5-13-2014

Cytochrome P450S and Uses Thereof

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(54) CYTOCHROME P450S AND USES THEREOF

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(21) Appl. No.: 13/986,446

(22) Filed: May 3, 2013

(65) Prior Publication Data

Related U.S. Application Data

(63) Continuation of application No. 13/199,349, filed on Aug. 26, 2011, now Pat. No. 8,445,231, which is a continuation of application No. 12/182,000, filed on Jul. 29, 2008, now Pat. No. 8,263,362, which is a continuation of application No. 10/097,559, filed on Mar. 8, 2002, now Pat. No. 7,405,057.

(60) Provisional application No. 60/274,421, filed on Mar. 9, 2001, provisional application No. 60/275,597, filed on Mar. 13, 2001.

(51) Int. Cl.
C12N 1/00 (2006.01)
C12N 1/06 (2006.01)
C12N 5/00 (2006.01)
C12N 5/07 (2010.01)

(52) U.S. Cl.
USPC ........ 435/69.1; 435/468; 435/348; 435/252.1; 435/252.2; 435/155; 435/419

(58) Field of Classification Search
None
See application file for complete search history.

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ABSTRACT

The invention features isolated cytochrome P450 polypeptides and nucleic acid molecules, as well as expression vectors and transgenic plants containing these molecules. In addition, the invention features uses of such molecules in methods of increasing the level of resistance against a disease caused by a plant pathogen in a transgenic plant, in methods for producing altered compounds, for example, hydroxylated compounds, and in methods of producing isoprenoid compounds.

29 Claims, 11 Drawing Sheets
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FIG. 1

farnesyl diphosphate ➔
EAS ➔

1-deoxycapsidiol
(3-hydroxy-5-epi-aristolochene)

3-deoxycapsidiol
(1-hydroxy-5-epi-aristolochene)

5-epi-aristolochene

+ NADPH
+ O₂

capsidiol
FIG. 2

Time after elicitation (h)

Enzyme activity (% of maximum)
FIG. 4A

FIG. 4B

KETLRLH-for 5'-AARGARACIYTIMGYTIACA-3'
KETLRLY-for 5'-AARGARACIYTIMGYTITA-3'
KETLRLR-for 5'-AARGARACIYTIMGYTMG-3'
FXPERF-for 5'-TTYIIIICIGARMGTTY-3'
FXPERF-rev 5'-RAAICKYTCIGGIIIRAA-3'
GRRXCP(A/G)-for 5'-GGIMGIMIIITGYCCIGS-3'
PFGXGRR-rev 5'-CKICKICIIIIIICRAAIGG-3'
T7 5'-GTAATACGACTCACTATAGGG-3'
T3 5'-CAATTAACCCTACTAAAGGG-3'

FIG. 4C
FIG. 7A
71D A+
71D A-

FIG. 7B
empty A+
empty A-

FIG. 7C
71D D+
71D D-

FIG. 7D
empty D+
empty D-
Figure 8C
CYTOCHROME P450S AND USES THEREOF

RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 13/199,349, filed Aug. 26, 2011 (now issued U.S. Pat. No. 8,445,231), which is a continuation of U.S. patent application Ser. No. 12/182,000, filed Jul. 29, 2008 (now issued U.S. Pat. No. 8,263,362), which is a continuation of U.S. patent application Ser. No. 10/907,559, filed Mar. 8, 2002 (now issued U.S. Pat. No. 7,405,057), which claims the benefit of U.S. Provisional Application Nos. 60/274,421 and 60/275,597, filed on Mar. 9, 2001 and Mar. 13, 2001, respectively, all of which are hereby incorporated by reference.

FIELD OF THE INVENTION

This invention relates to cytochrome P450s and uses thereof.

BACKGROUND OF THE INVENTION

Cytochrome P450s encompass a superfamily of oxidases responsible for the oxidation of numerous endobiotics and thousands of xenobiotics. In addition, in plants, cytochrome P450s play important roles in wound healing, pest resistance, signaling, and anti-microbial and anti-fungal activity.

Capsidiol is a bicyclic, dihydroxylated sesquiterpene produced by many Solanaceae species in response to a variety of environmental stimuli, including exposure to UV (Bacq et al., Plant Cell Physiol. 39:899-904, 1998) and infection by microorganisms (Molot et al., Physiol. Plant Pathol. 37:39-39, 1981; Stolle et al., Phytopathology 78:1193-1197, 1988; Keller et al., Planta. 205:467-476, 1998). It is the primary antibiotic or phytoalexin produced in tobacco in response to fungal elicitation, and it is derived from the isoprenoid pathway via its hydrocarbon precursor, 5-epi-aristolochene (FIG. 1). Several of the biosynthetic enzymes leading up to 5-epi-aristolochene formation have been studied (Chappell, Annu. Rev. Plant Physiol. Plant Mol. Biol. 46:521-547, 1995), especially 5-epi-aristolochene synthase (BAS) (Vogeli and Chappell, Plant Physiol. 88:1291-1296, 1988; Bacq and Chappell, Proc. Natl. Acad. Sci. USA. 93:6841-6845, 1996; Mathis et al., Biochemistry 36:8340-8348, 1997; Stark et al., Science 277:1815-1820, 1997), BAS commits carbon to sesquiterpene metabolism by catalyzing the cyclization of farnesyl diphosphate (FPP) to 5-epi-aristolochene. However, until the present invention, the enzyme(s) responsible for the conversion of 5-epi-aristolochene to capsidiol has yet to be fully identified and characterized.

Biochemical evidence from previous studies in tobacco (Whitehead et al., Phytochemistry 28:775-779, 1989) and green pepper (Hoshino et al., Phytochemistry 38:609-613, 1995) has suggested that the oxidation of 5-epi-aristolochene to capsidiol occurs in two steps, with one of the hydroxylation steps being constitutive and the other being mediated by an elicitor-inducible cytochrome P450 (FIG. 1). Because 1-deoxycapsidiol had been isolated from natural sources (Watson et al., Biochem. Soc. Trans. 11:589-590, 1983), Whitehead et al. (Phytochemistry 28:775-779, 1989), surmised that perhaps the biosynthesis of this intermediate was due to pathogen induction of a corresponding hydroxylase. They therefore prepared synthetic 1-deoxycapsidiol and reported a modest conversion of this compound to capsidiol when fed to control or unelicited tobacco cell cultures. This was further supported by their observation that radiolabeled 5-epi-aristolochene was only converted to capsidiol when fed to elicitor-induced cell cultures but not control cultures. Whitehead et al. (Phytochemistry 28:775-779, 1989) therefore concluded that the 3-hydroxylase, responsible for hydroxylation of 5-epi-aristolochene at C3 to generate 1-deoxycapsidiol, was pathogen elicitor inducible, while the 1-hydroxylase, responsible for hydroxylation 1-deoxycapsidiol at C1 to generate capsidiol, was constitutive. Hoshino et al. (Phytochemistry 38:609-613, 1995) added to the observations of Whitehead et al. (Phytochemistry 28:775-779, 1989) by directly measuring 3-hydroxylase activity in microsomal preparations of arachidonic acid-elicited Capsicum annuum fruits and seedlings. These assays consisted of incubating 5-epi-aristolochene with microsome preparations and subsequently determining the amount of 1-deoxycapsidiol generated by a combination of thin-layer chromatography (TLC) separations and gas chromatography (GC). Their evidence demonstrated that the conversion of 5-epi-aristolochene to 1-deoxycapsidiol was dependent on both NADPH and O2, and that 1-deoxycapsidiol accumulation in vitro was arrested by the P450 antagonists carbon monoxide (Omura and Sato, J. Biol. Chem. 239:2370-2378, 1964), anisomycin (Coolbaugh et al., Plant Physiol. 62:571-576, 1978), and ketoconazole (Rademacher, Annu. Rev. Plant Physiol. Physiol. Plant Mol. Biol. 51:501-531, 2000).

Recent results suggest that the hydroxylation of 5-epi-aristolochene is an important regulated step in capsidiol biosynthesis. In studies to evaluate the effectiveness of methyljasmonate as an inducer of capsidiol biosynthesis in tobacco cell cultures, Mandujano-Chávez et al. (Arch. Biochem. Biophys. 381:285-294, 2000), reported that the modest accumulation of this phytoalexin was accompanied by a strong induction of EAS. This result implied that steps before or after the sesquiterpene cyclase reaction were limiting. Using a bioin assay measuring the conversion rate of radiolabeled 5-epi-aristolochene to capsidiol, a very limited induction of the hydroxylase activity was observed in cells treated with methyl jasmonate relative to that in fungal elicitor-treated cells. This result pointed to the hydroxylase reactions as a potentially limiting step in capsidiol biosynthesis.

SUMMARY OF THE INVENTION

In one aspect, the invention features several isolated cytochrome P450 polypeptides (such as CYP71D20, CYP71D21, CYP73A27, CYP73A28, and CYP92A5, and P450s having substantial identity to these polypeptides), as well as isolated nucleic acid molecules that encode these P450s.

In related aspects, the invention features a vector (such as an expression vector) including an isolated nucleic acid molecule of the invention and a cell (for example, a prokaryotic cell, such as Agrobacterium or E. coli, or an eukaryotic cell, such as a mammalian, insect, yeast, or plant cell) including the isolated nucleic acid molecule or vector.

In yet another aspect, the invention features a transgenic plant or transgenic plant component including a nucleic acid molecule of the invention, wherein the nucleic acid molecule is expressed in the transgenic plant or the transgenic plant component. Preferably, the transgenic plant or transgenic plant component is an angiosperm (for example, a monocot or dicot). In preferred embodiments, the transgenic plant or transgenic plant component is a solanaceous, maize, rice, or cruciferous plant or a component thereof. The invention further includes a seed produced by the transgenic plant or transgenic plant component, or progeny thereof.

In another aspect, the invention features a method of providing an increased level of resistance against a disease caused by a pathogen in a transgenic plant. The method
involves: (a) producing a transgenic plant cell including the nucleic acid molecule of the invention integrated into the genome of the transgenic plant cell and positioned for expression in the plant cell; and (b) growing a transgenic plant from the plant cell wherein the nucleic acid molecule is expressed in the transgenic plant and the transgenic plant is thereby provided with an increased level of resistance against a disease caused by a plant pathogen.

In another aspect, the invention features a method for producing an altered compound, the method including the steps of contacting the compound with one or more of the isolated polypeptides disclosed herein under conditions allowing for the hydrolyzation, oxidation, demethylation, or methylation of the compound and recovering the altered compound.

In still another aspect, the invention features a hydroxylating agent including any of the isolated polypeptides disclosed herein.

In yet another embodiment, the invention features an isolated nucleic acid molecule that specifically hybridizes under highly stringent conditions to the complement of any one of the sequences described in SEQ ID NO:2 (CYP71D20), SEQ ID NO:4 (CYP71D21), SEQ ID NO:6 (CYP73A27), SEQ ID NO:8 (CYP73A28), or SEQ ID NO:12 (CYP92A5), wherein such a nucleic acid molecule encodes a cytochrome P450 polypeptide.

In another aspect, the invention features a host cell expressing a recombinant isoprenoid synthase and a recombinant cytochrome P450. In preferred embodiments, the host cell further expresses, independently or in combination, a recombinant acetyltransferase, methyltransferase, or fatty acyltransferase. In other preferred embodiments, the host expresses an endogenous or recombinant cytochrome reductase. Preferably, the host cell is a yeast cell, a bacterial cell, an insect cell, or a plant cell.

In a related aspect, the invention features a method for producing an isoprenoid compound, the method including the steps of: (a) culturing a cell that expresses a recombinant isoprenoid synthase and a recombinant cytochrome P450 under conditions wherein the isoprenoid synthase and the cytochrome P450 are expressed and catalyze the formation of an isoprenoid compound not normally produced by the cell; and (b) recovering the isoprenoid compound. In preferred embodiments, the host cell further expresses a recombinant acetyltransferase, a recombinant methyltransferase, or a recombinant fatty acyltransferase. In other preferred embodiments, the host cell expresses an endogenous or recombinant cytochrome reductase. Preferably, the host cell is a yeast cell, a bacterial cell, an insect cell, or a plant cell.

In yet another aspect, the invention features an isoprenoid compound produced according to the above-mentioned methods.

By “P450 polypeptide,” “cytochrome P450,” or “P450” is meant a polypeptide that contains a heme-binding domain and shows a CO absorption spectra peak at 450 nm according to standard methods, for example, those described herein. Such P450s may also include, without limitation, hydroxylase activity, dual hydroxylase activity, demethylase activity, or oxidae activity. Such enzymatic activities are determined using methods well known in the art.

By “polypeptide” is meant any chain of amino acids, regardless of length or post-translational modification (for example, glycosylation or phosphorylation).

By “substantially identical” is meant a polypeptide or nucleic acid exhibiting at least 80 or 85%, preferably 90%, more preferably 95%, and most preferably 97%, or even 98% identity to a reference amino acid sequence (for example, the amino acid sequence shown in SEQ ID NOS: 1, 3, 5, 7 and 11) or nucleic acid sequence (for example, the nucleic acid sequences shown in SEQ ID NOS: 2, 4, 6, 8 and 12, respectively). For polypeptides, the length of comparison sequences will generally be at least 16 amino acids, preferably at least 20 amino acids, more preferably at least 25 amino acids, and most preferably 35 amino acids. For nucleic acids, the length of comparison sequences will generally be at least 50 nucleotides, preferably at least 60 nucleotides, more preferably at least 75 nucleotides, and most preferably 110 nucleotides.

Sequence identity is typically measured using sequence analysis software (for example, Sequence Analysis Software Package of the Genetics Computer Group, University of Wisconsin Biotechnology Center, 1710 University Avenue, Madison, Wis. 53705, BLAST, or PILEUP/PRETTYBOX programs). Such software matches identical or similar sequences by assigning degrees of homology to various substitutions, deletions, and/or other modifications. Conservative substitutions typically include substitutions within the following groups: glycine, alanine, valine, isoleucine, leucine; aspartic acid, glutamic acid, asparagine, glutamine; serine, threonine; lysine, arginine; and phenylalanine, tyrosine.

By an “isolated polypeptide” is meant a P450 polypeptide (for example, a CYP71D20 (SEQ ID NO:1), CYP71D21 (SEQ ID NO:3), CYP73A27 (SEQ ID NO:5), CYP73A28 (SEQ ID NO:7), or CYP92A5 (SEQ ID NO:11) polypeptide) that has been separated from components that naturally accompany it. Typically, the polypeptide is isolated when it is at least 60%, by weight, free from the proteins and naturally-occurring organic molecules with which it is naturally associated. Preferably, the preparation is at least 75%, more preferably at least 90%, and most preferably at least 95%, by weight, a P450 polypeptide. An isolated P450 polypeptide may be obtained, for example, by extraction from a natural source (for example, a plant cell); by expression of a recombinant nucleic acid encoding a P450 polypeptide; or by chemically synthesizing the protein. Purity can be measured by any appropriate method, for example, column chromatography, polyacrylamide gel electrophoresis, or by HPLC analysis.

By “derived from” or “obtained from” is meant isolated from or having the sequence of a naturally-occurring sequence (e.g., CDNA, genomic DNA, synthetic, or combination thereof).

By “isolated nucleic acid molecule” is meant a nucleic acid molecule, e.g., a DNA molecule, that is free of the nucleic acid sequence(s) which, in the naturally-occurring genome of the organism from which the nucleic acid molecule of the invention is derived, flank the nucleic acid molecule. The term therefore includes, for example, a recombinant DNA that is incorporated into a vector; into an autonomously replicating plasmid or virus; or into the genomic DNA of a prokaryote or eukaryote; or that exists as a separate molecule (for example, a CDNA or a genomic or cDNA fragment produced by PCR or restriction endonuclease digestion) independent of other sequences. The term “isolated nucleic acid molecule” also includes a recombinant DNA which is part of a hybrid gene encoding additional polypeptide sequences.

By “specifically hybridizes” is meant that a nucleic acid sequence is capable of hybridizing to a DNA sequence at least under low stringency conditions, and preferably under high stringency conditions. For example, high stringency conditions may include hybridization at approximately 42°C in about 50% formamide, 0.1 mg/ml sheared salmon sperm DNA, 1% SDS, 2xSSC; 10% Dextran sulfate, a first wash at approximately 65°C in about 2xSSC, 1% SDS, followed by a second wash at approximately 65°C in about 0.1xSSC.
Alternatively high stringency conditions may include hybridization at approximately 42° C. in about 50% formamide, 0.1 mg/mL sheared salmon sperm DNA, 0.5% SDS, 5×SSPE, 1× Denhardt’s, followed by two washes at room temperature in 2×SSC, 0.1% SDS, and two washes at between 55-60° C. in 0.2×SSC, 0.1% SDS. Reducing the stringency of the hybridization conditions may involve lowering the wash temperature and/or washing at a higher concentration of salt. For example, low stringency conditions may include washing in 2×SSC, 0.1% SDS at 40° C.

By “transformed cell” is meant a cell into which (or into an ancestor of which) has been introduced, by means of recombinant DNA techniques, a DNA molecule encoding (as used herein) a P450 polypeptide.

By “positioned for expression” is meant that the DNA molecule is positioned adjacent to a DNA sequence which directs transcription and translation of the sequence (i.e., facilitates the production of, for example, a P450 polypeptide; a recombinant protein, or an RNA molecule).

By “reporter gene” is meant a gene whose expression may be assayed; such genes include, without limitation, beta-gluconicidase (GUS), Luciferase, chloramphenicol transacylase (CAT), green fluorescent protein (GFP), beta-galactosidase, herbicide resistant genes, and antibiotic resistance genes.

By “expression control region” is meant any minimal sequence sufficient to direct transcription. Included in the invention are promoter elements that are sufficient to render promoter-dependent gene expression controllable for cell-, tissue-, or organ-specific gene expression, or elements that are inducible by external signals or agents (for example, light, pathogen-, wound-, stress-, or hormone-inducible elements or chemical inducers such as salicylic acid (SA) or 2,2-dichloroisonicotinic acid (INA)); such elements may be located in the 5’ or 3’ regions of the native gene or engineered into a transgene construct.

By “operably linked” is meant that a gene and a regulatory sequence(s) are connected in such a way as to permit gene expression when the appropriate molecules (for example, transcriptional activator proteins) are bound to the regulatory sequence(s).

By “plant cell” is meant any self-propagating cell bounded by a semi-permeable membrane and typically is one containing a plastid. Such a cell also requires a cell wall if further propagation is desired. Plant cell, as used herein includes, without limitation, algae, cyanobacteria, seeds, suspension cultures, embryos, meristem regions, callus tissue, leaves, roots, shoots, gametophytes, sporophytes, pollen, and microspores.

By “plant component” is meant a part, segment, or organ obtained from an intact plant or plant cell. Exemplary plant components include, without limitation, somatic embryos, leaves, stems, roots, flowers, tendrils, fruits, scions, and rootstocks.

By “transgene” is meant any piece of DNA which is inserted by artifice into a cell and typically becomes part of the genome, for example, the nuclear or plastidic genome, of the organism which develops from that cell. Such a transgene may include a gene which is partly or entirely heterologous (i.e., foreign) to the transgenic organism, or may represent a gene homologous to an endogenous gene of the organism.

By “transgenic” is meant any cell which includes a DNA sequence which is inserted by artifice into a cell and becomes part of the genome of the organism which develops from that cell. As used herein, the transgenic organisms are generally transgenic plants and the DNA (transgene) is inserted by artifice into the nuclear or plastidic genome. A transgenic plant according to the invention may contain one or more engineered traits.

By “pathogen” is meant an organism whose infection of viable plant tissue elicits a disease response in the plant tissue. Such pathogens include, without limitation, bacteria, mycoplasmas, fungi, insects, nematodes, viruses, and viroids. Plant diseases caused by these pathogens are described in Chapters 11-16 of Agrios, Plant Pathology, 3rd ed., Academic Press, Inc., New York, 1988.

By “increased level of resistance” is meant a greater level of resistance to a disease-causing pathogen in a transgenic plant (or cell or seed thereof) of the invention than the level of resistance relative to a control plant (for example, a non-transgenic plant). In preferred embodiments, the level of resistance in a transgenic plant of the invention is at least 20% (and preferably 30% or 40%) greater than the resistance of a control plant. In other preferred embodiments, the level of resistance to a disease-causing pathogen is 50% greater, 60% greater, and more preferably even 75% or 90% greater than a control plant; with up to 100% above the level of resistance as compared to a control plant being most preferred. The level of resistance is measured using conventional methods. For example, the level of resistance to a pathogen may be determined by comparing physical features and characteristics (for example, plant height and weight, or by comparing disease symptoms, for example, delayed lesion development, reduced lesion size, leaf wilting and curling, water-soaked spots, and discoloration of cells) of transgenic plants.

By “purified antibody” is meant antibody which is at least 60%, by weight, free from proteins and naturally-occurring organic molecules with which it is naturally associated. Preferably, the preparation is at least 75%, more preferably 90%, and most preferably at least 99%, by weight, antibody, for example, an acquired resistance polypeptide-specific antibody. A purified P450 antibody may be obtained, for example, by affinity chromatography using a recombinantly-produced P450 polypeptide and standard techniques.

By “specifically binds” is meant an antibody which recognizes and binds a P450 protein but which does not substantially recognize and bind other molecules in a sample, for example, a biological sample, which naturally includes a P450 protein such as CYP71D20, CYP71D21, CYP73A27, CYP73A28, or CYP92A5.

Other features and advantages of the invention will be apparent from the following description of the preferred embodiments thereof, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a proposed alternative pathway for the biosynthesis of capsidial in elicitor-treated Nicotiana tabacum cells. 5-epi-aristolochene is synthesized from FPP by the action of a sesquiterpene cyclase, 5-epi-aristolochene synthase (EAS), and is subsequently hydroxylated at C1 and C3 to form capsidial.

FIG. 2 is a graph showing an induction time course for sesquiterpene cyclase enzyme activity and sesquiterpene hydroxylase activity in cellulase-treated cell cultures. Sesquiterpene cyclase (5-epi-aristolochene synthase, EAS) enzyme activity was determined in extracts prepared from control (open squares) and elicitor-treated (closed squares) cells collected at the indicated time points. Sesquiterpene hydroxylase activity was determined using an indirect assay for control (open circles) and elicitor-treated (closed circles) cells. Cell cultures were incubated with [1,4]-5-epi-aristolochene for 3 hours ending at the indicated time points.
before quantifying the incorporation of radioactivity into extracellular capsidiol, a dihydroxylated form of aristolochene (Mandujano-Chavez et al., Arch. Biochem. Biophys. 381: 285-294, 2000).

FIGS. 3A-3B are a series of graphs showing the dose-dependent inhibition of 5-epi-aristolochene hydroxylase activity, by aneyamidol and ketocoumarol. Cell cultures were incubated in the presence of cellulase (0.5 μg/mL) plus the indicated concentrations of aneyamidol (A) or ketocoumarol (B) for 12 hours prior to measuring the in vivo 5-epi-aristolochene hydroxylase activity in the cell suspension cultures (squares), or the EAS enzyme activity in extracts prepared from the collected cells (triangles). The in vitro activity of a purified EAS preparation (Back and Chappell, J. Biol. Chem. 270: 7375-7381, 1995) was also measured at the indicated inhibitor concentrations as an additional test for non-specific effects of these inhibitors (circles).

FIG. 4A is a schematic diagram of the primary structure of a generalized cytochrome P450 with conserved domains used for the design of PCR primers highlighted (SEQ ID NOS: 26-29).

FIG. 4B is a list of the degenerate P450-specific primers (SEQ ID NOS: 30-36) that were used in various combinations with vector specific primers in the amplification of cytochrome P450 cDNA fragments.

FIG. 4C is a scannogram of an ethidium bromide-stained agarose gel showing the PCR products amplified from a directionally cDNA library prepared with mRNA isolated from elicitor-treated cells using the degenerate primer GRRXCP (AG) for (SEQ ID NO: 35) and the T7 vector-specific primer (SEQ ID NO: 37). The T3 vector-specific primer is also shown (SEQ ID NO: 38).

FIG. 5 is a series of Northern blots showing the induction time course for CYP71D, CYP73A, CYP82E, CYP92A, and EAS transcript accumulation in elicitor treated cells. Total RNA was extracted from tobacco suspension cells incubated with the cellulase elicitor for the indicated durations, size fractionated by agarose gel electrophoresis under denaturing conditions, and transferred to a nylon membrane before probing with the respective full-length cDNAs. The uniformity of sample loading was verified by ethidium bromide staining of ribosomal RNA (Loading control).

FIGS. 6A-6B are a series of graphs showing carbon monoxide (CO) difference spectra of the microsomal fraction isolated from yeast expressing the CYP92A5 (A) and CYP71D20 (B) cDNAs. Expression of the respective plasmid constructs engineered into the yeast (WAT11) cells was induced by a galactose treatment, followed by isolation of microsomal preparations. The difference adsorption spectra of microsomes incubated in the presence (solid lines) and absence (broken lines) of carbon monoxide was determined.

FIGS. 7A-7D are a series of gas chromatograms of the reaction products formed upon incubation of microsomes isolated from WAT11 yeast cells containing the CYP71D20 expression construct (A and C) or vector control DNA (B and D) with sesquiterpene substrates. Microsomes isolated from the indicated yeast lines were incubated with 5-epi-aristolochene (A and B) or 1-deoxycapsidiol (C and D) in the presence (solid lines) or absence (dashed lines) of NADPH. The identities of 5-epi-aristolochene, 1-deoxycapsidiol, and capsidiol were verified by mass spectrometry.

FIGS. 8A-8D provide a sequence comparison of the amino acid sequence of Nicolitoca tabacum 5-epi-aristolochene (sesquiterpene) hydroxylase NcCYP71D20 (SEQ ID NO:1) with other plant terpene hydroxylases (SEQ ID NOS: 39-43). NcCYP71A5v1 (GenBank accession number CAAT70576) catalyzes the mono-hydroxylation of arnel and geraniol, lin-ear monoterpenes, while PaCYP71A1 (A35867) catalyzes the epoxidation of these substrates (Hallahan et al., Biochim. Biophys. Acta. 1201:94-100, 1994). MsCYP71D18 (AAD44150) and MpCYP71D13 (AAD44151) catalyze the mono-hydroxylation at C6 and C3 of limonene, a cyclic monoterpenone, respectively (Lupien et al., Arch. Biochem. Biophys. 358:181-192, 1999). AcCYP701A3 (AAX39505) encodes for kaurene oxidase, which catalyzes a 3-step reaction including a hydroxylation followed by oxidation of a sesquiterpene (Hellwell et al., Plant Physiol. 119:507-510, 1999). Shown are sequences from Mentha piperita (MPCYP71D13; SEQ ID NO:39), Mentha spicata (MsCYP71D18; SEQ ID NO:40), Nepeta racemosa (NcCYP71A5v1; SEQ ID NO:41), Nicotiana tabacum (NcCYP71D20; SEQ ID NO:11), Persea americana (PaCYP71A1; SEQ ID NO:42), and Arabidopsis thaliana (CYP701A3; SEQ ID NO:43). Conserved residues are shaded.

DETAILED DESCRIPTION

Capsidiol is a bicyclic, dihydroxylated sesquiterpene produced by several Solanaceae species in response to a variety of environmental stimuli. It is the primary antimicrobial compound produced by Nicotiana tabacum in response to fungal elicitation, and it is formed via the isoprenoid pathway from 5-epi-aristolochene. Much of the biosynthetic pathway for the formation of this compound has been elucidated, except for the enzyme(s) responsible for the conversion of the allylic sesquiterpene 5-epi-aristolochene to its dihydroxylated form, capsidiol.

Accordingly, an in vivo assay for 5-epi-aristolochene hydroxylase activity was developed and used to demonstrate a dose-dependent inhibition of activity by aneyamidol and ketocoumarol, two well-characterized inhibitors of cytochrome P450 enzymes. Using degenerate oligonucleotide primers designed to the well-conserved domains found within most P450 enzymes, including the eukaryotic binding domain, cDNA fragments representing four distinct P450 families (CYP71, CYP73, CYP82, and CYP92) were amplified from a cDNA library prepared against mRNA from elicitor-treated cells using PCR. The PCR fragments were subsequently used to isolate full-length cDNAs (CYP71D20 (SEQ ID NO:2) and D21 (SEQ ID NO:4), CYP73A27 (SEQ ID NO:6) and A28 (SEQ ID NO:8), CYP82E2 (SEQ ID NO:10), and CYP92A5 (SEQ ID NO:12)), and these in turn were used to demonstrate that the corresponding mRNAs were all induced in elicitor-treated cells, albeit with different induction patterns.

EXAMPLES

There now follows a description of the cloning of several P450s from Nicotiana tabacum. These examples are provided for the purpose of illustrating the invention, and are not to be considered as limiting.

Inhibition of the 5-Epi-Aristolochene to Capsidiol Conversion by P450 Antagonists

Using an indirect assay, a detailed induction time course of 5EAH activity in elicitor-induced cell cultures was determined relative to that of EAS activity (FIG. 2), the well-characterized sesquiterpene cyclase activity that catalyzes the formation of 5-epi-aristolochene from FPP (FIG. 1). Using assays for EAS and 5EAH, EAS activity is not detectable in control cell cultures, but is induced significantly within 3 hours and reaches its maximal level within 15 to 18 hours of elicitor-treatment. Similar to the EAS enzyme activity, 5EAH
activity was negligible in control cell cultures. Nonetheless, after an apparent lag phase of 8 hours, a rapid induction of hydroxylase activity was observed 10 hours post elicitor addition to the cell cultures, reaching a maximum by 18 hours followed by a rather gradual decline of 10 to 20% over the next 8 hours.

Tobacco cell suspension cultures treated with cellulase plus varying concentrations of anacardol or ketoconazole were pre-incubated for 12 hours before measuring the cells’ ability to convert exogenous supplied [3H] labeled 5-epi- aristolochene to radiolabeled capsidol during a subsequent 3 hour incubation period (FIGS. 3A-3B). Apparent activity of 5EAI was inhibited in a dose-dependent manner with approximately 50% inhibition by either 25 μM anacardol or ketoconazole, and more than 80% by 75 μM anacardol and 95% by 100 μM ketoconazole (FIGS. 3A and 3B). Importantly, neither the in vitro activity of recombinant EAs nor the induction of EAs in the elicitor-treated cell cultures was significantly affected by anacardol at concentrations as high as 100 μM (FIG. 3A). Ketoconazole also does not appear to affect the in vitro activity of EAs. However, the inducibility of cyclase activity in elicitor-treated cell extracts was inhibited by ketoconazole at concentrations above 50 μM (FIG. 3B). Therefore, the specificity of ketoconazole as an inhibitor of P450 type reactions should be assessed at or below a concentration of 50 μM under these experimental conditions. Isolation of Elicitor-Inducible Cytochrome P450 cDNAs

A two-step approach for the isolation of candidate P450 cDNAs was followed. A PCR strategy was first employed using a directional cDNA library prepared from mRNA isolated from elicitor-induced cells as the template and degenerate PCR primers (FIGS. 4A-4C). Sequence alignments of cytochrome P450s from multiple families across kingdoms were used to identify conserved regions to which a series of degenerate primers were prepared (FIGS. 4A and 4B). In cloning experiments, 450 to 550 by products were expected from reactions utilizing the primer prepared to the home-binding domain (GRRXCPXAVG) (SEQ ID NO:27 and 28) and the T7 vector primer (FIG. 4C). The mixtures of reaction products were then cloned and, approximately 100 of the cloned PCR fragments were sequenced. About half of the sequenced cDNAs contained signature sequences typical of P450 enzymes as revealed by Blast X database searches, and these corresponded to typical plant P450 family members of the CYP17, CYP37, CYP92 and CYP92 classes. Each of these PCR fragments was isolated multiple times in separate experiments. In addition, we isolated full-length cDNAs for these P450 family members. Table I compares the similarity and identity of the full-length cDNAs of P450 family members with those of their nearest family member in the GenBank database. In addition, FIGS. 8A-8D shows an amino acid alignment of several terpene cytochrome P450s. Alignments were performed using the algorithm of the MACVECTOR software suite.

| Table 1
<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
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<td>Cytochrome P450 cDNA clone</td>
<td>Nearest relative accession number</td>
<td>% Identity</td>
<td>% Similarity</td>
<td></td>
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<tr>
<td>CYP71D20</td>
<td>CYP71D7 (S. chacoense)</td>
<td>76.5</td>
<td>88.8</td>
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<tr>
<td>CYP71D21</td>
<td>CYP71D7 (S. chacoense)</td>
<td>76.3</td>
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<tr>
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<tr>
<td>CYP73A28</td>
<td>CYP73A15 (P. vulgaris)</td>
<td>79.6</td>
<td>92.4</td>
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<tr>
<td>CYP82E1</td>
<td>CYP82E1 (N. tabaci)</td>
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<td>100.0</td>
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</tr>
<tr>
<td>CYP92A5</td>
<td>CYP92A3 (N. tabaci)</td>
<td>95.5</td>
<td>98.6</td>
<td></td>
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</tbody>
</table>

The cloned fragments were used in a second step to isolate full-length clones from the cDNA library. Screening the cDNA library by hybridization with the CYP71 and CYP73 gene fragments yielded four full-length cDNAs, two CYP71Ds and two CYP73As. The former clones were designated CYP71D20 and CYP71D21, and the latter were designated CYP73A27 and CYP73A28. The other two cDNA fragments corresponded to tobacco cDNAs already found in the GenBank database, CYP82E1 and CYP92A3. These two cDNAs were cloned using specific primers designed with the help of the available sequence information to amplify the full-length cDNA.

Induction of Cytochrome P450 mRNAs in Elicitor-Treated Cells

To correlate a biochemical role for P450s in sesquiterpene metabolism, RNA blot analyses were used to determine the steady-state levels of the mRNAs coding for all four of the cytochrome P450 clones and EAs in control and elicitor-treated cells (FIG. 5). The mRNAs for all four of the P450s were rapidly and transiently induced with slightly different time courses relative to one another and to the EAs mRNA. CYP73A27 mRNA, for instance, displayed an induction pattern similar to that of EAs with the maximum mRNA level occurring 9 to 12 hours after elicitation. While the EAs mRNA remained high throughout the duration of the experiment, the CYP73A27 mRNA was negligible in cells 24 hours after elicitor-treatment. In contrast, the CYP71D1 mRNA was more rapidly induced than the EAs mRNA, reaching its maximum 6 to 9 hours after elicitation, and was declining by 12 hours when the EAs mRNA level was still very high. Functional identification of CYP71D20 as 5-Epi-Aristolochene Hydroxylase

To ascertain functional identity to the various P450 cDNAs, full-length cDNAs for CYP71D20, CYP82E1 and CYP92A5 were inserted into the yeast expression vector pYeDP60 (Urban et al., Biochimie 72:463-472, 1990; Pompon et al., Methods Enzymol. 272:51-64, 1996) and the expression of each in WAT11, a yeast line containing an integrated Arabidopsis thaliana cytochrome reductase gene (Pompon et al., Methods Enzymol. 272:51-64, 1996; Urban et al., J. Biol. Chem. 272: 19176-19186, 1997), was determined. Engineering the CYP73A27 cDNA required an extra modification because of an unusually long N-terminus with several hydrophilic residues that may interfere with proper intracellular targeting (Nedelkina et al., Plant Mol. Biol. 39:1079-1090, 1999). This unusual leader sequence therefore was replaced with the membrane anchoring sequence of CYP73A1, a carnitine 4-hydroxylase previously demonstrated to express well in yeast (Führedorf and Dixon, Arch. Biochem. Biophys. 305: 509-515, 1993; Pompon et al., Methods Enzymol. 272:51-64, 1996). Expression of all these cDNAs was under the control of the glucose-repressible, galactose-inducible GAL10-CYC1 promoter (Giuriento et al., Proc. Natl. Acad. Sci.)
In vivo 5-Epi-Aristolochene Hydroxylase Assay and Inhibition Studies

5-epi-aristolochene hydroxylase–activity was measured as the incorporation of [3H]-5-epi-aristolochene into extracellular capsiidial by intact cells. [3H]-5-epi-aristolochene was produced by incubating an excess of [3H]-farnesyl diphosphate (1 µM, 20.5 Ci/mmol) with recombinant 5-epi-aristolochene synthase (Back et al., Arch. Biochem. Biophys. 315:527-532, 1994; Rising et al., J. Am. Chem. Soc. 122: 1861-1866, 2000). The hexane extractable radioactivity from reactions was treated with a small amount of silica to remove any farnesol or residual FPP before quantifying the yield of radioactive 5-epi-aristolochene by liquid scintillation counting. The hexane solvent was removed under a gentle stream of N2 gas, and the dried residue was re-dissolved in acetone. Control and elicitor-treated cells were then incubated with [3H]-5-epi-aristolochene (approximately 100,000 dpm at 2.5 nM) for 3 hour periods at various points during an induction time course before collecting the cell and media samples. Detection and quantification of capsiidial in the extracellular culture media was performed as reported previously (Chappell et al., Phytochemistry 26:2259-2260, 1987), and the amount of radioactivity incorporated into capsiidial was determined. For these determinations, samples were separated by TLC, and the zones corresponding to capsiidial were scraped from the plate for scintillation counting.

Inhibition studies were performed by the addition of the P450 inhibitors ancamidol (Coolbaugh et al., Plant Physiol. 62:571-576, 1978; Hoshino et al., Phytochemistry 38:609-613, 1995) and ketocazole (Hoshino et al., Phytochemistry 38:609-613, 1995; Rademacher, Annu. Rev. Plant Physiol. Plant Mol. Biol. 51:501-531, 2000) directly to the cell cultures or enzyme assay mix. Cell cultures were incubated in the presence of cellulase (0.5 µg/mL) and indicated concentrations of ancamidol or ketoconazole for 12 hours prior to the addition of [3H]-5-epi-aristolochene. After a further 3 hour incubation period, the cells and media were collected. The amount of radioactivity incorporated into extracellular capsidial was determined as described above. To evaluate secondary effects of these inhibitors, the level of inducible sesquiterpene cyclase activity in the collected cells was determined according to Vogel et al. (Plant Physiol. 93:182-187, 1990), as well as in vitro assays with purified recombinant EAS (Back et al., Arch. Biochem. Biophys. 315:527-532, 1994) incubated with the indicated concentrations of ancamidol and ketoconazole.

All experiments were replicated in several independent trials. While the absolute values presented may have varied between experiments by as much as 50%, the trends and time courses were consistent throughout.

Construction of an Elicitor-Induced cDNA Library

Cell cultures were incubated with fungal elicitor (0.5 µg cellulase/mL) for 6 hours before collecting the cells by filtration. The cells were kept frozen at ~80°C until total RNA was extracted from them using Trizol (Life Technologies, Rockville, Md.) according to the manufacturer’s instructions. Poly(A)+ RNA was purified by two rounds of oligo (dT) cellulose column chromatography (Life Technologies, Rockville, Md.). cDNA synthesis and library construction were subsequently carried out using the UNI-ZAP XR library kit (Stratagene, La Jolla, Calif.), according to manufacturer’s instructions.

PCR Cloning Strategy

Cytochrome P450 cDNA fragments were amplified from the elicitor-induced cDNA library using various combinations of degenerate forward and reverse primers with the vector-specific T3 and T7 primers. The template DNA was
prepared from a 500 μL aliquot of the elicitor-induced cDNA library (3×10^6 pfu/μL) by heat denaturation at 70°C for 10 minutes, followed by phenol/chloroform extraction, ethanol precipitation and re-suspension in 500 μL of sterile, deionized water. Amplification reactions were performed in 50 μL volumes containing 50 mM KCl; 10 mM Tris-HCl, pH 8.8; 1.5 mM MgCl₂; 200 μM of each dNTP; 2 μL template DNA; 20 pmol each of forward and reverse primer; and 1 unit Taq Polymerase (Life Technologies, Rockville, Md.). Reactions were preheated at 94°C for 2 minutes, followed by thirty-five cycles of denaturing at 94°C for 1 minute, annealing at 50°C for 1 minute 30 seconds, and polymerization at 72°C for 2 minutes. The reactions were completed by a 10-minute extension at 72°C. Aliquots of the reaction products were examined for DNA products by agarose gel fractionation, and ligated directly into the pGEM-T Easy vector (Promega, Madison, Wis.). Resulting recombinant plasmids containing insert DNAs within the expected size range were sequenced using 17 and Sp6 primers.

DNA Sequencing

All the DNA sequencing reactions were performed using the BIGDYE™ Terminator Cycle sequencing kit (Perkin-Elmer, Wellesley, Mass.) with the sequences being read on an automated ABI Prism 310 Genetic Analyzer (Applied Biosystems, Foster City, Calif.). Computer assessment of the sequencing results was performed using the MACVECTOR (Oxford Molecular, Madison, Wis.) software package.

cDNA Library Screening

The cDNA library was screened with digoxigenin labeled probes. A 258 bp DNA fragment amplified from the pGEM-deq6.4 clone using gene-specific forward (5'-GGCG-GAAGAATTTGTCTGAGTAGCTTGTTTGC-3') (SEQ ID NO:13) and reverse (5'-GTACAAATGGTTGGTGGACGG-3') (SEQ ID NO:14) primers; and a 374 bp DNA fragment amplified from the pBKS-CYPB3.84 clone with specific forward (5'-GGTGTTGTGTTGAAATGCAGT-3') (SEQ ID NO:15) and reverse (5'-TTAAGCGCAAAAG-GCCTGAGACAAC-3') (SEQ ID NO:16) primers, were used to screen for CYP71Ds. The probes were labeled with digoxigenin-11-dUTP using the PCR DIG Labeling Mix (Roche Molecular Biochemicals, Indianapolis, Ind.), hybridized to plaque lifts of the cDNA library plated at approximately 10,000 PFUs per 150 mm plate, and was hybridization detected with the DIG detection system according to the manufacturer’s instructions (Roche Molecular Biochemicals, Indianapolis, Ind.). Plaques exhibiting strong hybridization were plaque purified, auto subcloned to their plasmid forms according to the manufacturer’s recommendations (Stratagene, La Jolla, Calif.), and then subjected to DNA sequencing as described above.

RNA Analysis

RNA gel blot analysis was carried out using 10 vgt aliquots of total RNA. RNA samples were heat-denatured at 70°C for 15 minutes in sample buffer (1x MOPS, 50% formamide, 16% formaldehyde, 30% glycerol, and 3% ethidium bromide), and the samples were loaded onto a Zeta Probe nylon membrane (Bio-Rad Laboratories, Hercules, Calif.) and hybridized according to the manufacturer’s recommendations. Full-length cDNA probes were labeled with [32P]-dCTP (PRIME-IT Kit, Stratagene, La Jolla, Calif.) prior to hybridization. After hybridization, the membranes were washed in 2×SSC/0.1% SDS once at room temperature followed by sequential washes in 0.2×SSC/0.1% SDS at 42°C and 65°C. Hybridization was detected with a PhosphorImager (Molecular Dynamics, model 445 SI).

Construction of Yeast Expression Vectors

The coding regions of the P450 cDNAs were cloned into the pYEDP50 expression vector (Urban et al., J. Biol. Chem. 272:19176-19186, 1990; Pompon et al., Methods Enzymol. 272:51-64, 1996). Appropriate BamHI, EcoRI, and SstI restriction sites (underlined) were introduced via PCR primers containing these sequences either upstream of the translation start site (ATG) or downstream of the stop codon (TAA or TGA). The primers used to amplify the CYP71D20 cDNA were

GGATCCATGCAATTTGCTAGTTGTTCC-3' (SEQ ID NO:17) and 5'-GGG
GGATCTCTACCTTCAAGAAGGTCTGAATAAGG-3' (SEQ ID NO:18), for the CYP82E1 cDNA 5'-CCC
GGATCCATGTATGTCTTCTCTTCCTCCC-3' (SEQ ID NO:19) and 5'-GGG
GGATCTCATAATTGATAAAAGCAGTAGGAGG-3' (SEQ ID NO:20), and for the CYP92A5 cDNA 5'-CCC
GGATCCATGCAATTTGCTAGTTGTTCC-3' (SEQ ID NO:21) and 5'-GGG
GGATCTCATAATTGATAAAAGCAGTAGGAGG-3' (SEQ ID NO:22). Two long, overlapping (italized) primers
5'-GCCCATATAGGGCGCGAAATGCTACATTC-CAAACCTCCGGGTGAAAATCTAAGGCTCACCAGTCTGCTCAACAGCAGTC-3' (SEQ ID NO:23) and 5'-GGG
GGATCCATGCAATTTGCTAGTTGTTCC-3' (SEQ ID NO:17) and 5'-GGG
GGATCTCATAATTGATAAAAGCAGTAGGAGG-3' (SEQ ID NO:20).

cDNAs were amplified using full-length cDNA templates, whereas CYP82E1 was amplified directly from the cDNA library template. Amplifications were performed in 50 μL reactions containing 1× Pfx amplification buffer; 1 mM MgSO₄; 300 μM of each dNTP; 10 ng template DNA; 20 pmol each of forward and reverse primer; and 1.25 units PLATINUM® Pfx Polymerase (Life Technologies, Rockville, Md.). Reactions were preheated at 94°C for 2 minutes, followed by thirty-five cycles of denaturing at 94°C for 15 seconds, annealing at 55°C for 30 seconds, and elongating at 68°C for 1.5 minutes. PCR products were ligated into the pGEM-T Easy vector (Promega, Madison, Wis.) and subcloned into the pYEDP60 vector. The resulting constructs were validated by a combination of PCR and DNA sequencing.

Yeast Expression Studies

Verified pYEDP60-P450 cDNA constructs were introduced into the yeast WAT111 line, a derivative of the W303-1B strain (MATa; ade-2-1; his-3-11; leu-2-3,-112; ura-3-1; can4; cys4*), provided by Dr. P. Urban (Centre de Généétique Moléculaire, CNRS, Gif-sur-Yvette, France). The endogenous NADPH-cytochrome P450 reductase (CPR1) locus has been replaced with ATR1, a NADPH-cytochrome P450 reductase from Arabidopsis thaliana (Pompon et al., Methods Enzymol. 272:51-64, 1996; Urban et al., J. Biol. Chem. 272:19176-19186, 1997), in the WAT11 line. Yeast was grown overnight in a 30°C shaker in YPD (1 g yeast extract; 1 g/L peptone; 20 g/L glucose; 200 mg/L adenine) liquid media. Cultures were harvested at an A₆₀₀ between 0.5 and 1.5. Cells were collected by centrifugation at 2,500 g for 5 minutes at 4°C, and resus-
5-Epi-Aristolochene-1,3-Dihydroxylase Assays

5-epi-aristolochene-1,3-dihydroxylase assays were performed in 0.5 mL polyethylene tubes in 100 μL volumes. 5-epi-aristolochene or 1-deoxycapsidanol dissolved in hexane was added to the tube, and the organic solvent was removed by incubation of the open tube at 30°C. 5-epi-aristolochene and 1-deoxycapsidanol were resuspended in 2 μL dimethyl sulfoxide before adding the reaction mixture. Reactions were carried out in 100 mM Tris-Cl, pH 7.5, to which microsomal protein was added to a final concentration of 1 mg/mL. Reactions were initiated by the addition of 2 mM NADPH. The final concentration of 5-epi-aristolochene and 1-deoxycapsidanol in these assays varied from 20 to 50 μM. After incubation for variable lengths of time at 30°C, the reactions were extracted with two volumes of ethyl acetate. The organic extracts were concentrated and evaluated by GC and GC-MS along with standards of 5-epi-aristolochene (Whitehead et al., Phytochemistry 28:775-779, 1989; Rising et al., J. Am. Chem. Soc. 122:1861-1866, 2000), 1-deoxycapsidanol (Whitehead et al., Phytochemistry 29:479-182, 1990), and capsidalin (Whitehead et al., Phytochemistry 26:1367-1369, 1987; Milat et al., Phytochemistry 30:2171-2173, 1991). GC analysis was routinely performed with an HP5890 GC equipped with a Hewlett-Packard HP-5 capillary column (30 m x 0.25 mm, 0.25 μm phase thickness) and FID as described previously (Rising et al., J. Am. Chem. Soc. 122:1861-1866, 2000). GC-MS analysis was performed at the University of Kentucky Mass Spectrometry Facility using a Varian 3400 gas chromatograph and a Finnigan INCO5 50 quadrupole mass selective detector. The GC was equipped with a J&W DB-5 ms capillary column (15 m x 0.25 mm, 0.25 μm phase thickness) and run with He as the carrier gas (10 psi). Splitless injections were done at an injection port temperature of 280°C. The column temperature was maintained at 40°C for 1 minute and then increased to 280°C at 10°C per minute. Following separation by the GC column, samples were introduced directly into the electron impact ionization source. Mass spectra were acquired at 70 eV, scanning from 40-440 Da in 1 second.

Production of Cytochrome P450s

Using the standard molecular techniques described herein, the isolation of additional cytochrome P450 coding sequences is readily accomplished. For example, using all or a portion of the amino acid sequence of any of the disclosed P450s, one may readily design P450-specific oligonucleotide probes, including P450 degenerate oligonucleotide probes (i.e., a mixture of all possible coding sequences for a given amino acid sequence). These oligonucleotides may be based upon the sequence of either DNA strand and any appropriate portion of the P450 nucleotide sequence. General methods for designing and preparing such probes are provided, for example, in Ausubel et al., 2000, Current Protocols in Molecular Biology, Wiley Interscience, New York, and Berger and Kimmel, Guide to Molecular Cloning Techniques, 1987, Academic Press, New York. These oligonucleotides are useful for P450 gene isolation, either through their use as probes capable of hybridizing to a P450 complementary sequence, or as primers for various amplification techniques, for example, polymerase chain reaction (PCR) cloning strategies.

Hybridization techniques and screening procedures are well known to those skilled in the art and are described, for example, in Ausubel et al. (supra); Berger and Kimmel (supra); Chen et al. (Arch. Biochem. Biophys. 324:255, 1995); and Sambrook et al. (Molecular Cloning: A Laboratory Manual, Cold Spring Harbor Laboratory Press, New York). If desired, a combination of different oligonucleotide probes
may be used for the screening of a recombinant DNA library. The oligonucleotides may be detectably labeled using methods known in the art and used to probe filter replicas from a recombinant DNA library. Recombinant DNA libraries are prepared according to methods well known in the art, for example, as described in Ausubel et al. (supra), or they may be obtained from commercial sources.

As discussed above, P450 oligonucleotides may also be used as primers in a polymerase chain reaction (PCR) amplification cloning strategy. PCR methods are well known in the art and are described, for example, in PCR Technology, Erlich, ed., Stockton Press, London, 1989; PCR Protocols: A Guide to Methods and Applications, Innis et al., eds., Academic Press, Inc., New York, 1990; and Ausubel et al. (supra). Primers are optionally designed to allow cloning of the amplified product into a suitable vector, for example, by including appropriate restriction sites at the 5' and 3' ends of the amplified fragment (as described herein). If desired, a P450 gene may be isolated using the PCR “RACE” technique, or Rapid Amplification of cDNA Ends (see, e.g., Innis et al. (supra)). By this method, oligonucleotide primers based on a P450 sequence are oriented in the 3' and 5' directions and are used to generate overlapping PCR fragments. These overlapping 3'- and 5'-end RACE products are combined to produce an intact full-length cDNA. This method is described in Innis et al. (supra) and Frohman et al. (Proc. Natl. Acad. Sci. U.S.A. 85:8998, 1988).

Additional methods for identifying sequences encoding P450s are provided in Maughan et al. (Arch. Biochem. Biophys. 341:104-111, 1997) and Clark et al. (Plant Mol. Biol. 33:875-885, 1997).

Useful P450 sequences may be isolated from any appropriate organism. Confirmation of a sequence’s relatedness to a P450 polypeptide disclosed herein may be accomplished by a variety of conventional methods, for example, by comparing the sequence with a known P450 sequence found in a database. In addition, the activity of any P450 may be evaluated according to any of the techniques described herein.

P450 Polypeptide Expression

P450 polypeptides may be produced by transformation of a suitable host cell with all or part of a P450 DNA (for example, anyone of the P450 cDNAs described herein) in a suitable expression vehicle or with a plasmid construct engineered for increasing the expression of a P450 polypeptide in vivo.

Those skilled in the field of molecular biology will appreciate that any of a wide variety of expression systems may be used to provide the recombinant protein. The precise host cell used is not critical to the invention. The P450 protein may be produced in a prokaryotic host, for example, E. coli TB 1, or in an eukaryotic host, for example, Saccharomyces cerevisiae, insect cells, mammalian cells (for example, COS 1 or NIH 3T3 cells), or any of a number of plant cells including, without limitation, algae, tree species, ornamental species, temperate fruit species, tropical fruit species, vegetable species, legume species, monocots, dicots, or in any plant of commercial or agricultural significance. Particular examples of suitable plant hosts include, but are not limited to, Conilfers, Petunia, Tomato, Potato, Tobacco, Grape, Arabidopsis, Lettuce, Sunflower, Oilseed rape, Flax, Cotton, Sugarbeet, Celery, Soybean, Alfalfa, Medicago, Lotus, Vigna, Cucumber, Carrot, Eggplant, Cauliflower, Horseradish, Morning Glory, Poplar, Walnut, Apple, Asparagus, Grape, Rice, Maize, Millet, Onion, Barley, Orchard grass, Oat, Rye, Tobacco and Wheat.

Such cells are available from a wide range of sources including: the American Type Culture Collection (Rockland, Md.); or from any of a number of seed companies, for example, W. Atlee Burpee Seed Co. (Warminster, Pa.), Park Seed Co. (Greenwood, S.C.), Johnny Seed Co. (Albion, Me.), or Northerup King Seeds (Hartsville, S.C.). Descriptions and sources of useful host cells are also found in Vasil F. K., Cell Culture and Somatic Cell Genetics of Plants, Vol I, II, III; Laboratory Procedures and Their Applications, Academic Press, New York, 1984; Dixon, R. A., Plant Cell Culture—A Practical Approach, IRL Press, Oxford University, 1985; Green et al., Plant Tissue and Cell Culture, Academic Press, New York, 1987; and Gasser and Fraley, Science 244:1293, 1989.

For prokaryotic expression, DNA encoding a P450 polypeptide is carried on a vector operably linked to control signals capable of effecting expression in the prokaryotic host. If desired, the coding sequence may contain, at its 5' end, a sequence encoding any of the known signal sequences capable of effecting secretion of the expressed protein into the periplasmic space of the host cell, thereby facilitating recovery of the protein and subsequent purification. Prokaryotes most frequently used are various strains of E. coli; however, other microbial strains may also be used. Plasmid vectors are used which contain replication origins, selectable markers, and control sequences derived from a species compatible with the microbial host. Examples of such vectors are found in Povels et al. (supra) or Ausubel et al. (supra). Commonly used prokaryotic control sequences (also referred to as “regulatory elements”) are defined herein to include promoters for transcription initiation, optionally with an operator, along with ribosome binding site sequences. Promoters commonly used to direct protein expression include the beta-lactamase (penicillinate), the lactose (lac), the tryptophan (Trp) (Goeddel et al., Nucl. Acids Res. 8:4057, 1980), and the tac promoter systems, as well as the lambda-derived PsbL promoter and N-gene ribosome binding site (Simatake et al., Nature 292:128, 1981).

One particular bacterial expression system for P450 production is the E. coli pET expression system (Novagen). According to this expression system, DNA encoding a P450 is inserted into a pET vector in an orientation designed to allow expression. Since the P450 gene is under the control of the T7 regulatory signals, P450 expression is dependent on inducing the expression of T7 RNA polymerase in the host cell. This is typically achieved using host strains which express T7 RNA polymerase in response to IPTG induction. Once produced, recombinant P450 is then isolated according to standard methods known in the art, for example, those described herein.

Another bacterial expression system for P450 production is the pGEX expression system (Pharmacia). This system employs a GST gene fusion system that is designed for high-level expression of a gene or gene fragment as a fusion protein with rapid purification and recovery of the functional gene product. The P450 of interest is fused to the carboxyl terminus of the glutathione S-transferase protein from Schistosoma japonicum and is readily purified from bacterial lysates by affinity chromatography using Glutathione Sepharose 4B. Fusion proteins can be recovered under mild conditions by elution with glutathione. Cleavage of the glutathione S-transferase domain from the fusion protein is facilitated by the presence of recognition sites for site-specific proteases upstream of this domain. For example, proteins expressed in pGEX-2T plasmids may be cleaved with thrombin; those expressed in pGEX-3X may be cleaved with factor Xa.

Other prokaryotic systems useful for expressing eukaryotic P450s are described by Cooper (Muttat. Res. 45:45-52, 2000) and Dong et al. (Arch. Biochem. Biophys. 327:254-
expression cassette for such a protein, e.g., cytochrome P450, at a multiplicity of infection of 1 to 10. The infected cells are generally cultured in a standard insect cell culture medium for 24 to 48 hours prior to recovering the protein using standard molecular biology techniques. If desired, a P450 polypeptide may also be produced in insect cells directly transfected with a DNA construct containing an expression cassette encoding the P450.

Furthermore, any of the cytochrome P450s described herein may be produced in yeast, for example, *Pichia pastoris*. In order to produce the P450, yeast cells are transformed with an expression cassette containing, for example, a promoter such as the AOX1 or phosphoglycerate kinase gene promoter, the P450 gene to be expressed, and a terminator. Such an expression cassette may contain an origin of replication or it may be integrated into the yeast genomic DNA. The expression cassette is generally introduced by lithium acetate transformation or by the use of spheroplasts. In order to select for successfully transformed cells, the yeast are plated, for example, on minimal media which only allows yeast carrying the introduced expression cassette to grow.

In addition, expression of recombinant proteins in yeast using a *Hansenula polymorpha* expression system is described in U.S. Pat. Nos. 5,741,674 and 5,672,487.

A P450 may also be produced by a stably-transfected plant cell line or by a transgenic plant. Such genetically-engineered plants are useful for a variety of industrial and agricultural applications as discussed below. Importantly, this invention is applicable to gymnosperms and angiosperms, and will be readily applicable to any new or improved transformation or regeneration method.

A number of vectors suitable for stable transfection of plant cells or for the establishment of transgenic plants are available to the public; such vectors are described in Pourwels et al. (supra), Weissbach and Weissbach (supra), and Gelvin et al. (supra). Conditions for constructing such cell lines are described in, e.g., Weissbach and Weissbach (supra), and Gelvin et al. (supra). Typically, plant expression vectors include (1) a cloned P450 gene under the transcriptional control of 5' and 3' regulatory sequences and (2) a dominant selectable marker. Such plant expression vectors may also contain, if desired, a promoter regulatory region (for example, one conferring inducible or constitutive expression, or environmentally- or developmentally-regulated, or pathogen- or wound-inducible, or cell- or tissue-specific expression), a transcription initiation start site, a ribosome binding site, an RNA processing signal, a transcription termination site, and/or a polyadenylation signal.

The P450 DNA sequence of the invention may, if desired, be combined with other DNA sequences in a variety of ways. The P450 DNA sequence of the invention may be employed with all or part of the gene sequences normally associated with a P450. In its component parts, a DNA sequence encoding a P450 is combined in a DNA construct having a transcription initiation control region capable of promoting transcription and translation in a host cell.

In general, the constructs will involve regulatory regions functional in plants which provide for production of a P450 as discussed herein. The open reading frame coding for the P450, or a functional fragment thereof, will be joined at its 5' end to a transcription initiation regulatory region such as the sequence naturally found in the 5' upstream region of a P450 structural gene, for example, a CYP71D20 (SEQ ID NO:2) or CYP71D21 (SEQ ID NO:3) gene. Numerous other transcription initiation regions are available which provide for constitutive or inducible regulation.
For applications when developmental, cell, tissue, hormonal, environmental, or pathogen-inducible expression are desired, appropriate 5' downstream non-coding regions are obtained from other genes; for example, from genes regulated during seed development, embryo development, leaf development, or in response to a pathogen.

Regulatory transcript termination regions may also be provided in DNA constructs of this invention as well. Transcript termination regions may be provided by the DNA sequence encoding a P450 or any convenient transcript termination region derived from a different gene source. The transcript termination region will contain preferably at least 1-3 kb of sequence 3' to the structural gene from which the termination region is derived.

An example of a useful plant promoter according to the invention is a cauliflower mosaic virus (CaMV) promoter. These promoters confer high levels of expression in most plant tissues, and the activity of these promoters is not dependent on virally encoded proteins. CaMV is a source for both the 35S and 19S promoters. In most tissues of transgenic plants, the CaMV 35S promoter is a strong promoter (see, e.g., Odell et al., Nature 313:810, 1985). The CaMV promoter is also highly active in monocots (see, e.g., Dekeyser et al., Plant Cell 2:591, 1990; Terada and Shimamoto, Mol. Gen. Genet. 220:389, 1990). Moreover, activity of this promoter can be further increased (i.e., between 2-10 fold) by duplication of the CaMV 35S promoter (see, e.g., Kay et al., Science 236:1299, 1987; Ow et al., Proc. Natl. Acad. Sci. U.S.A. 84:4870, 1987; and Fang et al., Plant Cell 1:141, 1989). Other useful plant promoters include, without limitation, the nopaline synthase promoter (An et al., Plant Physiol. 88:547, 1988) and the octopine synthase promoter (Fromm et al., Plant Cell 1:977, 1989).

For certain applications, it may be desirable to produce the P450 gene product in an appropriate tissue, at an appropriate level, or at an appropriate developmental time. For this purpose, there is an assortment of gene promoters, each with its own characteristic traits embodied in its regulatory sequences, which have been shown to be regulated in response to the environment, hormones, and/or developmental cues. These include gene promoters that are responsible for heat-regulated gene expression (see, e.g., Callis et al., Plant Physiol. 88:965, 1988; Takahashi and Komeda, Mol. Gen. Genet. 219:365, 1989; and Takahashi et al., Plant J. 2:751, 1992); light-regulated gene expression (e.g., the pea rbcS-3A described by Kuhlemeier et al. (Plant Cell 1:471, 1989); the maize rbcS promoter described by Schaffiner and Sheen (Plant Cell 3:597, 1991); or the chlorophyll a/b-binding protein gene found in pea described by Simpson et al. (EMBO J. 4:2723, 1985); hormone-regulated gene expression (for example, the abscisic acid (ABA) responsive sequences from the Em gene of wheat described by Marcotte et al. (Plant Cell 1:969, 1989); the ABA-inducible HVA1 and HVA2, and the rd29A promoters described for barley and Arabidopsis by Straub et al. (Plant Cell 6:617, 1994), Shen et al. (Plant Cell 7:295, 1994); and wounding-induced gene expression (for example, of wani described by Siebertz et al. (Plant Cell 1:961, 1989); or organ-specific gene expression (for example, of the tuber-specific storage protein gene described by Roshal et al. (EMBO J. 6: 1155, 1987); the 23-kDa zein gene from maize described by Schmittner et al. (EMBO J. 7:1249, 1988); or the French bean beta-phaseolin gene described by Bustos et al. (Plant Cell 1:839, 1989); and pathogen-inducible gene expression described by Chappell et al. in U.S. Ser. Nos. 08/471,983, 08/443,639; and 08/577,483, hereby incorporated by reference.

Plant expression vectors may also optionally include RNA processing signals, for example, introns, which have been shown to be important for efficient RNA synthesis and accumulation (Callis et al., Genes and Dev. 1:1183, 1987). The location of the RNA splice sequences can dramatically influence the level of transgene expression in plants. In view of this fact, an intron may be positioned upstream or downstream of a P450-encoding sequence in the transgene to modulate levels of gene expression.

In addition to the aforementioned 5' regulatory control sequences, the expression vectors may also include regulatory control regions which are generally present in the 3' regions of plant genes (Thornburg et al., Proc. Natl. Acad. Sci. U.S.A. 84:744, 1987; An et al., Plant Cell 1:115, 1989). For example, the 3' terminator region may be included in the expression vector to increase stability of the mRNA. One such terminator region may be derived from the PI-II terminator region of potato. In addition, other commonly used terminators are derived from the octopine or nopaline synthase signals.

The plant expression vector also typically contains a dominant selectable marker gene used to identify those cells that have become transformed. Useful selectable genes for plant systems include genes encoding antibiotic resistance genes, for example, those encoding resistance to hygromycin, kanamycin, bleomycin, G418, streptomycin, or spectinomycin. Genes required for photosynthesis may also be used as selectable markers in photosynthetic-deficient strains. Alternatively, the green-fluorescent protein from the jellyfish Aequorea victoria may be used as a selectable marker (Sheen et al., Plant J. 7:877, 1995; Chiu et al., Current Biology 6:325, 1996). Finally, genes encoding herbicide resistance may be used as selectable markers; useful herbicide resistance genes include the bar gene encoding the enzyme phosphinothricin acetyltransferase and conferring resistance to the broad-spectrum herbicide BASTA (Hoechst AG, Frankfurt, Germany).

Efficient use of selectable markers is facilitated by a determination of the susceptibility of a plant cell to a particular selectable agent and a determination of the concentration of this agent which effectively kills most, if not all, of the transformed cells. Some useful concentrations of antibiotics for tobacco transformation include, e.g., 75-100 μg/mL (kanamycin), 20-50 μg/mL (hygromycin), or 5-10 μg/mL (bleomycin). A useful strategy for selection of transformants for herbicide resistance is described, e.g., by Vasil et al., supra.

It should be readily apparent to one skilled in the art of molecular biology, especially in the field of plant molecular biology, that the level of gene expression is dependent, not only on the combination of promoters, RNA processing signals, and terminator elements, but also on how these elements are used to increase the levels of selectable marker gene expression.

Plant Transformation

Upon construction of the plant expression vector, several standard methods are available for introduction of the vector into a plant host, thereby generating a transgenic plant. These methods include (1) Agrobacterium-mediated transformation (A. tumefaciens or A. rhizogenes) (see, e.g., Lichtenstein and Fuller, In: Genetic Engineering, vol. 6, PJW Rigby, ed, London, Academic Press, 1987; and Lichtenstein, C. P., and Draper, J., In: DNA Cloning, Vol II, D. M. Glover, ed, Oxford, IRL Press, 1985); (2) the particle delivery system (see, e.g., Gordon-Kamm et al., Plant Cell 2:603, 1990; or BioRad Technical Bulletin 1867, supra); (3) microinjection protocols (see, e.g., Green et al., supra); (4) polyethylene glycol (PEG) procedures (see, e.g., Draper et al., Plant Cell Physiol. 23:451, 1982, or, e.g., Zhang and Wu, Theor. Appl. Genet.
and carrying a selectable marker (for example, kanamycin resistance), is transformed into *Agrobacterium*. Transformation of leaf discs (for example, of tobacco leaf discs), with vector-containing *Agrobacterium* is carried out as described by Horsch et al. (Science 227:1229, 1985). Putative transformants are selected after a few weeks (for example, 3 to 5 weeks) on plant tissue culture media containing kanamycin (e.g., 100 μg/mL). Kanamycin-resistant shoots are then placed on plant tissue culture media without hormones for root initiation. Kanamycin-resistant plants are then selected for greenhouse growth. If desired, seeds from self-fertilized transgenic plants can then be sown in soil-less medium and grown in a greenhouse. Kanamycin-resistant progeny are selected by sowing surface sterilized seeds on hormone-free kanamycin-containing media. Analysis for the integration of the transgene is accomplished by standard techniques (see, for example, Ausubel et al. (supra); Geier et al. (supra)).

Transgenic plants expressing the selectable marker are then screened for transmission of the transgene DNA by standard immunoblot and DNA detection techniques. Each positive transgenic plant and its transgenic progeny is unique in comparison to other transgenic plants established with the same transgene. Integration of the transgene DNA into the plant genomic DNA is in most cases random, and the site of integration can profoundly affect the levels and the tissue and developmental patterns of transgene expression. Consequently, a number of transgenic lines are usually screened for each transgene to identify and select plants with the most appropriate expression profiles.

Transgenic lines are generally evaluated for levels of transgene expression. Expression at the RNA level is determined initially to identify and quantitate expression-positive plants. Standard techniques for RNA analysis are employed and include PCR amplification assays using oligonucleotide primers designed to amplify only transgenic RNA templates and solution hybridization assays using transgene-specific probes (see, e.g., Ausubel et al. (supra)). The RNA-positive plants are then analyzed for protein expression by Western immunoblot analysis using specific antibodies to the P450 (see, e.g., Ausubel et al., supra). In addition, in situ hybridization and immunocytochemistry according to standard protocols can be done using transgene-specific nucleotide probes and antibodies, respectively, to localize sites of expression within transgenic tissue.

Once the recombinant P450 is expressed in any cell or in a transgenic plant (for example, as described above), it may be isolated, e.g., using affinity chromatography. In one example, an anti-P450 antibody (e.g., produced as described in Ausubel et al., supra, or by any standard technique) may be attached to a column and used to isolate the polypeptide. Lysis and fractionation of P450-producing cells prior to affinity chromatography may be performed by standard methods (see, e.g., Ausubel et al., supra). Once isolated, the recombinant protein can, if desired, be further purified, for example, by high performance liquid chromatography (see, e.g., Fisher, Laboratory Techniques in Biochemistry and Molecular Biology, eds., Work and Burdon, Elsevier, 1980).

These general techniques of polypeptide expression and purification can also be used to produce and isolate useful P450 fragments or analogs.

Use

The aforementioned cytochrome P450 polypeptides of the invention are useful in the biosynthesis of hormones, lipids, and secondary metabolites, and may also help plants tolerate potentially harmful exogenous chemicals such as herbicides, pesticides, and pollutants. In addition, such cytochrome P450
polypeptides are useful in the chemical defense of plants against insects, as well as against bacterial, viral, and fungal infection.

Engineering Plant Disease Resistance

Plasmid constructs designed for the expression of a P450 gene product are useful, for example, for activating plant defense pathways that confer anti-pathogenic properties to a transgenic plant, for example, the production of phytoalexins. P450 genes that are isolated from a host plant (e.g., Nicotiana) may be engineered for expression in the same plant, a closely related species, or a distantly related plant species. For example, a P450 gene may be engineered for constitutive low-level expression and then transformed into a Nicotiana host plant. Alternatively, the P450 gene may be engineered for expression in other solanaceous plants, including, but not limited to, potato and tomato. To achieve pathogen resistance, it is important to express a P450 protein at an effective level. Evaluation of the level of pathogen protection conferred to a plant by ectopic expression of the P450 gene is determined according to conventional methods and assays.

Industrial Applications

The invention also includes engineering host cells to include novel isoprenoid metabolic pathways useful in the production of new isoprenoid compounds. By introducing genes encoding an isoprenoid synthase (as disclosed in U.S. Pat. No. 5,824,774 and WO 00/17327) and a cytochrome P450, an acyltransferase, a methyl transferase, and a fatty acid transferase, or a combination thereof, various isoprenoid reaction products may be modified, controlled, or manipulated, resulting in enhancement of production of numerous isoprenoid reaction products, for example, the production of novel monoterpenes, diterpenes, and sesquiterpenes. Such compounds are useful as phytoalexins, insecticides, perfumes, and pharmaceuticals such as anti-bacterial and fungal agents.

In one working example, an isoprenoid synthase or a chimeric isoprenoid synthase (as disclosed in U.S. Pat. No. 5,824,774 and WO 00/17327) and a P450 gene are introduced into yeast, for example, using any of the procedures described herein. If desired, such cells may also express, either independently or in combination, an acetyltransferase (see, for example, Walker et al., Proc. Natl. Acad. Sci. U.S.A. 18:583-587, 2000), a methylase transferase gene (see, for example, Dierer et al., Plant Cell 12:853-870, 2000), or a fatty acyltransferase gene, as well as a cytochrome reductase. Cells are then cultured under standard conditions and the production of isoprenoid compounds is assayed according to methods known in the art. Isoprenoid compounds are further purified according to methods well known in the art. Cells expressing novel isoprenoid compounds are taken as useful in the invention.

Such methods provide a unique approach for producing novel isoprenoid starting materials and end products. Either prokaryotic or eukaryotic cells transformed with any of the aforementioned enzymes (or combinations thereof) may be used. Moreover, isoprenoid compounds may be produced in any number of ways known in the art including an in vitro combination of purified enzymes with an appropriate substrate or direct fermentation using a host cell which expresses any combination of the aforementioned enzymes and the appropriate substrates sufficient to drive production of isoprenoid compounds.

The invention is also useful for the production of insect attractants and deterrents, which may either deter insect pests or attract insect predators. In addition, the invention is also useful for generating novel flavorings and perfumes.

Other Embodiments

From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention, and can make various changes and modifications of the invention to adapt it to various uses and conditions. Thus, other embodiments are also within the claims.

All publications and patents mentioned in this specification are hereby incorporated by reference to the same extent as if each individual publication or patent was specifically and individually indicated to be incorporated by reference.

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<212> TYPE: DNA
<213> ORGANISM: Nicotiana tabacum

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<211> LENGTH: 534
<212> TYPE: PRT
<213> ORGANISM: Nicotiana tabacum

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Phe Pro Leu Thr Tyr Ile Ser Leu Ile Val Leu Leu Leu Pro Leu Ile
35  40  45
Ile Asn Phe Leu Cys Val Lys Pro Gln Asn Asn Leu Pro Pro Gly Pro
50  55  60
Thr Ala Val Pro Ile Phe Gly Asn Trp Leu Gln Val Gly Asn Asp Leu
65  70  75  80
Arg His Gln Leu Leu Ala Thr Met Ser Gln Thr Tyr Gly Pro Ile Phe
85  90  95
Leu Leu Lys Leu Gly Ser Asn Leu Ala Val Ser Asn Pro Glu
100 105 110
Leu Ala Asn Gln Val Leu His Thr Gln Gly Val Glu Phe Gly Ser Arg
115 120 125
Pro Arg Asn Val Phe Asp Ile Phe Thr Gly Asn Gln Gly Glu Asp Met
130 135 140
Val Phe Thr Ile Tyr Gly Asp His Trp Arg Lys Met Arg Arg Ile Met
145 150 155 160
Thr Leu Pro Phe Thr Asn Tyr Val Val His Gln Tyr Ser Asp Met
165 170 175
Trp Glu Asn Glu Met Asp Leu Val Val Asp Asp Leu Lys Asn Glu
180 185 190
Lys Val Lys Tyr Asp Gly Ile Val Ile Arg Lys Arg Leu Gin Leu Met
195 200 205
Leu Tyr Asn Ile Met Tyr Arg Met Met Phe Asp Ala Lys Phe Glu Ser
210 215 220
Gln Asp Asp Pro Leu Phe Ile Glu Ala Thr Lys Phe Asn Ser Glu Arg
225 230 235 240
Ser Arg Leu Ala Gln Ser Phe Asp Tyr Asn Tyr Gly Asp Phe Ile Pro
245 250 255
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260 265 270
Gln Thr Arg Arg Leu Ala Phe Asn Lys Tyr Phe Val Gly Lys Arg
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Ile Asp His Ile Ile Asp Ala Glu Met Lys Gly Glu Ile Ser Glu Gln
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Asn Val Leu Tyr Ile Val Glu Asn Ile Asn Val Ala Ala Ile Glu Thr
325 330 335
Thr Leu Trp Ser Met Glu Trp Ala Ile Ala Glu Leu Val Asn His Pro
340 345 350
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355 360 365
Lys Ser Val Lys Glu Ser Asn Leu His Glu Leu Pro Tyr Leu Ala
370 375 380
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385 390 395 400
Pro His Met Asn Leu Glu Glu Ala Lys Lys Gly Gly Thr Thr Ile Pro
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<212> TYPE: DNA
<213> ORGANISM: Nicotiana tabacum
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<210> SEQ ID NO 9
<211> LENGTH: 519
<212> TYPE: PRF
<213> ORGANISM: Nicotiana tabacum

<400> SEQUENCE: 9

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Leu Asn Pro Leu Pro Pro Ile Pro Gly Gly Tyr Pro Val Ile Gly
35  40  45
His Leu Phe Tyr Phe Asn Asn Asn Gly Asp Asp Arg His Phe Ser
50  55  60
Gln Lys Leu Gly Asp Leu Ala Asp Tyr Gly Pro Val Phe Thr Phe
65  70  75  80
Arg Leu Gly Phe Arg Arg Phe Leu Ala Val Ser Ser Tyr Glu Ala Met
85  90  95
Lys Glu Cys Phe Ser Thr Asn Asp Ile His Phe Ala Asp Arg Pro Ala
100 105 110
Leu Leu Tyr Gly Glu Tyr Leu Cys Tyr Asn Asn Ala Met Leu Ala Val
115 120 125
Ala Lys Tyr Gly Pro Tyr Trp Lys Asn Arg Lys Leu Val Asn Gin
130 135 140
Glu Leu Leu Ser Val Ser Arg Leu Glu Lys Phe Lys His Val Arg Phe
145 150 155 160
Ser Ile Val Glu Asn Ile Lys Glu Leu Tyr Asn Cys Asp Ser Pro
165 170 175
Met Val Lys Ile Asn Leu Ser Asp Trp Ile Asp Lys Leu Thr Phe Asp
180 185 190
Ile Ile Ile Met Val Val Gly Lys Thr Tyr Asn Asn Gly His Gly
195 200 205
Glu Ile Leu Lys Ala Ala Phe Gin Lys Phe Met Val Gin Aln Met Glu
210 215 220
Ile Glu Leu Tyr Asp Val Phe His Ile Pro Phe Phe Tyr Pro Leu Asp
225 230 235 240
Leu Thr Gly Asn Ile Lys Ala Met Lys Gin Thr Phe Lys Asp Ile Asp
245 250 255
Asn Ile Ile Gin Gly Trp Leu Asp Glu His Ile Lys Arg Glu Thr
260 265 270
Lys Asp Val Gly Gly Glu Asn Gin Asp Phe Ile Asp Val Leu Leu
275 280 285
Ser Lys Arg Ser Asn Glu His Leu Gly Asp Gly Tyr Ser His Asp Thr
290 295 300
Thr Ile Lys Ala Thr Val Phe Thr Leu Val Leu Asp Ala Thr Asp Thr
305 310 315 320
Leu Ala Leu His Ile Lys Trp Val Met Ala Leu Met Ile Asn Asn Lys
325 330 335
Asn Val Met Lys Lys Ala Gin Glu Glu Met Asp Thr Ile Val Gly Arg
Ala Ile Val Lys Glu Val Leu Arg Leu His Pro Pro Ala Pro Leu Ser 370 375 380
Val Gln His Leu Ser Val Lys Asp Cys Val Val Asn Gly Tyr His Ile 385 390 395 400
Pro Lys Gly Thr Ala Leu Leu Thr Asn Ile Met Lys Leu Gln Arg Asp 405 410 415
Pro Gln Ile Trp Val Asp Pro Asp Thr Phe Asp Pro Glu Arg Phe Leu 420 425 430
Thr Thr Asn Ala Ala Ile Asp Tyr Arg Gly Gin His Tyr Glu Leu Ile 435 440 445
Pro Phe Gly Ser Gly Arg Arg Ala Cys Pro Ala Met Asn Tyr Ser Leu 450 455 460
Gln Val Glu His Leu Ser Ile Ala His Leu Ile Gin Gly Phe Asn Phe 465 470 475 480
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<Q10> SEQ ID NO 10
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<Q13> ORGANISM: Nicotiana tabacum

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cggcaatttct cctaaattct cggatgagtt gcggaaatgct cttatatccctc 240
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aatatacatt tgcagaaag gaacaccttca attgtcatt tgcatacggg tttaaatatta
gcatactcgg ctaacagcgg ctttgtatag ccaccaaggg tggcctaac tttaccaag
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<210> SEQ ID NO: 11
<211> LENGTH: 509
<212> TYPE: PRT
<213> ORGANISM: Nicotiana tabacum

<400> SEQUENCE: 11

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Leu Pro Pro Gly Pro Lys Pro Trp Pro Ile Ile Gly Asn Leu Asn Leu
Ile Gly Asn Leu Pro His Arg Ser Ile His Glu Leu Ser Leu Lys Tyr
Gly Pro Ile Met Glu Leu Glu Phe Gly Thr Phe Pro Val Val Val Gly
Ser Ser Val Glu Met Ala Lys Val Phe Leu Lys Ser Met Asp Ile Asn
Phe Val Gly Arg Pro Lys Thr Ala Ala Gly Lys Tyr Thr Thr Tyr Asn
Tyr Ser Asp Ile Thr Trp Ser Ser Pro Tyr Gly Pro Tyr Trp Arg Glu Ala
Arg Arg Met Cys Leu Met Glu Leu Phe Ser Thr Lys Arg Leu Asp Ser
Tyr Glu Tyr Ile Arg Ala Glu Leu His Ser Leu Leu His Asn Leu
Asn Lys Ile Ser Gly Lys Pro Ile Val Leu Lys Asp Tyr Leu Thr Thr
Leu Ser Leu Asn Val Ile Ser Arg Met Val Leu Gly Lys Arg Tyr Leu
Asp Glu Ser Glu Asn Ser Ile Val Thr Pro Glu Phe Lys Lys Met
Leu Asp Glu Leu Phe Leu Leu Asn Gly Val Leu Asn Ile Gly Asp Ser
Leu Pro Trp Ile Asp Phe Met Asp Leu Gin Gly Tyr Val Lys Arg Met
Lys Phe Val Ser Lys Phe Asp Lys Phe Leu Glu His Val Ile Asp
Gl u His Asn Val Arg Arg Asn Gly Val Glu Asn Tyr Ile Ala Lys Asp
Met Val Asp Val Leu Leu Gin Leu Ala Asp Asp Pro Thr Leu Glu Val
Lys Leu Glu Arg His Gly Val Lys Ala Phe Thr Gin Asp Met Leu Ala
Gly Gly Thr Glu Ser Ser Ala Val Thr Val Glu Trp Ala Ile Ser Glu
Leu Leu Lys Lys Pro Glu Ile Phe Lys Ala Thr Glu Leu Asp
Arg Val Ile Gly Gln Asn Arg Trp Val Gln Glu Lys Asp Ile Pro Asn
Leu Pro Tyr Ile Glu Ala Ile Val Lys Glu Thr Met Arg Leu His Pro
Val Ala Pro Met Leu Val Pro Arg Glu Cys Arg Glu Asp Cys Lys Val
Ala Gly Tyr Asp Val Lys Gly Thr Arg Val Leu Val Ser Val Trp
Thr Ile Gly Arg Asp Pro Thr Leu Trp Asp Glu Pro Glu Ala Phe Lys
Pro Glu Arg Phe His Glu Lys Ser Ile Asp Val Lys Gly His Asp Phe
Glue Leu Leu Pro Phe Gly Ala Gly Arg Arg Met Cys Pro Gly Tyr Ann
Leu Gly Leu Lys Val Ile Gln Ala Ser Leu Ala Asn Leu Ile His Gly
Phe Asn Trp Ser Leu Pro Asp Ann Met Thr Pro Glu Asp Leu Asp Met
Asp Glu Ile Phe Gly Leu Ser Thr Pro Lys Lys Phe Pro Leu Ala Thr
Val Ile Glu Pro Arg Leu Ser Pro Lys Leu Tyr Ser Val

<210> SEQ ID NO 12
<211> LENGTH: 1530
<212> TYPE: DNA
<213> ORGANISM: Nicotiana tabacum
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cgatcatcgc caaactctaa cctattcgcc aatcttctcct atgcgctaat caacgagactt 180
tcaactcaagt acgggcacat tattgacactc caatctggag aattccctcct tgtttggtg 240
tttctccgct aatagcggcag gttttcttcc aatcactgtgct attttattttg ttgagccagg 300
cctaaacgag cgccgctggaa gtacacact aacaaattttg cagatatatttg atgtgcctct 360
tatgacacat atgggacgtgca gcactatgag atgtgacctaa tggaaattatg cagcagaaaa 420
cgtctctgggatt catcagagta tattgggctct gaggaattgc atctctgctct ccataatttg 480
aataaaatg caggaagacc aatgtgctct aaagattattg tggcaatgttg gagtttaaat 540
gttattagga ggattttactt ggaggaggg tatttggaac acctttgggtgc gattttgct 600
aaccccac gccatttgac gcatgtgattct gttctaaattg tggatctttg 660
atggaagttg cattttctct gaggtatttttt gcatttctttt aagttaattatg taagggattg 720
aatattgaca gcacagatttt ttggatcgctg ttagcatattc gcaataacgctt 780
agggcagatg gattttgagtt ttcattttct tattggcttg cgattttgac cagtaaagct 840
gctagagcgc agtggcgtgta agttaagctg cagacatgct gtggctttttct 900
gatattttg ctggtggagcc gcagagtttta gcagagcttg tggagtggc cattctggag 960
ctggtaaaga agcagagat tttcagaaaag gctacagag aatggatcg agtaatggg 1020
cagaaatagc gggtacaaga aaaaagacatt ccaaatcttc cttacataga ggcaaatagc 1080
aagacacta tgcgactgca ccccttggca ccaagtgtgg tgcacccgga gttctcagaa 1140
gactgtaagg tagcaggtga cgaogttaag aagagaacca gggtccctgt gagogttag 1200
actattgga gagaaccttc atttggtgac gacgccgagc gcttcagacc gggagggctc 1260
cacagaaagc cacagtgttt taagagcagat gattttgagc tttgcccatt tggagctggg 1320
agaggagtgt gccggggtta taactttgggct cttaaagttgca ttcaagctag cttagcatat 1380
ccttacatag gattaacctg gtctttgct ctaataatag ctoctgggga cctgagcagat 1440
gttggagatt tttggtcttc cacacctaaa aagtttccccat ttgctactgt gatttgagcca 1500
agactttcact caaaaactta cttctgttga 1530

<210> SEQ ID NO 13
<211> LENGTH: 36
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene
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<210> SEQ ID NO 14
<211> LENGTH: 23
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene
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gtacaatagtg gaggtgacag atg 23

<210> SEQ ID NO 15
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<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene
<400> SEQUENCE: 15
gttgggtttgg aatgcagt 18

<210> SEQ ID NO 16
<211> LENGTH: 25
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
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ttagcgagca atagcgtgta agaca 25

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<213> ORGANISM: Artificial sequence
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<211> LENGTH: 33
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
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<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 18

ggggaaattct tactctcag aaggttgata agg

<210> SEQ ID NO 19
<211> LENGTH: 30
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 19

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<210> SEQ ID NO 20
<211> LENGTH: 33
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 20

ggggaaattct caatattgat aagcgttgg agg

<210> SEQ ID NO 21
<211> LENGTH: 33
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 21

cccgcatcca tgtatcccttt cagcttggtt tcc

<210> SEQ ID NO 22
<211> LENGTH: 33
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 22

ggggagctct cactgcgaag aagattgata agg

<210> SEQ ID NO 23
<211> LENGTH: 76
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
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<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 23

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gtccccagcag tgcg

<210> SEQ ID NO 24
<211> LENGTH: 76
<212> TYPE: DNA
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<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

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atgggacaa tacta

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<211> LENGTH: 33
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
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<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 gene

<400> SEQUENCE: 25

ggggcgtcct tattgcagca tagcgtggaa gac

<210> SEQ ID NO 26
<211> LENGTH: 7
<212> TYPE: PRT
<213> ORGANISM: Nicotiana tabacum
<220> FEATURE:
<223> OTHER INFORMATION: Nicotiana tabacum p450 protein
<220> FEATURE:
<221> NAME/KEY: Variant
<222> LOCATION: (1) (7)
<223> OTHER INFORMATION: Xaa = any amino acid

<400> SEQUENCE: 26

Lys Glu Thr Leu Arg Leu Xaa
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<210> SEQ ID NO 27
<211> LENGTH: 11
<212> TYPE: PRT
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<220> FEATURE:
<223> OTHER INFORMATION: Nicotiana tabacum p450 protein
<220> FEATURE:
<221> NAME/KEY: Variant
<222> LOCATION: (4) (8)
<223> OTHER INFORMATION: Xaa = any amino acid

<400> SEQUENCE: 27

Pro Phe Gly Xaa Gly Arg Arg Xaa Cys Pro Ala
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<210> SEQ ID NO 28
<211> LENGTH: 11
<212> TYPE: PRT
<213> ORGANISM: Nicotiana tabacum
<220> FEATURE:
<223> OTHER INFORMATION: Nicotiana tabacum p450 protein
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<221> NAME/KEY: Variant
<222> LOCATION: (4) (8)
<223> OTHER INFORMATION: Xaa = any amino acid

<400> SEQUENCE: 28

Pro Phe Gly Xaa Gly Arg Arg Xaa Cys Pro Gly
1 5 10
Phe Xaa Pro Glu Arg Phe
1  5

Ala Ala Arg Gly Ala Arg Ala Cys Ile Tyr Thr Ile Met Gly Ile Tyr
1  5  10  15
Thr Ile Cys Ala
20

Ala Ala Arg Gly Ala Arg Ala Cys Ile Tyr Thr Ile Met Gly Ile Tyr
1  5  10  15
Thr Ile Thr Ala
20

Ala Ala Arg Gly Ala Arg Ala Cys Ile Tyr Thr Ile Met Gly Ile Tyr
1  5  10  15
Thr Ile Met Gly
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Thr Thr Tyr Ile Ile Ile Cys Ile Gly Ala Arg Met Gly Ile Thr
1  5  10  15
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<210> SEQ ID NO 34
<211> LENGTH: 18
<212> TYPE: PRT
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 protein

<400> SEQUENCE: 34

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<210> SEQ ID NO 35
<211> LENGTH: 20
<212> TYPE: PRT
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 protein

<400> SEQUENCE: 35

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1  5  10  15
Cys Ile Gly Ser
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<210> SEQ ID NO 36
<211> LENGTH: 20
<212> TYPE: PRT
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from Nicotiana tabacum p450 protein

<400> SEQUENCE: 36

Cys Lys Ile Cys Lys Ile Cys Ile Ile Ile Ile Cys Ile Cys Arg Ala
1  5  10  15
Ala Ile Gly Gly
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<210> SEQ ID NO 37
<211> LENGTH: 21
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from T7 bacteriophage promoter

<400> SEQUENCE: 37

gtatacgac tcactataagg g

<210> SEQ ID NO 38
<211> LENGTH: 21
<212> TYPE: DNA
<213> ORGANISM: Artificial sequence
<220> FEATURE:
<223> OTHER INFORMATION: Derived from T3 bacteriophage promoter

<400> SEQUENCE: 38

cataaaccc tcactaaagg g

<210> SEQ ID NO 39
<211> LENGTH: 500
<212> TYPE: PRT
<213> ORGANISM: Mentha piperita

<400> SEQUENCE: 39

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Leu Thr Gly Ile Arg Lys Asn Asn Leu Leu Leu Val Pro Thr Pro Tyr 485 490 495
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<210> SEQ ID NO. 40
<211> LENGTH: 496
<212> TYPE: PRT
<213> ORGANISM: Mentha spicata

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Asn Leu Pro Pro Ser Pro Pro Lys Leu Pro Val Ile Gly His Leu His 35 40 45
Phe Leu Trp Gly Gly Leu Pro Gln His Val Phe Arg Ser Ile Ala Gln 50 55 60
Lys Tyr Gly Pro Val Ala His Val Gln Leu Gly Glu Val Tyr Ser Val 65 70 75 80
Val Leu Ser Ser Ala Glu Ala Lys Gln Ala Met Lys Val Leu Asp 85 90 95
Pro Asn Phe Ala Asp Arg Phe Asp Gly Ile Gly Ser Arg Thr Met Trp 100 105 110
Tyr Asp Lys Asp Ile Ile Phe Ser Pro Tyr Asn Asp His Trp Arg 115 120 125
Gln Met Arg Arg Ile Cys Val Thr Glu Leu Leu Ser Pro Lys Asn Val 130 135 140
Arg Ser Phe Gly Tyr Ile Arg Gln Glu Ile Glu Arg Leu Ile Arg 145 150 155 160
Leu Leu Gly Ser Ser Gly Gly Ala Pro Val Asp Val Thr Glu Glu Val 165 170 175
Ser Lys Met Ser Cys Val Val Val Cys Arg Ala Ala Phe Gly Ser Val 180 185 190
Leu Lys Asp Gln Ser Leu Ala Glu Leu Val Lys Glu Ser Leu Ala 195 200 205
Leu Ala Ser Gly Phe Glu Leu Ala Asp Leu Tyr Pro Ser Ser Ser Leu 210 215 220
Leu Asn Leu Leu Ser Leu Asn Lys Tyr Arg Leu Gln Arg Met Arg Arg 225 230 235 240
Arg Leu Asp His Ile Leu Asp Gly Phe Leu Glu Glu His Arg Glu Lys 245 250 255
Lys Ser Gly Glu Phe Gly Gly Asp Ile Val Asp Val Leu Phe Arg 260 265 270
Met Gln Lys Gly Ser Asp Ile Lys Ile Pro Ile Thr Ser Asn Cys Ile 275 280 285
Lys Gly Phe Ile Phe Asp Thr Phe Ser Ala Gly Ala Glu Thr Ser Ser 290 295 300
Thr Thr Ile Ser Trp Ala Leu Ser Glu Leu Met Arg Asn Pro Ala Lys
305 310 315 320
Met Ala Lys Val Gln Ala Glu Val Arg Ala Leu Lys Gly Lys Thr
325 330 335
Val Val Asp Leu Ser Glu Val Gln Glu Leu Lys Tyr Leu Arg Ser Val
340 345 350
Leu Lys Glu Thr Leu Arg Leu His Pro Pro Phe Pro Leu Ile Pro Arg
355 360 365
Gln Ser Arg Glu Glu Cys Glu Val Asn Gly Tyr Thr Ile Pro Ala Lys
370 375 380
Thr Arg Ile Phe Ile Asn Val Trp Ala Ile Gly Arg Asp Pro Gln Tyr
385 390 395 400
Trp Glu Asp Pro Asp Thr Phe Pro Glu Arg Phe Asp Glu Val Ser
405 410 415
Arg Asp Phe Met Gly Asn Asp Phe Glu Phe Ile Pro Phe Gly Ala Gly
420 425 430
Arg Arg Ile Cys Pro Gly Leu His Phe Gly Leu Ala Asn Val Glu Ile
435 440 445
Pro Leu Ala Gln Leu Leu Tyr His Phe Asp Trp Lys Leu Pro Gln Gly
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465 470 475 480
Pro Lys Lys Asn Val Cys Leu Val Pro Thr Leu Tyr Lys Ser Pro
485 490 495

<210> SEQ ID NO 41
<211> LENGTH: 569
<212> TYPE: PRT
<213> ORGANISM: Nepeta racemosa

<400> SEQUENCE: 41
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1  5  10  15
Phe Leu Leu Phe Leu Asn Lys Trp Arg Arg Ser Tyr Ser Gly Lys Thr
20 25  30
Pro Pro Pro Ser Pro Pro Lys Leu Pro Val Ile Gly Asn Leu His Gln
35 40  45
Leu Gly Leu Tyr Pro His Arg Tyr Leu Gln Ser Leu Ser Arg Arg Tyr
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**Note:** The sequence is continued in the next page.
The invention claimed is:

1. A method for producing a host cell comprising an isoprenoid compound, comprising:
   a) providing a host cell that comprises heterologous nucleic acid encoding an isoprenoid synthase, and heterologous nucleic acid encoding one or more protein(s) comprising a cytochrome P450 polypeptide, wherein: the isoprenoid synthase catalyzes production of an isoprenoid compound that is a diterpene or sesquiterpene; and
   a) cytochrome P450 polypeptide(s) catalyzes hydroxylation, oxidation, demethylation or methylation of a diterpene or sesquiterpene;
   b) culturing the host cell under conditions suitable for expressing the isoprenoid synthase and the cytochrome P450 polypeptide(s) under conditions for producing a diterpene or a sesquiterpene isoprenoid compound not normally produced by the host cell to produce a diterpene or sesquiterpene isoprenoid compound not normally produced by the host cell, wherein the synthase and the cytochrome P450 polypeptide(s) together catalyze the formation of a diterpene or sesquiterpene isoprenoid compound in the host cell, wherein the diterpene or sesquiterpene isoprenoid compound is not normally produced by the cell.

2. The method of claim 1, wherein at least one of the cytochrome P450 polypeptide(s) is a CYP71, CYP73, CYP92 or CYP92 family cytochrome P450.

3. The method of claim 2, wherein each of the CYP71, CYP73, CYP92 and CYP92 family cytochrome P450 polypeptides is encoded by nucleic acid that can be amplified with degenerate primers based on one of SEQ ID NOS: 26-29.

4. The method of claim 1, wherein at least one cytochrome P450 polypeptide has dual hydroxylase activity.

5. The method of claim 1, wherein at least one cytochrome P450 polypeptide has oxidase activity.

6. The method of claim 1, wherein at least one cytochrome P450 polypeptide has oxidase activity.

7. The method of claim 1, wherein:
   a) the isoprenoid compound produced by the isoprenoid synthase is a sesquiterpene; and
   b) the isoprenoid synthase is a sesquiterpene synthase.

8. The method of claim 1, wherein:
   a) an isoprenoid compound produced by the isoprenoid synthase is a diterpene; and
   b) the isoprenoid synthase is a diterpene synthase.

9. The method of claim 1, wherein the host cell is a yeast cell, a bacterial cell, an insect cell or a plant cell.

10. The method of claim 1, wherein the host cell is a yeast cell.

11. The method of claim 10, wherein the yeast is Saccharomyces cerevisiae.

12. The method of claim 1, wherein at least one of the cytochrome P450 polypeptides is selected from among 5-epi-aristolochene hydroxylase and kaurene oxidase.

13. A host cell, comprising nucleic acid encoding a diterpene or sesquiterpene isoprenoid synthase, and nucleic acid encoding one or more cytochrome P450 polypeptide(s), wherein:
   a) the nucleic acid encoding the synthase and the nucleic acid encoding the P450 polypeptide(s) are heterologous to the host cell;
   b) the synthase catalyzes production of a diterpene or sesquiterpene compound;
   c) the P450 polypeptide(s) catalyze(s) hydroxylation, oxidation, demethylation or methylation of a diterpene or sesquiterpene;
   d) at least one of the P450 polypeptide(s) catalyzes the hydroxylation, oxidation, demethylation or methylation of a diterpene or sesquiterpene whose production is catalyzed by the synthase; and
   e) the host cell thereby can produce a diterpene or sesquiterpene compound not normally produced by the host cell nor by the synthase in the absence of the P450 polypeptide(s).

14. The host cell of claim 13, wherein at least one of the P450 polypeptide(s) catalyzes the dual hydroxylation of a diterpene or sesquiterpene whose production is catalyzed by the synthase.

15. The host cell of claim 13, wherein at least one of the P450 polypeptide(s) is a CYP71, CYP73, CYP92 or CYP92 family cytochrome P450 encoded by nucleic acid that can be amplified with degenerate primers based on one of SEQ ID NOS: 26-29.

16. The host cell of claim 13, wherein at least one of the P450 polypeptide(s) comprises a CYP71, CYP73, CYP92 or CYP92 family cytochrome P450 polypeptide.

17. The host cell of claim 13 that is a yeast cell, a bacterial cell, an insect cell or a plant cell.
18. The host cell of claim 13 that is a yeast cell.

19. The host cell of claim 13, wherein at least one of the cytochrome P450 polypeptide(s) is selected from among 5-epi-aristolochene hydroxylase and kaurene oxidase.

20. A method for producing an isoprenoid compound, comprising:
   a) providing a host cell that comprises heterologous nucleic acid encoding an isoprenoid synthase, and heterologous nucleic acid encoding one or more protein(s) comprising a cytochrome P450 polypeptide, wherein: the isoprenoid synthase catalyzes production of an isoprenoid compound that is a diterpene or sesquiterpene; and
   b) culturing the host cell under conditions suitable for expressing the isoprenoid synthase and the cytochrome P450 polypeptide(s) and under conditions for producing a diterpene or a sesquiterpene isoprenoid compound not normally produced by the host cell to produce a diterpene or sesquiterpene isoprenoid compound not normally produced by the host cell, wherein the synthase and the cytochrome P450 polypeptide(s) together catalyze the formation of the diterpene or sesquiterpene isoprenoid compound; and
   c) isolating a diterpene or sesquiterpene isoprenoid compound not normally produced by the cell.

21. A method for producing a host cell comprising an isoprenoid compound, comprising:
   a) providing a host cell that comprises heterologous nucleic acid encoding an isoprenoid synthase, and heterologous nucleic acid encoding one or more protein(s) comprising a cytochrome P450 polypeptide, wherein: the isoprenoid synthase catalyzes production of an isoprenoid compound that is a diterpene or sesquiterpene; and
   b) culturing the host cell under conditions suitable for expressing the isoprenoid synthase and the cytochrome P450 polypeptide(s) and under conditions for producing a diterpene or a sesquiterpene isoprenoid compound not normally produced by the host cell to produce a diterpene or sesquiterpene isoprenoid compound not normally produced by the host cell, wherein the synthase and the cytochrome P450 polypeptide(s) together catalyze the formation of a diterpene or sesquiterpene isoprenoid compound not normally produced by the cell; and
   c) isolating the host cell that comprises an isoprenoid compound not normally produced by the cell.

22. The method of claim 21, further comprising isolating an isoprenoid compound produced by the host cell.

23. The method of claim 1, further comprising collecting a fermentation medium in which the host cell is cultured; and isolating an isoprenoid compound.

24. The method of claim 20, wherein at least one of the cytochrome P450 polypeptide(s) is selected from among 5-epi-aristolochene hydroxylase and kaurene oxidase.

25. A method for producing an isoprenoid compound, comprising:
   a) providing a host cell that expresses heterologous nucleic acid encoding a first recombinant protein comprising an isoprenoid synthase, and a second recombinant protein comprising a cytochrome P450 polypeptide, wherein: the isoprenoid synthase catalyzes production of an isoprenoid compound that is a diterpene or sesquiterpene; and
   b) culturing the host cell under conditions suitable for expressing the first recombinant protein comprising an isoprenoid synthase and the second recombinant protein comprising the cytochrome P450 polypeptide and under conditions for producing the diterpene or a sesquiterpene isoprenoid compound not normally produced by the host cell, wherein the first and second recombinant protein together catalyze the formation of a diterpene or sesquiterpene isoprenoid compound; and
   c) isolating a diterpene or sesquiterpene isoprenoid compound not normally produced by the cell.

27. The method of claim 26, wherein at least one of the cytochrome P450 polypeptide(s) is selected from among 5-epi-aristolochene hydroxylase and kaurene oxidase.

28. The method of claim 26, wherein the host cell is a yeast cell, a bacterial cell, an insect cell or a plant cell.

29. The method of claim 26, wherein the host cell is a yeast cell.

* * * * *
UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 8,722,363 B2
APPLICATION NO. : 13/986446
DATED : May 13, 2014
INVENTOR(S) : Chappell et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

IN THE TITLE PAGES:

In Item (71) Applicants, insert:

--Joseph Chappell, Lexington, KY (US)--

Signed and Sealed this
Twenty-ninth Day of July, 2014

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office