transcriptionally to optimize the supply of terpene precursors (IPP and DMAPP) (Figure 1). By dividing the mevalonate pathway into two modules (upper module: including the genes *atoB*, *hmgS* and truncated *hmgR*; lower module: including the genes *mevK*, *pmK*, *pmd* and *idi*), the pathway was systematically balanced by promoter engineering and identified the best (strain #32 and #31, Figure 3C and D). The strains #32, #31 produced about 181 and 124 mg/L of geraniol, respectively. After the mevalonate pathway balance, substrate channelling

strategy was further tested. The rationale was that in *E. coli*, the native ispA might compete with RhNUDX1 for GPP as their substrate. The fusion of GPPS with RhNUDX1 could facilitate NUDX1 to access GPP immediately after GPP was produced by GPPS. Such strategy has been successfully applied to produce C11 terpenoids with markedly increased yields. With the orientation of RhNUDX1-GPPS, two linkers were compared: short (GGGGSGGPGS (SEQ ID NO: 17)) and medium (GGGGSGGGSGGGSGGPGS (SEQ ID NO: 18)). The geraniol yield of short linker (119 mg/L) was about as twofold high as that of medium linker (64 mg/L). However, both designs have lower yields than the non-fused GPPS and NUDX1 (Figure 4). This could be due to the fusion protein negatively affect the protein folding. Further study is required to understand the underlying mechanism.

[00195] Removing geraniol degrading pathways and abiotic optimization

[00196] Next, the aim was to reduce the production of byproducts (geranial and citronellol). In previous constructed strains, different strains were observed to have different product distribution. Some strains produced up to 30% (the percentage was calculated by normalizing with the total yield of the three monoterpenes: geraniol, geranial and citronellol) of geranial (Figure 2C) and some produced only 2% of geranial (AgGPPS with RBS-2, Figure 3A). Similarly, some strain produced ~8% and some had lower than 1% of citronellol. As geranial is the main by-product, the gene *yjgB* (an alcohol dehydrogenase), which was reported to be responsible for the oxidation of geraniol to geranial, was deleted. Indeed, *yjgB* deletion strain resulted in the increase in geraniol yield by 47% from 119 to 176 mg/L. Simultaneously, the geraniol production was reduced by 70% from 51 to 15 mg/L (Figure 5).

[00197] Interestingly, during these experiments, the carbon sources and inducers were also observed to have dramatic effects on the distribution. Specifically, geraniol percentage in the auto-induction defined media was higher than that in IPTG-induced defined media. In view of the serendipitous finding, the tuning of auto-induction media and inducers was further explored. With the two best strain #32 and #31, series of different concentrations of lactose or IPTG were tested. The geraniol production gradually increased as lactose concentration increases and plateaued at 40 and 30 mM of lactose for strains #32 and #31, respectively (Figure 6A and B). In the meantime, the production of geranial and citronellol decreased and remained lowest at 30-50 mM of lactose (For strain #32, 40-50 mM of lactose; for strain #31, 30-50 mM of lactose). In the best condition at 40mM lactose, strain #32 produced 219, 10, 2.9 mg/L of geraniol, geranial and citronellol, respectively (i.e., the geraniol percentage was

close to 97%). In contrast, the tuning of IPTG dosages had no clear effect on the production of various monoterpenes for both strains #32 and #31 (Figure 6C). Overall, in IPTG-induced defined media, the percentage of geranial (7-18 mg/L, or 15-22%) and citronellol (4.5-9 mg/L or 5-11%) were relatively high and the geraniol production (60-80 mg/L, or 65-80%) was relatively low as compared to lactose auto-induction media.

[00198] Exploration of other enzymes and combinations

[00199] In addition to RhNUDX1 enzyme, the other types of enzymes to produce geraniol were also compared. As the GES from sweet basil (ObGES) has relatively lower K_m value than other GESs from *Cinnamomum tenuipile* and *Camptotheca acuminata* (Happy tree), ObGES was chosen. Also, NudI from *Escherichia coli*, which is more over GPP than many other microbial Nudix hydrolases reported, was selected. However, RhNUDX1 were found to outperform ObGES and NudI for geraniol biosynthesis (Figure 7A and B). The yield of geraniol using RhNUDX1 almost doubled than the other two enzymes. We also tested N-terminal fused ObGES (Cm-Ob) with the chloramphenicol acetyltransferase leader sequence (CM29*) which was reported to boost the yield of geraniol. However, the increase in geraniol yield was very obvious in our study (Figure 7A and B).

[00200] Next, the combination of various enzymes with additional GPPS or co-utilization of RhNUDX1 and ObGES was explored. Though the GPPS was optimized in Figure 3, the GPP supply is speculated to limit the production of geraniol. If so, the expression of additional GPPS could boost the geraniol production. However, in all the designs (RhNUDX1-ispA, ObGES-ispA, or Cb-Ob), additional AgGPPS reduced the geraniol yield by 7-47% (Figure 7A and C). The combination of RhNUDX1-ObGES-ispA-AgGPPS resulted in the lowest production of geraniol (32.4 mg/L). The data indicated: 1) oversupply of GPPS was detrimental, instead of beneficial, for geraniol production; 2) the two enzymes (ObGES and RhNUDX1) seemed to compete with each rather than working synergistically. The new combinations led to perturbation of the overall pathway and reduced geraniol production. Thus, the mevalonate pathway was re-optimized, and obtained a new strain (RhNUDX1-AgGPPS*) whose yield (254 mg/L) was higher the strain 32 (or NUDX1-ispA, Figure 7C and D).

[00201] Biosynthesis of geranyl acetate

[00202] On top of the knowledge learnt from geraniol, the production of geranyl acetate using RhNUDX1 and RhAAT1, the rose alcohol acyltransferase (Figure 1) was explored.

Using the same strategy of pathway balancing, two strains GA11 and GA21 had the highest yield of geranyl acetate (Figure 8A). Further tuning of the lactose concentration resulted in highest yield of geranyl acetate in strain GA11 (686 mg/L, Figure 8B), about 1.7 fold higher than the yield of geraniol (254 mg/L). Similar boosting effect was also reported previously that the esterification of geraniol can increase the product yield.

[00203] Batch and Fed-batch fermentation of geraniol and geranyl acetate

[00204] As the auto-induction media led to highest yield of geraniol by minimizing its degradation into other products (geranial and citronellol), a new bioprocess was developed based on the concept of auto-induction media. High-cell-density batch fermentation was explored by increasing the key nutrient supply (carbon, nitrogen and MgSO₄). The medium including 10 g/L glucose, 50 g/L of glycerol, 20 g/L (58 mM) lactose, 6 g/L (NH₄)₂SO₄ and 1.5 g/L MgSO₄ was first tested. Other nutrients were maintained the same as our previously used defined medium (see Material and Methods). In such as batch fermentation, up to an OD₆₀₀ of 77 was achieved, and the geraniol titre reached 957 mg/L in 67 h (Figure 9A). In addition, the production of citronellol was observed to increase rapidly in the late stage of fermentation and reached 250 mg/L at 72h. Concurrently, geraniol and geranial dropped slightly from 67 to 72 h. Citronellol was reduced from geraniol/geranial in *E. coli*, however, the enzyme was still unknown. In the future, identification of the enzyme and deletion of the enzyme from the genome to minimize the formation of citronellol will be explored.

[00205] Next, the production of geranyl acetate in a fed-batch fermentation was tested as previously used in the production of viridiflorol and amorphadiene. Within 70h, the strain GA11 produced 2.65 g/L of geranyl acetate, with an OD₆₀₀ of 144.

[00206] Deletion of *ackA* and *pta* genes

[00207] While developing the bioprocesses, lots of acetic acid (up to 10 g/L) was produced along with the geranyl acetate. In *E. coli*, the main route to produce acetate is through acetate kinase (*ackA*) and phosphate acetyltransferase (*pta*). Together, the two enzymes convert 1 acetyl-CoA to 1 acetate and 1 ATP. As the mevalonate and geraniol pathway also started from acetyl-CoA, the acetic acid production competed directly with geraniol biosynthesis. Hence, the deletion of *ackA* and *pta* on geranyl acetate bioproduction was evaluated. The deletion of *ackA* and *pta* markedly improved the titre of geranyl acetate by 3.7-4.8-fold from 1.6 to 7.8 g/L in the media with 20 g/L glycerol or from 2.6 to 9.5 g/L in the media with 30 g/L glycerol (Figure 10). In addition, the acetic acid production was greatly reduced as

witnessed by pH difference. After 3-day cultivation, the pH values of the wildtype (“-“) dropped from 7.2 to about 5.0, indicating the acetic acid production was pretty high. In constant, the mutant strain (“ Δ ackApta“) pH remained about 7.0. The carbon yield reached about >24% which is about 2-3 times higher than the best achievement in the literature.

[00208] In addition to geranyl acetate, the deletion of *ackA* and *pta* also worked for the biosynthesis of geraniol.

[00209] Tryptone Supplementation

[00210] Next, the effect of tryptone supplementation on geraniol production was evaluated. A very positive impact of tryptone supplementation on geraniol production was observed. With supplementation of only 2 g/L of tryptone, the geraniol production increased by 130% from 292 to 684 mg/L (Figure 11). Further increase of tryptone could not increase the geraniol yield anymore. The change of OD₆₀₀ values was not very significant.

[00211] Organic Effects

[00212] While testing the strains in flasks, geraniol production was consistently lower than that in tubes while geraniol production was higher than in tubes. The hypothesis was that the extracellular geraniol was not stable and might be oxidized by oxygen to geranial. To test this hypothesis, more organic (dodecane was used here) was used in flasks that might protect geraniol from further oxidation. Therefore, different volumetric ratio of dodecane to media from 0.1 to 1 were evaluated. At the ratio of 0.1-0.2, the effect was not obvious on geraniol, although geraniol production was increased from 129 to 276 mg/L. However, as the ratio further increased to 0.5 and 1.0, the production of geraniol was significantly boosted and the formation of geranial was also reduced. The geraniol titre increased to 907 mg/L in flasks with the ratio of 1.0, about 2.6-fold higher than that with the ratio of 0.1-0.2.

[00213] **Table 6. Summary of sequence listing.**

Description	DNA/Protein sequence	SEQ ID NO
RBS-1	gagatataataacgagataaggaaaagacaaa	SEQ ID NO: 1
RBS-2	gccgagatataataacgagataaggaaaagacaaa	SEQ ID NO: 2
RBS-3	tgccaactttaaagaggcctaaa	SEQ ID NO: 3
RBS-4	ttgtttaacttaagaaggagatatacat	SEQ ID NO: 4
RBS-5	ttgtttaacttaacaaggaggagatatacat	SEQ ID NO: 5
Polypeptide sequence of AgGPPS	MAYSAMATMGYNGMAASCHTLHPTSPL KPFHGASTSLEAFNGEHMGLLRGYSKRK LSSYKNPASRSSNATVAQLLNPPQKGKKA VEFDNFKYMDSKAMTVNEALNKAIPRLRY PQKIYESMRYSLLAGGKRVRPVLCAACE LVGGTEELAIPTACAIEMIHTMSLMHDDL	SEQ ID NO: 6

	PCIDNDDLRRGKPTNHKIFGEDTAVTAGN ALHSYAFEHIAVSTSKTVGADRILRMVSE LGRATGSEGVMGGQMVDIASEGDP SIDL QTLEWIIHKTAMLLECSVVCGAIIGGASE IVIERARRYARCVGLLFQVVDDILDVTKSS DELGKTAGKDLISDKATYPKLMGLEKAK EFSDELLNRAKGELSCFDPVKAAPLLGLA DYVAFRQN	
Polypeptide sequence of AgGPPS truncated from the amino acid positions 2 to 85	MFDENKYMSKAMTVNEALNKAIPRLYP QKIYESMRYSLLAGGKRVLPVLCIAACEL VGGTEELAIPTACAIEMIHTMSLMHDDL CIDNDDLRRGKPTNHKIFGEDTAVTAGNA LHSYAFEHIAVSTSKTVGADRILRMVSEL GRATGSEGVMGGQMVDIASEGDP SIDLQ TLEWIIHKTAMLLECSVVCGAIIGGASEI VIERARRYARCVGLLFQVVDDILDVTKSS DELGKTAGKDLISDKATYPKLMGLEKAK EFSDELLNRAKGELSCFDPVKAAPLLGLA DYVAFRQN	SEQ ID NO: 7
Polypeptide sequence of FPPS isolated from <i>Escherichia coli</i>	MVLTNKTVISGSKVKSLSAQS SSSGPSS SEEDDSRDIESLDKKIRPLEELEALLSSGNT KQLKNKEVAALVIHGKLPYALEKKLGD TTRAVAVRRKALSILAEAPVLASDRLPYK NYDYDRVFGACCENVIGYMPLPVG VIGPL VIDGTSYHIPMATTEGCLVASAMRGCKAI NAGGGATTVLTKDGMTRGPVVRFP TLKR SGACKIWLDSEEGQNAIKKAFNSTSRFAR LQHIQTCLAGDLLFMRFTTTGDAMGMN MISKGVEYSLKQMVEEYGWEDMEVVS SGNYCTDKKPAAINWIEGRGKSVVAEATI PGDVVRKVLKSDVSALVELNIAKNLVGS AMAGSVGGFNAHAANLVTAVFLALGQD PAQNVESNCITLMKEVDGDLRISVSMPSI EVTIGGGTVLEPQGAMLDLLGV R GPHA TAPGTNARQLARIVACAVLAGELSLCAAL AAGHLVQSHMTHNRKPAEPTKPNNL DAT DINRLKDGSVTCIKS	SEQ ID NO: 8
Polypeptide sequence of FPPS isolated from <i>Escherichia coli</i> comprising a mutation of serine to phenylalanine mutation at amino acid position 80	MDFPQQLEACVKQANQALS RFIAPLPFQN TPVVETMQYGALLGGKRLRPFLVYATGH M FGVSTNTLDAPAAAVECIHAYFLIHDDL AMDDDDLRRGLPTCHVKFGEANAILAGD ALQTLAFSILSDADMPEVSDRDRISMISEL ASASGIAGMCGGQALDLDAEGKHVPLDA LERIHRHKTGALIRAAVRLGALSAGDKGR RALPVL DKYAESIGLAFQVQDDILDVVG D TATLGKRQGADQQLGKSTYPALLGLEQA RKKARDLIDDARQSLKQLAEQSLDTSALE	SEQ ID NO: 9

	ALADYIIQRNK	
Polypeptide sequence of FPPS isolated from <i>Saccharomyces cerevisiae</i>	MASEKEIRRERFLNVFPKLVEELNASLLA YGMPEACDWYAHSLNYNTPGGKLNRG LSVVDTYAILSNTVEQLGQEEYEKVAIL GWCIELLQAYFLVADDMMDKSITRRGQP CWYKVPEVGEIAINDAFMLEAAIYKLLKS HFRNEKYYIDITELFHEVTFQTELGQLMD LITAPEDKVDLSKFSCLKKHSFIVTFKTAYY SFYLPVALAMYVAGITDEKDLKQARDVLI PLGEYFQIQDDYLD CFGTPEQIGKIGTDIQ DNKCSWVINKALELASAEQRKTLDENYG KKDSVAEAKCKKIFNDLKIEQLYHEYEEESI AKDLKAKISQVDES RGFKADVLTAFLNK VYKRSK	SEQ ID NO: 10
FPPS isolated from <i>Saccharomyces cerevisiae</i> comprising a mutation of asparagine to tryptophan at amino acid position 127	MASEKEIRRERFLNVFPKLVEELNASLLA YGMPEACDWYAHSLNYNTPGGKLNRG LSVVDTYAILSNTVEQLGQEEYEKVAIL GWCIELLQAYFLVADDMMDKSITRRGQP CWYKVPEVGEIAIWD AFMLEAAIYKLLKS HFRNEKYYIDITELFHEVTFQTELGQLMD LITAPEDKVDLSKFSCLKKHSFIVTFKTAYY SFYLPVALAMYVAGITDEKDLKQARDVLI PLGEYFQIQDDYLD CFGTPEQIGKIGTDIQ DNKCSWVINKALELASAEQRKTLDENYG KKDSVAEAKCKKIFNDLKIEQLYHEYEEESI AKDLKAKISQVDES RGFKADVLTAFLNK VYKRSK	SEQ ID NO: 11
FPPS isolated from <i>Saccharomyces cerevisiae</i> comprising a mutation of phenylalanine to tryptophan at amino acid position 96	MASEKEIRRERFLNVFPKLVEELNASLLA YGMPEACDWYAHSLNYNTPGGKLNRG LSVVDTYAILSNTVEQLGQEEYEKVAIL GWCIELLQAYWL VADDMMDKSITRRGQP CWYKVPEVGEIAINDAFMLEAAIYKLLKS HFRNEKYYIDITELFHEVTFQTELGQLMD LITAPEDKVDLSKFSCLKKHSFIVTFKTAYY SFYLPVALAMYVAGITDEKDLKQARDVLI PLGEYFQIQDDYLD CFGTPEQIGKIGTDIQ DNKCSWVINKALELASAEQRKTLDENYG KKDSVAEAKCKKIFNDLKIEQLYHEYEEESI AKDLKAKISQVDES RGFKADVLTAFLNK VYKRSK	SEQ ID NO: 12
FPPS isolated from <i>Saccharomyces cerevisiae</i> comprising mutations of asparagine to tryptophan at amino acid	MASEKEIRRERFLNVFPKLVEELNASLLA YGMPEACDWYAHSLNYNTPGGKLNRG LSVVDTYAILSNTVEQLGQEEYEKVAIL GWCIELLQAYWL VADDMMDKSITRRGQP CWYKVPEVGEIAIWD AFMLEAAIYKLLKS HFRNEKYYIDITELFHEVTFQTELGQLMD LITAPEDKVDLSKFSCLKKHSFIVTFKTAYY SFYLPVALAMYVAGITDEKDLKQARDVLI	SEQ ID NO: 13

position 127, and phenylalanine to tryptophan mutation at amino acid position 96	PLGEYFQIQDDYLD CFGTPEQIGKIGTDIQ DNKCSWVINKALELASAEQRKTLDENYG KKDSVAEAKCKKIFNDLKIEQLYHEYEEESI AKDLKAKISQVDES RGFKADVLTAFLNK VYKR SK	
Polypeptide sequence of NUDX1 isolated from <i>Rosa hybrida</i>	MGNETVVVAETAGSIKVAVVVCLLRGQN VLLGRRRSSLGDSTFSLPSGHLEFGESFE ECAARELKEETDLDIGKIELLTVTNNLFLD EAKPSQYVAVFMRAVLADPRQEPQNIEPE FCDGWGWYEWDLNLPKPLFWPLDNVVQD GFNPFPPT	SEQ ID NO: 14
Polypeptide sequence of NUDX1 isolated from <i>Arabidopsis thaliana</i>	MSTGEAIPRVAVVVFILNGNSILLGRRRSS IGNST FALPGGHLEFGESFEECAAREVMEETGLK IEKMKLLTVTNNVFKEAPTPSHYVSVSIR AVLVDPSQEPKNMEPEKCEGWDWYDWE NLPKPLFWPLEKLFSGSFNPFTHG GGD	SEQ ID NO: 15
Nucleic acid sequence of GES isolated from <i>Ocimum basilicum</i> (ObGES)	atgCAGCACATGGAGGAGAGCTCTTCCAA GCGCCGTGAATACTTGCTGGAGGAAAC GACTCGCAAACCTCCAGCGCAACGATAC CGAATCCGTGGAAAACTGAAACTCAT TGATAACATCCAGCAACTGGGCATCGGT TATTACTTCGAGGACGCAATTAACGCTG TGCTGCGTTCTCCGTTCTCTACAGGTGA AGAAGATCTGTTACCCGCCGCTCTGCGT TTCCGTCTGCTGCGTCACAACGGCATTG AGATCTCCCCGGAAATCTTCTGAAGTT TAAAGACGAACGTGGTAAATTTCGACGA GTCCGATACCCTCGGCCTGCTGAGCCTG TACGAAGCTTCCAACCTGGGTGTTGCAG GTGAAGAAATTCTGGAAGAAGCGATGG AATTTGCCGAGGCACGCCTGCGCCGCTC GCTGTCCGAACCGGCCGCGCCGCTGCAT GGCGAAGTGGCGCAGGCTCTTGACGTC CCGCGCCATCTGCGTATGGCGCGCCTGG AAGCACGTGCTTTATCGAACAGTACGG CAAACAGTCTGATCATGACGGTGACCTC CTGGAACCTGGCTATTCTGGATTATAACC AGGTGCAGGCGCAGCACCAGTCCGAAC TGACTGAAATCATCCGTTGGTGGAAG AGTTGGGACTTGTCGATAAACTGTCCTT CGGCCGCGACCGTCCGCTGGAATGTTTC CTGTGGACTGTAGGCCTGCTGCCAGAAC CGAAGTACTCCTCTGTACGTATCGAGCT CGCTAAAGCGATCTCCATCTTATTGGTC ATTGATGATATTTTCGATACCTACGGTG AAATGGATGATCTGATCCTGTTACCGA TGCTATCCGTCGTTGGGATCTGGAAGCG	SEQ ID NO: 16

	ATGGAAGGTCTGCCGGAATATATGAAA ATCTGCTACATGGCCCTGTATAACACCA CGAACGAAGTTTGCTACAAAGTACTGC GTGATACCGGTCGTATCGTACTTCTGAA CCTCAAATCCACATGGATTGACATGATT GAGGGTTTCATGGAAGAAGCGAAATGG TTCAACGGCGGTTTCGGCACCGAAACTG GAGGAGTACATCGAAAATGGTGTGTCT ACCGCAGGCGCATACATGGCCTTTGCCC ACATTTTCTTCCTGATTGGCGAAGGCGT TACGCACCAGAACTCCAGCTGTTCAACC CAAAAACCGTACCCGAAAAGTGTTTAGC GCCGCCGGTCGCATCCTGCGTCTGTGGG ATGATCTGGGCACCGCAAAAGAAGAGC AGGAACGTGGTGATCTGGCGTCTGCGT TCAGCTGTTTATGAAGGAAAAATCCCTG ACTGAAGAAGAAGCGCGTTCTCGTATCC TGGAAGAAATTAAAGGTCTGTGGCGCG ATTTAAACGGCGAACTGGTGTACAACA AAAACCTGCCGCTTTCATCATCAAAGT TGCGCTGAATATGGCGCGCGCGTCTCAA GTTGTATACAAACACGATCAGGATACGT ATTCAGCTCCGTAGATAACTACGTAGA CGCTCTGTTTTTACTCAGTGA	
Linker sequence of the engineered fusion protein	GGGGSGGPGS	SEQ ID NO: 17
Linker sequence of the engineered fusion protein	GGGGSGGGSGGGSGGGSGGPGS	SEQ ID NO: 18
Nucleic acid sequence of <i>atoB</i> gene	atgggtaacgtgttacaagccgggctggggcaaaatccggcgc gtcaggcactgttaaaaagcgggctggcagaaacgggtgcggg attcacgggtcaataaagtatgtggttcgggtcttaaaagtgtggcg cttgccgccaggccattcaggcaggtcaggcgcagagcattgt ggcggggggtatggaaaatgatgattagccccctactactcga tgcaaaagcacgctctggtatcgtcttgagacggacaggttat gacgtaatcctgcgcgatggcctgatgtgccaccatggttat catatggggattaccgccgaaaacgtggctaagagtacggaat taccctgaaatgcaggatgaactggcgctacattcacagcgtaa agcggcagccgcaattgagtcgggtgctttacagccgaaatcgt cccggtaaatgtgtcactcgaaagaaaaccttcgtcttcagtcga gacgaattcccgaagcgaattcaacggctgaagcgtagtgctc attgcgcccggccttcgataaagcaggaacagtcaccgctggga acgctctggtatfaacgacgggtgctgccgctctggtgattatgga agaatctgcggcgtggcagcagccttacccttgctcgcga ttaaagttatgccagcgggtggcgtccccccgcattgatgggta tggggccagtacctgccacgcaaaaagcgttacaactggcggg gctgcaactggcggatattgatctcattgaggctaataagcattt	SEQ ID NO: 19

	gctgcacagttccttgccttgggaaaaacctgggctttgattctg agaaagtgaatgtcaacggcggggccatcgctcgggcatcc tateggtgccagtgggtgctctgtattctgtcacactattacatgcca tgcaggcacgcgataaaacgctggggctggcaacactgtgcatt ggcgccggtcagggaattgcgatgggtgattgaacggttgaattaa	
Nucleic acid sequence of <i>hmgS</i> gene	atgaaactctcaactaaactttgttggtgtgtattaaaggaagact taggccgcaaaagcaacaacaattacacaatacaaaacttgcaaat gactgaactaaaaaacaagaccgctgaacaaaaaccaga cctcaaatgtcgggtattaaaggtatcaaatctacatccaactca atgtgtcaaccaatctgagctagagaaatttgatggcgtttctcaag gtaaatacacaattggtctggccaaaccaatgcttttgcatt gacagagaagatactactcgtatgctcctaactgtttgtctaagt gatcaagagttacaacatcgacaccaaaaaattggtagattaga agtcggtactgaaactctgattgacaagtcgaagctgtcaagtct gtcttgatgcaattgtttgtgaaaactgacgtcgaaggtattga cacgcttaatgcctgttacgggtgtaccaacgcgttgtcaactctt tgaactggattgaatctaacgcatgggatggtagagacgccattg tagtttgcgggtatattgccatctacgataagggtgccgcaagacc aacgggtggtgccggtactgttctatgtggatcggctctgatgct ccaattgtattgactctgtaagagctcttacctgaacacgccta cgattttacaagccagattcaccagcgaatactctacgtcgtatg gtcattttcattaaactgttacgtcaaggtcttgatcaagtttaca gagttattccaagaaggctatttctaagggttggttagcgtccc gctggttcggatgcttgaacgttttgaatatttcgactacaacgtt ttccatgtccaacctgtaaattgtcacaaaaatatacggtagatt actatataacgatttcagagccaatcctcaattgtcccagaagttg acgccgaattagctactcgcgattatgacgaatcttaaccgataa gaacattgaaaaaacttttgaatgttgctaagccattccacaag agagagttgcccaatcttgaattgtccaacaaacacaggtaacat gtacaccgcatctgttatgccgcctttgcatctctattaaactatgtt ggatctgacgacttacaaggcaagcgtgttggttattttcttacgg ttccggttagctgcatctctatattcttgcataattgttggtgacgtc caacatattatcaaggaattagatattactaacaattagccaaga gaatcaccgaaactccaaaggattacgaagctgccatcgaattga gagaaaatgcccatgtgaagaagaacttcaaacctcaaggtcca ttgagcatttgcaagtggtgttactacttgaccaacatcgatgac aaatttagaagatcttacgatgttaaaaaataa	SEQ ID NO: 20
Nucleic acid sequence of <i>mevK</i> gene	atgagcttaccgttctctgacttcggcaccgggcaagttatcat cggcgagcactctgctgtttacaacaacggcagttgcggcctc cgtatctgcactgcgcacttatctgctgatctctgaaagctccgcc ccggatactattgaactggactttccggacatttctttaaccacaa atggagcattaacgactttaacgcgatcactgaagatcaggtaaa ctcccagaaactggcaaaagcacagcaggctaccgatggtctga gccaggaactggtgtccctcctcgatcctttgctggctcaactctc ggaatgttccattaccatgctgctttctgtttctgtatatgtttgtg cctctgcccgcacgcgaaaaacatcaaatctctctgaaatcgact ctgccgattggtgccgacctgggttcgtccgcatctattccgttcc cctggcgctggccatggcctatctggcggtctgatcgggtccaa	SEQ ID NO: 21

		cgacctggaaaaactctcggaaaacgataagcacatcgtaacc agtgggcgttcacggtgaaaaatgtatccacggtaccccatccg gtatcgataatgcggttgctacctacggtaacgcgttactgttcga aaaaattctcataacggtactatcaactaacaactcaaatftt ggacgattttccggcgattccgatgatcctgacttacaccgcac ccgcgtagcaccaaggatctggtgcacgcgttcgtgactcgtg accgaaaaattcccggaggttatgaaccgatcctggatgcaatg ggtgagtgcgcgtgcagggttagaaatcatgacaaaactgtc gaagtgtaaagggtacggacgacgaagctgtgaacaacaac gaactgtatgaacagctgctggaactgatccgtatcaaccacggc ctgctggtcagcattggtgtgagccaccggcctggaactgatt aaaaatcttccgatgacctgcgcattggttctaccaagctgactg gtgctggcggcggtggctgttctctgacctcctgcgtcgcgata taccaggaacaatcgactcgtcaaaaaaaactgcaggatg actttcttatgaaccttcgaaccgacctgggcgtaccggctg ttgtctctgtccgcaaaaactgaacaaagatctgaaatcaaa tctctcgtcttcagctgttgaacaaaaactaccaccaacaaca aattgatgacctgctgctccgggcaacaccaactaccgtggac ttctaa	
Nucleic sequence gene	acid of <i>pmk</i>	atgtctgagcttcgcgtttctccgctccgggcaaggccctgctg gccggaggctatctggtgctggacacaaatatgaagcgtttgta gttggtctgtctgccgtagcatgcggtcgcgaccgtaggggt cgctgcagggttcagataaatcaggtgcgagtgaaaagcaaa cagtttaaagacggtgagtggtgtatcacattagcccgaatctg gttttatcccggtagccatcggcggttcaaaaacccgttcattgaa aaagtatttgccaacgttttctctattttaaacctaactgtagact actgtaaccgtaacctgttcgtgattgataatttctctgacgatctta ccattcccagggaagacagcgttacggaacaccgtggcaaccgtc gtctgtcgtttcattccaccgtatcgaagaagtccgaagactgg cctgggtagctctgcaggcctggttaccgtcctgactactgctctg gcctctttttgtgtcggatctggaacaaacgttgacaaatatcgt gaggtlaattcataacctggctcaggctgcacactgccaggcgca gggcaaaatcggtccggttccgatgttgcgtcggcagcttatgg ctccattcgttaccgtcgttcccgcctgctctgatctcaaacctgc cggatattggtagcgcaacctacggatcgaagctggctcacctg gtggatgaggaagattggaatatcaccattaaatctaaccacctgc cgtctggcctgacctgtggatgggtgatataaaaacggctctg aaaccgtcaaacgtgtacagaaagttaagaattggtatgattctca catgccggaatccctgaaaatctacaccgagctggatcacgcga actcacgtttcatggacggtctgtccaaactggaccgtctgcacg aaaccacgatgattacagcgaccagatcttcgaatctctggaac gtaacgactgcacctgtcaaaaatacccggaatcacccaagttc gtgacgcggtagcgaccatccgccgtctttccgtaaaatcacta aggaaagcggcgctgacatgaaccggcggttcagacctccct gctggacgattgccagactctgaaaggggtgctgacctgtctgat tccgggtgcgggtggttatgacgtatcgagtgatcacgaaaca ggatgtagacctgcgtgcgcagactgcaaacgacaaacgtttta gcaagtagaatggctggatgttaccaggcggttgggggtgttc	SEQ ID NO: 22

Nucleic acid sequence of <i>pmd</i> gene	gtaaagaaaaggaccctgaaacctacctggataaataa atgaccgtttacacagcatccgttacccgacccgtcaacatcgca acccttaagtattgggggaaaaggacacgaagttgaatctgcc caccaattcgtccatatcagtgactttatcgcaagatgacctcaga acgttgacctctgcggctactgcacctgagttgaacgcgacactt tgtggftaatggagaaccacacagcatcgacaatgaaagaact caaaattgtctgcgcgacctacgccaattaagaaaggaaatgga atcgaaggacgcctcattgccacattatctcaatggaaactccac attgtctccgaaaataactttcctacagcagctggtttagcttctcc gctgctggctttgctgcattggtctctgcaattgctaagttataccaa ttaccacagtcaacttcagaataatcccgtatagcaagaaagggg tctggttcagctttagatcgtttggtggcgatagtgccctggga aatgggaaaagctgaagatggtcatgattccatggcagtacaaat cgcagacagctctgactggcctcagatgaaagcttgtgtcttagtc gtcagcgatataaaaaggatgtgagttccactcagggtatgcaat tgaccgtggcaacctccgaactatttaaagaaagaattgaacatgt cgtaccaagagattgaagtcagcgtaaagccattgttgaaaaa gatttcgccacctttgcaaaggaaacaatgatggattccaactcttt ccatgccacatgtttggactctttccctccaatattctacatgaatga cactccaagcgtatcatcagttggtgccacaccattaatcagtttt acggagaaacaatcgttgcatcacggttgatgcaggtcctaaatg ctgtgtgtactacttagctgaaaatgagtcgaaactcttgcatttat ctataaattgtttggctctgttctggatgggacaagaaatttactac tgagcagcttgaggctttcaaccatcaatttgaatcatctaactttac tgacagtgaaattggatcttgagttgcaaaggatgttgccagagtg attttaactcaagtcggttcaggcccacaagaacaacgaatctt tgattgacgcaaagactggtctaccaaaaggaataa	SEQ ID NO: 23
Nucleic acid sequence of <i>idi</i> gene	atgcatcatcatcacatcacgagctccaaacggaacacgtcattt tattgaatgcacagggagttcccacgggtacgtggaagatg ccgcacacacggcagacacccgcttacatctcgcgttctccagtt ggctgttfaatgcaaaaggacaattattagttaccgccgcgact gagcaaaaaagcatggcctggcgtgtggactaactcggtttgtg ggcaccacaactgggagaaagcaacgaagacgcagtgatcc gccgttgccgttatgagcttggcgtggaaattacgcctctgaatc tatctatcctgactttcgtaccgcgccaccgatccgagtggcatt gtggaaaatgaagtgtgtccggtatttgcgcacgcaccactagt gcgttacagatcaatgatgatgaagtgatggattatcaatggtgtg atttagcagatgtattacacggtattgatgccacgccgtggcggt cagtccttggtgatgcaggcgacaaatcgcaagccaga aaacgattatctgcatttaccagcttaataa	SEQ ID NO: 24
Nucleic acid sequence of <i>RhNUDX1</i> gene	ATGcatcacatcacatcacGGTAACGAAACTG TGGTAGTCGCAGAAACCGCGGGTAGCA TCAAAGTTGCCGTTGTGGTTTGTCTGTT GCGTGGTCAAAACGTGCTCCTGGGTCGT CGTCGCTCCTCTCTGGGTGACAGCACCT TCTCTCTGCCGAGCGGCCACTTAGAATT TGGTGAATCTTTCGAAGAATGTGCCGCC CGTGAGCTGAAAGAAGAAACGGATCTG	SEQ ID NO: 25

		GACATCGGTAAAATCGAGCTGCTGACC GTAACCAACAACCTGTTCCCTGGATGAAG CTAAACCGTCCCAGTATGTTGCAGTGTT CATGCGTGCTGTTCTGGCCGATCCGCGT CAGGAGCCGCAGAACATTGAACCCGAA TTCTGCGACGGCTGGGGTTGGTACGAAT GGGATAACTTACCGAAGCCACTGTTCTG GCCGCTCGACAACGTGGTCCAGGATGG CTTCAACCCGTTCCCGACTTAA	
Nucleic acid sequence of <i>NudI</i> gene		gtgcgacaacggactattgtatgccctttgattcaaatgatggtg cttatttgcgtgtaaaatggccgacgatcgcgcggtttccccggt caatgggcgatttcgggtggcggcgtggagcctggcgaacgaa ttgaagaggcactacgccgcgaaattcggaagaactgggaga acagctgctttgacagaaatcacgccgtggaccttcagcgatga tattcgaccaagacgtatgcagatggtcgaaggaagagattta tatgattacctgattttgactgcgtttctgccaaccgagaagtga aataaacgaagagtttcaggactacgcgtgggtaaaacctgaag atctggtgcattatgatttgaatgtcgccaccgaaaaacgttacgt ttgaaaggctcttctgtaa	SEQ ID NO: 26
Polypeptide sequence of truncated <i>hmgR</i> gene		MVLTNKTVIS GSKVKSLSSA QSSSSGPSSS SEEDDSRDIE SLDKKIRPLE ELEALLSSGN TKQLKNKEVA ALVIHGKLPL YALEKKLGDT TRAVAVRRKA LSILAEAPVL ASDRLPYKNY DYDRVFGACC ENVIGYMPLP VGVIGPLVID GTSYHIPMAT TEGCLVASAM RGCKAINAGG GATTVLTKDG MTRGPVVRFP TLKRSGACKI WLDSEEGQNA IKKAFNSTSR FARLQHIQTC LAGDLLFMRF RTTTGDAMGM NMISKGVEYS LKQMVEEYGW EDMEVVSMSG NYCTDKKPAA INWIEGRGKS VVAEATIPGD VVRKVLKSDV SALVELNIAK NLVGSAMAGS VGGFNAHAAN LVTAVFLALG QDPAQNVESS NCITLMKEVD GDLRISVSMP SIEVGTIGGG TVLEPQGAML DLLGVRGPHA TAPGTNARQL ARIVACAVLA GELSLCAALA AGHLVQSHMT HNRKPAEPTK PNNLDATDIN RLKDGSVTCI KS	SEQ ID NO: 27
Nucleic acid sequence of truncated <i>hmgR</i> gene		atggtttaaccaataaaaacagtcatttctggatcgaaagtcaaaag tttatcatctgcgcaatcgagctcatcaggaccttcacatctagt aggaagatgattcccgcatattgaaagcttgataagaaaatac gtcctttagaagaattagaagcattattaagtagtggaatacaaa	SEQ ID NO: 28

	acaattgaagaacaaagaggctgccttggttattcacggtaa gttacctttgtacgctttggagaaaaattaggtgatactacgaga gcggttcggtacgttaggaaggctcttcaattttggcagaagctc ctgtattagcatctgatcgtttaccatataaaaattatgactacgacc gcgtatttggcgcttgtgtgaaaatgtataggtacatgcctttgc ccgttgggtgtataggcccccttggttatcgtggtacatctatcata taccaatggcaactacagagggttgttggtagcttctgccatgcg tgctgtgaaggcaatcaatgctggcggtggtgcaacaactgtttta actaaggatggtatgacaagagggccagtagtccgtttcccaact ttgaaaagatctggtgcctgtaagatatggttagactcagaagag ggacaaaacgcaattaaaaaagcttttaactctacatcaagatttg cacgtctgcaacataatcaactgtctagcaggagatttactcttc atgagatttagaacaactactggtgacgcaatgggtatgaatatga tttctaagggtgtcgaatactcattaaagcaaatggtagaagagtat ggctgggaagatatggagggtgtctccgtttctgtaactactgta ccgacaaaaaccagctgccatcaactggatcgaaggtcgtggt aagagtgtcgtcgcagaagctactattcctggtgatgtgtcagaa aagtgttaaaaagtgtgttccgattggtgagttgaacattgcta agaatttgggttgatctgcaatggctgggtctgttgggtggatlaac gcacatgcagctaatttagtgacagctgttttcttgccattaggaca agatcctgcacaaaatgtgaagttccaactgtataacattgatga aagaagtggacggtgatttgagaatttccgtatccatgccatccat cgaagtaggtaccatcggtggtggtactgttctagaaccacaagg tgccatgttggaactattaggtgtaagaggcccgcatgctaccgct cctggtaccaacgcacgtcaattagcaagaatagttcctgtgcc gtcttggcaggtgaattatccttatgtgtgccttagcagccggcc atttgggtcaaaagtcataatgacccacaacaggaaacctgctgaac caacaaaacctaacatttggacgccactgatataaatcgtttgaa agatgggtccgtcacctgcattaaatcctaa	
Nucleic acid sequence of T7 promoter	aaattaatacgactcactataggggaattgtgagcggataaca	SEQ ID NO: 29
Nucleic acid sequence of TM1 promoter	aaattaatacgactcactaatgggaattgtgagcggataaca	SEQ ID NO: 30
Nucleic acid sequence of TM2 promoter	aaattaatacgactcactcgagggaattgtgagcggataaca	SEQ ID NO: 31
Nucleic acid sequence of TM3 promoter	aaattaatacgactcactataaggaattgtgagcggataaca	SEQ ID NO: 32
Nucleic acid sequence of TV1 promoter	aaattaatacgactcactaTAGGGgaattgtgagcggataac a	SEQ ID NO: 33
Nucleic acid sequence of TV2 promoter	aaattaatacgactcactaCAGACgaattgtgagcggataac a	SEQ ID NO: 34
Nucleic acid	aaattaatacgactcactaGCGGAgaattgtgagcggataac	SEQ ID NO: 35

sequence of TV3 promoter	a	
Nucleic acid sequence of TV4 promoter	aaattaatacgactcactaacaccgaattgtgagcggataaca	SEQ ID NO: 36
Oligo sequence of spk2m1-f	GGTAGTGGCGGCGGTGGCAGCGGTGGC CCGGGCAGCatgcatcatcatcacatcacgag	SEQ ID NO: 37
Oligo sequence of spk2m1-r	CACCGCCGCCACTACCACCGCCGCCGCT GCCACCGCCACCAGTCGGGAACGGGTT GAAGC	SEQ ID NO: 38
Oligo sequence of spk2s1-f	GCGGTGGCCCCGGGCAGCatgcatcatcatcacat cacgag	SEQ ID NO: 39
Oligo sequence of spk2s1-r	GCCCCGGGCCACCGCTGCCACCGCCACC AGTCGGGAACGGGTTGAAGC	SEQ ID NO: 40
Oligo sequence of yjbB gRNA	TATGCCGCAAAAGAAGCGGG	SEQ ID NO: 41
Oligo sequence of tnaA gRNA	CACGAATGCGGAACGGTTCA	SEQ ID NO: 42
RBS sequence of AgGPPS (GPPS2) (RBS-1)	Gagatataataacgagataaggaaaagacaaa	SEQ ID NO: 43
Protein sequence (N-term 35NT) of AgGPPS (GPPS2) (RBS-1)	Atgttcgattcaacaaatacatggacagcaaagccatga	SEQ ID NO: 44
RBS sequence of AgGPPS (GPPS2) (RBS-2)	gccgagatataataacgagataaggaaaagacaaa	SEQ ID NO: 45
Protein sequence (N-term 35NT) of AgGPPS (GPPS2) (RBS-2)	Atgttcgattcaacaaatacatggacagcaaagccatga	SEQ ID NO: 46
RBS sequence of ERG20_N127W (GPPS3) (RBS-3)	Tgccaaactttaaagaggcctaaa	SEQ ID NO: 47
Protein sequence (N-term 35NT) of ERG20_N127W (GPPS3) (RBS-3)	Atggcttcagaaaaagaattaggagagagagattcttga	SEQ ID NO: 48
RBS sequence of ERG20_N127W (GPPS3) (RBS-2)	gccgagatataataacgagataaggaaaagacaaa	SEQ ID NO: 49
Protein sequence (N-term 35NT) of ERG20_N127W (GPPS3) (RBS-2)	Atggcttcagaaaaagaattaggagagagagattcttga	SEQ ID NO: 50
RBS sequence of	Tgccaaactttaaagaggcctaaa	SEQ ID NO: 51

ERG20_96_127 (GPPS3b) (RBS-3)		
Protein sequence (N-term 35NT) of ERG20_96_127 (GPPS3b) (RBS-3)	Atggcttcagaaaaagaaattaggagagagagattcttga	SEQ ID NO: 52
RBS sequence of ERG20_96_127 (GPPS3b) (RBS-2)	gccgagatataataacgagataaggaaaagacaaa	SEQ ID NO: 53
Protein sequence (N-term 35NT) of ERG20_96_127 (GPPS3b) (RBS-2)	Atggcttcagaaaaagaaattaggagagagagattcttga	SEQ ID NO: 54
RBS sequence of IspA (GPPS1) (RBS-4)	Tttgtttaactttaagaaggagatatacat	SEQ ID NO: 55
Protein sequence (N-term 35NT) of IspA (GPPS1) (RBS-4)	Atgcatcatcatcaccatcacgactcgactttccgcgcgc	SEQ ID NO: 56
RBS sequence of IspA (GPPS1) (RBS-5)	Tttgtttaactttaacaaggaggatatacat	SEQ ID NO: 57
Protein sequence (N-term 35NT) of IspA (GPPS1) (RBS-5)	Atgcatcatcatcaccatcacgactcgactttccgcgcgc	SEQ ID NO: 58
RBS sequence of RBS-SAR (hmgs (S))	tttgtttaactttaagaaggagatatacat	SEQ ID NO: 59
RBS sequence of RBS-SAR (atoB (A))	atcgattcacaacacgttgatgaagtgatt	SEQ ID NO: 60
RBS sequence of RBS-SAR (thmgR (R))	ctcgagaataaggaggttaagtc	SEQ ID NO: 61
RBS sequence of RBS-MPPI (MK (M))	aacacaaacagaggggaaaaaa	SEQ ID NO: 62
RBS sequence of RBS-MPPI (PMK (P))	tcactagacacatcgataaggaggtacct	SEQ ID NO: 63
RBS sequence of RBS-MPPI (MVD (P))	tccttatcattccatcccataagagaggcact	SEQ ID NO: 64
RBS sequence of RBS-MPPI (idi (I))	ccccactcaggaataataagagaggacct	SEQ ID NO: 65

Polypeptide sequence of hmgR	MPPLFKGLKQMAKPIAYVSRFSAKRPIHII LFSLIISAFAYLSVIQYYFNGWQLDSNSVF ETAPNKDSNTLFQECSHYYRDSSLDGWV SITAHEASELPAPHHYYLLNLFNNSPNETD SIPELANTVFEKDNTKYILQEDLSVSKEISS TDGTKWRLRSDRKSFLDVKTLAYSLYDV FSENVQTADPDFVLMVTAYLMMFYTIFG LFNDMRKTGSNFWLSASTVVNSASSLFLA LYVTQCILGKEVSALTLEGLPFIVVVVGF KHKIKIAQYALEKFERVGLSKRITTDEIVF ESVSEEGGRLIQDHLLCIFAFIGCSMYAHQ LKTLTNFCILSAFILIFELILTPTFYSAIALR LEMNVIHRSTIIKQTLIEDGVVPSTARIISK AEKKSVSFLNLSVVVIIMKLSVILLFVFIN FYNFGANWVND AFNSLYFDKERVSLPDFI TSNASENFKEQAI VSVTPLLYYKPIKSYQR IEDMVLLLLRNVSVAIRDRFVSKLVLSAL VCSAVINVYLLNAARIHTSYTADQLVKTE VTKKSFTAPVQKASTPVL TNKTVISGSKV KSLSSAQSSSSGPSSSSEEDDSRDIESLDKK IRPLEELEALLSSGNTKQLKNKEVAALVIH GKLPLYALEKKLGD TTRAVAVRRKALSIL AEAPVLASDRLPYKNYDYDRVFGACCEN VIGYMPLPVGVIGPLVIDGTSYHIPMATTE GCLVASAMRGCKAINAGGGATTVLTKDG MTRGPVVRFP TLKRS GACKIWL DSEEGQ NAIKKAFNSTSR FARLQHIQTCLAGDLLF MRFR TTTGDAMGMNMISKGVEYSLKQM VEEYGWEDMEVVS VSGNYCTDKKPAAIN WIEGRGKSVVAEATIPGDVVRKVLSKSDVS ALVELNIAKNLVGSAMAGSVGGFNAAHAA NLVTAVFLALGQDPAQNVESNCITLMKE VDGDLRISVSMPSIEVGTIGGGTVLEPQGA MLDLLGVRGPHATAPGTNARQLARIVAC AVLAGELSLCAALAAAGHLVQSHMTHNRK PAEPTKPNNLDATDINRLKDGSVTCIKS	SEQ ID NO: 66
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[00214] **Equivalents**

The foregoing examples are presented for the purpose of illustrating the invention and should not be construed as imposing any limitation on the scope of the invention. It will readily be apparent that numerous modifications and alterations may be made to the specific embodiments of the invention described above and illustrated in the examples without departing from the principles underlying the invention. All such modifications and alterations are intended to be embraced by this application.

Claims

What is claimed is:

1. A host cell comprising one or more vectors comprising a polynucleotide sequence encoding:
 - one or more genes of the mevalonate pathway; and one or more genes of the Nudix pathway.
2. The host cell according to any one of claim 1, wherein the host cell comprises two vectors, wherein
 - a. a first vector comprising a polynucleotide sequence encoding one or more genes of the mevalonate pathway; and
 - b. a second vector comprising a polynucleotide sequence encoding one or more genes of the Nudix pathway.
3. The host cell according to claims 1 or 2, wherein the one or more genes of the mevalonate pathway is selected from the group consisting of HMG-CoA synthase (*hmgS*), acetoacetyl-CoA thiolase (*atoB*), HMG-CoA reductase (*hmgR*), mevalonate kinase (*mevK*), phosphomevalonate kinase (*pmk*), mevalonate pyrophosphate decarboxylase (*pmd*) and (isopentenyl diphosphate) IPP isomerase (*idi*), and the one or more genes of the Nudix pathway is *NUDX1* or *NudI*.
4. The host cell according to claim 3, wherein the *hmgR* gene is truncated.
5. The host cell according to any one of claims 2 to 4, wherein the second vector further comprises a polynucleotide sequence encoding one or more diphosphate synthase genes, prenyltransferase genes or combinations thereof in the host cell.
6. The host cell according to any one of claims 2 to 5, wherein the polynucleotide sequence in each of the vectors is operably linked to an inducible promoter, wherein the inducible promoter is a wild-type T7 RNA polymerase promoter or a variant of the wild-type T7 RNA polymerase promoter.
7. The host cell according to any one of claims 2 to 6, wherein the first vector comprises
 - a. a polynucleotide sequence encoding the *hmgS*, *atoB*, *hmgR* genes of the mevalonate pathway operably linked to a first inducible promoter; and
 - b. a polynucleotide sequence encoding the *mevK*, *pmk*, *pmd* and *idi* genes of the mevalonate pathway operably linked to a second inducible promoter.

8. The host cell according to any one of claims 5 to 7, wherein the second vector further comprises a polynucleotide sequence encoding a ribosomal binding site (RBS) that is located upstream of the polynucleotide sequence encoding the polynucleotide sequence encoding the Nudix pathway gene, the polynucleotide sequence encoding the diphosphate synthase gene or prenyltransferase gene, or combinations thereof.
9. The host cell according to claim 8, wherein the polynucleotide sequence encoding the RBS in the second vector is selected from the group consisting of SEQ ID NO: 1, SEQ ID NO: 2, SEQ ID NO: 3, SEQ ID NO: 4 and SEQ ID NO: 5
10. The host cell according to any one of claims 5 to 9, wherein the diphosphate synthase or the prenyltransferase is a geranyl pyrophosphate synthase (GPPS) or a farnesyl diphosphate synthase (FPPS).
11. The host cell according to claim 10, wherein the GPPS is isolated from *Abies grandis* (AgGPPS).
12. The host cell according to claim 11, wherein the AgGPPS is truncated at the N-terminal.
13. The host cell according to claim 12, wherein the truncated AgGPPS comprises the polypeptide sequence as set forth in SEQ ID NO: 7.
14. The host cell according to claim 10, wherein the FPPS is isolated from *Saccharomyces cerevisiae* or *Escherichia coli*.
15. The host cell according to claim 14, wherein the FPPS is mutated at one or more amino acid positions.
16. The host cell according to claim 15, wherein the mutated FPPS from *Escherichia coli* comprises the polypeptide sequence as set forth in SEQ ID NO. 9, and wherein the mutated FPPS from *Saccharomyces cerevisiae* comprises the polypeptide sequence as set forth in SEQ ID NO. 11, SEQ ID NO. 12, or SEQ ID NO. 13.
17. The host cell according to any one of claims 2 to 16, wherein the *NUDX1* is isolated from a plant.
18. The host cell according to claim 17, wherein the *NUDX1* is isolated from *Rosa hybrida* and has about 70%, 80%, 90% or 100% identity with the polypeptide sequence set forth in SEQ ID NO: 14, or wherein the *NUDX1* is isolated from

Arabidopsis thaliana and has about 70%, 80%, 90% or 100% identity with the polypeptide sequence set forth in SEQ ID NO: 15.

19. The host cell according to any one of claims 2 to 17, wherein the *NudI* is isolated from a prokaryote.
20. The host cell according to any one of claims 5 to 19, wherein the *NUDX1* or *NudI* is co-expressed with the diphosphate synthase or the prenyltransferase.
21. The host cell according to any one of claims 5 to 20, wherein the second vector further comprises one or more of:
 - a. a polynucleotide sequence encoding a geranyl synthase enzyme (GES) isolated from a plant, wherein the polynucleotide sequence encoding the GES is located upstream of the polynucleotide sequence encoding the diphosphate synthase or the prenyltransferase, and wherein the GES is co-expressed with the diphosphate enzyme or the prenyltransferase, and/or the nudix enzyme;
 - b. a polynucleotide sequence encoding a multiple antibiotic resistance protein (MarA) which is located downstream of the polynucleotide sequence encoding the diphosphate synthase or the prenyltransferase; or
 - c. a polynucleotide sequence encoding an alcohol acyltransferase (AAT) enzyme which is located downstream of the polynucleotide sequence encoding the diphosphate synthase or the prenyltransferase; or combinations thereof.
22. The host cell according to any one of claims 1 to 21, wherein the host cell is deficient in the *pta* gene, the *ackA* gene or the *ackA* and *pta* genes.
23. The host cell according to any one of claims 1 to 22, wherein the host cell is deficient in at least one gene involved in amino acid synthesis, oxidation of terpenoids, amino acid degradation or a combination thereof.
24. The host cell according to claim 23, wherein the host cell is deficient in *aroA*, *serC*, *yjgB* and *tnaA* genes, or wherein the host cell is deficient in *aroA*, *serC* and *tnaA* genes.
25. The host cell according to any one of claims 1 to 24, wherein the host cell is a bacterial cell.
26. The host cell according to claim 25, wherein the bacterial cell is an *Escherichia coli* cell.

27. An engineered fusion protein comprising
a diphosphate synthase or prenyltransferase of the mevalonate pathway and a nudix hydrolase; or
a diphosphate synthase or prenyltransferase of the mevalonate pathway, a nudix hydrolase and a geranyl synthase enzyme (GES) of the terpene synthase pathway;
or
a diphosphate synthase or prenyltransferase of the mevalonate pathway and a GES of the terpene synthase pathway.
28. The engineered fusion protein according to claim 27, wherein the diphosphate synthase or prenyltransferase is located downstream of the nudix hydrolase.
29. The engineered fusion protein according to claims 27 or 28, wherein the GES is located between the diphosphate synthase and the nudix hydrolase or between the prenyltransferase and the nudix hydrolase.
30. The engineered fusion protein according to any one of claims 27 to 29, further comprising one or more linker sequences, wherein the one or more linker sequences is located between the nudix hydrolase and the diphosphate synthase or prenyltransferase of the fusion protein; wherein the linker is linked to the C-terminal of the nudix hydrolase and the N-terminal of the diphosphate synthase or prenyltransferase; and wherein the linker sequence comprises the sequence set forth in SEQ ID NO: 17 or SEQ ID NO: 18.
31. A method of geraniol, geranyl acetate, or geraniol and geranyl acetate production comprising culturing the host cell according to any one of claims 1 to 26 in a culture medium, wherein the culture medium comprises an inducer and at least one carbon substrate.
32. The method according to claim 31, wherein the inducer is lactose or IPTG, and wherein the at least one carbon substrate is selected from the group consisting of glucose, glycerol, lactose, sucrose and combinations thereof.
33. A kit for producing geraniol, geranyl acetate, or geraniol and geranyl acetate, wherein the kit comprises the host cell of any one of claims 1 to 26 with instructions for use.
34. The kit according to claim 33, wherein the host cell is dissolved in solution or lyophilized.

35. The kit according to claim 34, wherein the host cell is preserved by deep freezing.