

URIDINE DIPHOSPHATE-DEPENDENT GLYCOSYLTRANSFERASE ENZYMERELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No.
5 62/866,148, filed June 25, 2019, the entire disclosure of which is hereby incorporated by
reference in its entirety.

TECHNICAL FIELD

The present disclosure relates to enzymes, encoding polynucleotides, host cells, and
10 methods for producing glycosylated substrates.

DESCRIPTION OF THE TEXT FILE SUBMITTED ELECTRONICALLY

The contents of the text file submitted electronically herewith are incorporated herein
by reference in their entirety: a computer readable format copy of the Sequence Listing
15 (filename: MAN-024PC_Sequence Listing_ST25.txt; date recorded: June 24, 2020; file size:
28,457 bytes).

BACKGROUND

High intensity sweeteners possess a sweetness level that is many times greater than
20 the sweetness level of sucrose. They are essentially non-caloric and are commonly used in
diet and reduced-calorie products, including foods and beverages. High intensity sweeteners
do not elicit a glycemic response, making them suitable for use in products targeted to
diabetics and others interested in controlling their intake of carbohydrates.

Steviol glycosides are a class of compounds found in the leaves of *Stevia rebaudiana*
25 Bertoni, a perennial shrub of the *Asteraceae* (*Compositae*) family native to certain regions
of South America. They are characterized structurally by a single base, steviol, differing by
the presence of carbohydrate residues at positions C13 and C19. They accumulate in *Stevia*

leaves, composing approximately 10% to 20% of the total dry weight. On a dry weight basis, the four major glycosides found in the leaves of Stevia typically include stevioside (9.1%), Rebaudioside A (3.8%), Rebaudioside C (0.6-1.0%) and dulcoside A (0.3%). Other known steviol glycosides include Rebaudiosides B, C, D, E, F and M, steviolbioside and rubusoside.

5 The minor glycosylation product Rebaudioside M (RebM) is estimated to be about 200-350 times more potent than sucrose, and is described as possessing a clean, sweet taste with a slightly bitter or licorice aftertaste. Prakash I. et al., Development of Next Generation Stevia Sweetener: Rebaudioside M, *Foods* 3(1), 162-175 (2014). Reb M is of great interest to the global food industry.

10 Processes for preparing steviol glycosides from the stevia plant are not sustainable, and are not suitable for providing the minor glycosylation products of stevia leaves. Accordingly, there remains a need for sustainable and economical methods for preparing compositions comprising steviol glycosides, including highly purified steviol glycoside compositions. Further, methods are needed for producing substantial amounts of the minor
15 glycosylation products, such as RebM, and others.

SUMMARY OF THE INVENTION

In various aspects, the present invention provides uridine diphosphate (UDP)-dependent glycosyltransferase (UGT) enzymes capable of catalyzing the transfer of a
20 monosaccharide moiety from an NDP-sugar (*e.g.*, UDP-sugar) to the 3' carbon of a sugar moiety of a substrate, such as a terpenoid glycan, thereby functioning as a "1-3 UGT." In other aspects, the invention provides polynucleotides encoding the 1-3 UGT, and host cells comprising the same. In still other aspects, the invention provides methods for preparing glycosylated substrates, including steviol glycosides, using the enzyme and host cells of this
25 disclosure.

The 1-3 UGT exhibits high glycosyltransferase activity on terpenoid glycosides, such as steviol glycosides. For example, the 1-3 UGT catalyzes transfer of a monosaccharide moiety from an NDP-sugar to the 3' carbon of a sugar moiety on a terpenoid glycan, such as stevioside and RebD. That is, where the substrate is a steviol glycoside, the 1-3 UGT can

catalyze NDP-dependent transfer of a monosaccharide moiety to the 3' carbon of both the C13- or C19-linked glucose moieties. In various embodiments, the 1-3 UGT catalyzes the biosynthesis of RebM.

In one aspect, the invention provides a 1-3 UGT enzyme comprising an amino acid sequence that is at least about 75% identical to the amino acid sequence of SEQ ID NO: 5 or SEQ ID NO: 6. In some embodiments, the enzyme comprises an amino acid substitution at positions corresponding to positions 29, 200, 357, and 414 of SEQ ID NO: 1 (*Stevia rebaudiana* UGT76G1). Substitutions at these positions, which are included in the enzyme of SEQ ID NOS: 5 and 6 (positions 183, 354, 54, and 111, respectively, in SEQ ID NO: 5) can provide dramatic improvements in activity relative to the enzyme of SEQ ID NO: 1.

In some embodiments, the 1-3 UGT enzyme comprises an insertion (with respect to SEQ ID NO: 1) of from 5 to about 15 amino acids, or about 6 to about 12 amino acids, after the position corresponding to position 155 of SEQ ID NO: 5. In some embodiments, the insertion is a flexible and hydrophilic sequence, which may be predominately Glycine and Serine residues. In some embodiments, the sequence is GSGGSG (SEQ ID NO: 7) or GSGGSGGSG (SEQ ID NO: 8).

In various embodiments, the 1-3 UGT enzyme shows improved conversion of stevioside to Reb A, and improved conversion of RebD to RebM, as compared to UGT76G1-L200A (SEQ ID NO: 3).

In some embodiments, the identity of amino acids at positions corresponding to positions 183, 354, 54, and 111 of SEQ ID NO: 5, allows for further modification at other positions. For example, in some embodiments, the 1-3 UGT enzyme comprises an amino acid sequence that is at least about 60% identical to the amino acid sequence of SEQ ID NO: 5, wherein the UGT enzyme comprises: a glycine (G) or threonine (T) at the position corresponding to position 54 of SEQ ID NO: 5; a leucine (L) or isoleucine (I) at the position corresponding to position 111 of SEQ ID NO: 5; a methionine (M) or leucine (L) at the position corresponding to position 183 of SEQ ID NO: 5; and an alanine (A), or glycine (G), or serine (S) at the position corresponding to position 354 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme

comprises a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT has two or three of a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5, a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5, and a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. These modifications can provide substantial improvements to the activity of the enzyme, relative to the amino acid identity at the corresponding position of SEQ ID NO: 1.

In some embodiments, the 1-3 UGT enzyme includes one or more of: a deletion of amino residues 159 to 161 with reference to the amino acid sequence of SEQ ID NO: 5, a substitution at position 262 (e.g., L262Q), a substitution at position 294 (e.g., R294), and a substitution at position 413 (e.g., D413E), in each case with reference to the amino acid sequence of SEQ ID NO: 5.

In embodiments, the 1-3 UGT enzyme includes a deletion of amino residues 159 to 161 as well as the amino acid substitutions L262Q, R294P and D413E, each with reference to the amino acid sequence of SEQ ID NO: 5. An exemplary UGT enzyme according to these embodiments is disclosed herein as SEQ ID NO: 6).

In some embodiments, the 1-3 UGT enzyme includes a deletion of residues of one or more of residues E225 to T232 with reference to the amino acid sequence of SEQ ID NO: 6. In these or other embodiments, the 1-3 UGT enzyme includes one or more amino acid substitutions at positions selected from position 72 (e.g., S72Q), position 305 (e.g., A305C), position 345 (e.g., Y345F), and position 428 (e.g., L428I), in each case with reference to the amino acid sequence of SEQ ID NO: 6. In exemplary embodiments, the 1-3 UGT enzyme includes a deletion of amino residues E225 to T232 as well as the amino acid substitutions S72Q, A305C, Y345F, and L428I, in each case with reference to the amino acid sequence of SEQ ID NO: 6. An exemplary UGT enzyme in accordance with these embodiments is disclosed herein as SEQ ID NO: 9).

In some embodiments, the amino acid modifications described herein are alternatively applied to SrUGT76G1, or circular permutants thereof.

In other aspects, the invention provides polynucleotides encoding the 1-3 UGT enzyme disclosed herein, as well as host cells comprising the same. The host cell may be a microorganism, a fungal cell, an algal cell, or a plant cell. The plant may be a stevia plant or, more particularly, a *Stevia rebaudiana* plant. Stevia plants naturally express the enzymes
5 required to synthesize steviol and steviol glycosides, but they produce only trace amounts of highly glycosylated steviol glycosides such as RebM. In contrast, the RebM content of a stevia or *Stevia rebaudiana* plant expressing a polynucleotide encoding the 1-3 UGT may produce comparatively high levels of RebA, RebD, and/or RebM; or other typically minor steviol glycosides comprising a 1-3 glycosylation such as RebB, RebG, RebI, and Reb4. In
10 various embodiments, the cell is a microbial cell, such as *E. coli*.

In the various embodiments, the host cell may express one or more additional UGT enzymes selected from C-13 UGT enzyme, a C-19 UGT enzyme, and a 1-2 UGT enzyme. “C-13 UGT” or UGTc13 is a glycosyltransferase capable of glycosylating steviol or a steviol glycoside at its C13 hydroxyl group. “C-19 UGT” or UGTc19 is a glycosyltransferase
15 capable of glycosylating steviol or a steviol glycoside at its C19 carboxyl group. “1-2 UGT” or UGT1-2 is a glycosyltransferase capable of β 1,2 glycosylation of the C2’ of a 13-O-glucose, and/or a 19-O-glucose. “1-3 UGT” or UGT1-3 is a glycosyltransferase capable of β 1,3 glycosylation of the C3’ of a 13-O-glucose, and/or a 19-O-glucose.

In some embodiments, the host cell expresses (in addition to the 1-3 UGT enzyme)
20 a heterologous C-13 UGT enzyme, a heterologous C-19 UGT enzyme, and a heterologous 1-2 UGT enzyme, and is thus capable of glycosylating steviol and steviol glycoside substrates to produce RebM.

In some embodiments, the host cell (e.g., bacterial or yeast cell) produces steviol substrate by expression of endogenous and/or heterologous enzymes for biosynthesis of
25 steviol. In these embodiments, the cell produces steviol glycosides, such as RebM, from carbon sources such as glucose, sucrose, or glycerol, among others.

In some aspects, the invention provides a method for transferring a monosaccharide group to a substrate. The method comprises contacting an NDP-sugar (e.g., UDP-monosaccharide) and the substrate with the 1-3 UGT enzyme described herein, or with a
30 host cell expressing the 1-3 UGT enzyme or a lysate thereof. Various substrates can be

glycosylated according to this disclosure, including but not limited to terpenoids. In some embodiments, the substrate is a terpenoid substrate, and can be a diterpenoid, such as steviol and/or steviol glycosides. In some embodiments, the substrate comprises stevioside and/or RebD. In various embodiments, the nucleotide diphosphate is UDP or ADP, or other NDP
5 capable of acting as a glycosyl donor molecule. In various embodiments, the monosaccharide is glucose, galactose, fructose, rhamnose, or xylose. In some embodiments, the monosaccharide is glucose. The NDP-sugar can be supplied exogenously for in vitro reactions, or is produced endogenously by a host cell for embodiments that employ microbial fermentation or biotransformation reactions. Various modifications can be made to the host
10 cell to increase available UDP-glucose to support the reactions.

In some embodiments, the substrate comprises a plant extract, which is optionally a stevia leaf extract. In various embodiments, a microbial cell expressing the 1-3 UGT may be fed with steviol or a lower order steviol glycoside for the production of higher order steviol glycosides, including RebD and RebM. Advanced intermediates from stevia leaf extract are
15 readily available from existing industrial extraction of steviol glycosides.

In various embodiments, the 1-3 UGT converts a lower order steviol glycoside to a higher order steviol glycoside. For example, the UGT enzyme may have 1-3' UGT activity for the conversion of steviobioside to Rebb, rubusoside to RebG, stevioside to Reb A, Reb A to Rebi, RebG to Reb4, RebE to Reb D, and/or Reb D to Reb M. Alternatively, the UGT
20 may be used in combination with another 1-3 UGT enzyme or enzymes having a preference of specificity for certain substrates. For example, one UGT may preferentially act as a 1-3 UGT on C13 glycosyl substrates whereas another UGT enzyme preferentially acts as a 1-3 UGT on C19 glycosyl substrates.

In some embodiments, the method comprises growing the host cell in the presence
25 of the substrate. The substrate may be fed to the culture, or in some embodiments, the substrate is synthesized by the host cell. In some embodiments, the substrate comprises steviol or comprises a mixture of stevioside and RebA as major components, and the host cell expresses a plurality of UGT enzymes to produce target steviol glycosides, such as RebM.

DESCRIPTION OF THE FIGURES

Figure 1 shows the chemical structure of Rebaudioside M (RebM), a minor component of the steviol glycoside family. RebM is a derivative of the diterpenoid steviol (box) with six glucosyl modifications.

5 **Figure 2** shows glycosylation pathways from steviol to RebM and other steviol glycosides. UGTc13 is a glycosyltransferase capable of glycosylating steviol or a steviol glycoside at its C13 hydroxyl group. UGTc19 is a glycosyltransferase capable of glycosylating steviol or a steviol glycoside at its C19 carboxyl group. UGT1-2 is a glycosyltransferase capable of β 1,2 glycosylation of the C2' of a 13-O-glucose, and/or a 19-O-glucose. UGT1-3 is a glycosyltransferase capable of β 1,3 glycosylation of the C3' of a 13-O-glucose, and/or a 19-O-glucose.

15 **Figure 3** shows an amino acid sequence alignment of SrUGT76G1 (SEQ ID NO: 1) and MbUGT1-3_2 (SEQ ID NO: 6), which is a circularly permuted version of SrUGT76G1. Panel A shows the N-terminal portion of SrUGT76G1 aligned to the C-terminal portion of MbUGT1-3_2. Panel B shows the C-terminal portion of SrUGT76G1 aligned to the N-terminal portion of MbUGT1-3_2.

20 **Figure 4** shows the percent conversion of stevioside to RebA, and percent conversion of RebD to RebM in vitro by the following glycosyltransferases: UGT76G1-L200A (SEQ ID NO: 3), MbUGT1-3_0 (SEQ ID NO: 4), MbUGT1-3_1 (SEQ ID NO: 5), and MbUGT1-3_2 (SEQ ID NO: 6).

Figure 5 shows the fold improvement for conversion of stevioside to RebA and for conversion of RebD to RebM, compared to UGT76G1-L200A. MbUGT1-3_1 and MbUGT1-3_2 show very stark improvements in enzyme productivity for both conversions.

DETAILED DESCRIPTION OF THE INVENTION

25 In various aspects, the present invention provides uridine diphosphate-dependent glycosyltransferase (UGT) enzymes capable of catalyzing the transfer of a monosaccharide moiety from an NDP-sugar (*e.g.*, UGT-glucose) to the 3' carbon of a sugar moiety of a substrate, such as a terpenoid glycan, thereby functioning as a "1-3 UGT." In other aspects,

the invention provides polynucleotides encoding the 1-3 UGT, and host cells comprising the same. In still other aspects, the invention provides methods for preparing glycosylated substrates, including steviol glycosides, using the enzyme and host cells of this disclosure.

The 1-3 UGT enzyme exhibits high glycosyltransferase activity on terpenoid glycosides, such as steviol glycosides. For example, the 1-3 UGT enzyme catalyzes transfer of a monosaccharide moiety from an NDP-sugar to the 3' carbon of a sugar moiety on a terpenoid glycan, such as stevioside and RebD. That is, where the substrate is a steviol glycoside, the 1-3 UGT can catalyze NDP-dependent transfer of a monosaccharide moiety to the 3' carbon of both the C13- or C19-linked sugar (e.g., glucose) moieties. In some embodiments, the 1-3 UGT enzyme has a higher rate or productivity for glycosylation at the C19-linked sugar, as compared to at the C13-linked sugar. In some embodiments, the monosaccharide is glucose, but in other embodiments, the monosaccharide may be galactose, fructose, rhamnose, xylose, or other monosaccharide.

In various embodiments, the 1-3 UGT catalyzes the biosynthesis of RebM. The structure of RebM is shown in **Figure 1**. RebM comprises a steviol scaffold with six glycosylations: (1) a C13 O-glycosylation, (2) a C13 1-2 glycosylation, (3) a C13 1-3 glycosylation, (4) a C19 O-glycosylation, (5) a C19 1-2 glycosylation, and (6) a C19 1-3 glycosylation. As shown in **Figure 2**, the 1-3 UGT can produce RebM through the transfer of an additional glucose to RebD substrate. Further, the 1-3 UGT enzyme can catalyze the transfer of a monosaccharide to other steviol glycoside substrates, producing products such as RebB (from steviolbioside), RebG (from rubusoside), Reb4 (from RebG), RebA (from stevioside), RebD (from RebE), and RebI (from RebA). In some embodiments, the substrate comprises a plant extract, such as a stevia leaf extract, and the 1-3 UGT (along with the action of other glycosyltransferase enzymes) is able to glycosylate the various major or minor glycosylation products to produce a product that is predominately RebM.

In one aspect, the invention provides a 1-3 UGT enzyme comprising an amino acid sequence that is at least about 75% identical to the amino acid sequence of SEQ ID NO: 5 or SEQ ID NO: 6. In some embodiments, the 1-3 UGT comprises an amino acid sequence that is at least about 80% identical to SEQ ID NO: 5 or 6. In some embodiments, the amino acid sequence is at least about 85% identical to SEQ ID NO: 5 or 6, or at least about 90%

identical to SEQ ID NO: 5 or 6, or at least about 95% identical to SEQ ID NO: 5 or 6, or at least about 98% identical to SEQ ID NO: 5 or 6. In some embodiments, the amino acid sequence comprises the amino acid of SEQ ID NO: 5 or 6.

In some embodiments, the 1-3 UGT enzyme comprises an amino acid sequence that is at least about 75% identical to the amino acid sequence of SEQ ID NO: 9. In some embodiments, the 1-3 UGT comprises an amino acid sequence that is at least about 80% identical to SEQ ID NO: 9. In some embodiments, the amino acid sequence is at least about 85% identical to SEQ ID NO: 9, or at least about 90% identical to SEQ ID NO: 9, or at least about 95% identical to SEQ ID NO: 9, or at least about 98% identical to SEQ ID NO: 9. In some embodiments, the amino acid sequence comprises the amino acid of SEQ ID NO: 9.

For example, the amino acid sequence may have from 1 to 20 amino acid modifications independently selected from substitutions, deletions, and insertions, with respect to the amino acid sequence SEQ ID NO: 5 or 6. In some embodiments, the amino acid sequence has from 1 to 10 amino acid modifications (e.g., from 1 to 5) independently selected from substitutions, deletions, and insertions, with respect to the amino acid sequence of SEQ ID NO: 5 or 6. In some embodiments, the UGT amino acid sequence has from 1 to 20 amino acid modifications independently selected from substitutions, deletions, and insertions, with respect to the amino acid sequence of SEQ ID NO: 9. In some embodiments, the amino acid sequence has from 1 to 10 amino acid modifications (e.g., from 1 to 5) independently selected from substitutions, deletions, and insertions, with respect to the amino acid sequence of SEQ ID NO: 9. Amino acid modifications to the amino acid sequence of SEQ ID NO: 5, 6, or 9, can be guided by available enzyme structures and construction of homology models. Exemplary structures are described in, e.g., Li, et al., "Crystal Structure of *Medicago truncatula* UGT85H2—insights into the Structural Basis of a Multifunctional (iso) Flavonoid Glycosyltransferase," *J. of Mol. Biol.* 370.5 (2007): 951-963 as well as Lee et al., "Molecular Basis for Branched Steviol Glucoside Biosynthesis," *PNAS* 116:13131-13136 (2019). Publicly available crystal structures (e.g., PDB entry: 2PQ6) may be used to inform amino acid modifications. For example, one or more amino acid modifications can be made to the active site or in the vicinity of the active site to improve the binding of substrate, and/or to improve reaction geometries of these substrates with catalytic side chains.

In some embodiments, the enzyme comprises an amino acid substitution at positions corresponding to positions 29, 200, 357, and 414 of SEQ ID NO: 1 (*Stevia rebaudiana* UGT76G1). Substitutions at these positions, which are included in the enzyme of SEQ ID NOS: 5, 6, and 9 (positions 183, 354, 54, and 111, respectfully, in SEQ ID NO: 5) can provide dramatic improvements in activity. In some embodiments, the identity of amino acids at positions corresponding to positions 183, 354, 54, and 111 of SEQ ID NO: 5, allows for further modification at other positions. For example, in some embodiments, the 1-3 UGT enzyme comprises an amino acid sequence that is at least about 60% identical to the amino acid sequence of SEQ ID NO: 5, 6, or 9, wherein the UGT enzyme comprises: a glycine (G) or threonine (T) at the position corresponding to position 54 of SEQ ID NO: 5; a leucine (L) or isoleucine (I) at the position corresponding to position 111 of SEQ ID NO: 5; a methionine (M) or leucine (L) at the position corresponding to position 183 of SEQ ID NO: 5; and an alanine (A), or glycine (G), or serine (S) at the position corresponding to position 354 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT has two or three of a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5, a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5, and a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. These modifications can provide substantial improvements to the activity of the enzyme.

The 1-3 UGT enzyme may comprise other substitutions at the position corresponding to position 54 of SEQ ID NO: 5, other than Serine, which is at the corresponding position (357) of SEQ ID NO: 1. Thus, in some embodiments, the substitution at the position corresponding to position 54 of SEQ ID NO: 5 is a hydrophobic amino acid, such as alanine (A), valine (V), leucine (L), isoleucine (I), phenylalanine (F), or methionine (M). In some embodiments, the amino acid at the position corresponding to position 54 of SEQ ID NO: 5 has a side chain that does not have the ability to provide a hydrogen bond. In other embodiments, the amino acid at the position corresponding to position 54 of SEQ ID NO: 5 is Glycine (G), asparagine (N), cysteine (C), glutamine (Q), threonine (T), or tyrosine (Y).

In various embodiments, the 1-3 UGT enzyme comprises a leucine (L) amino acid at the position corresponding to position 111 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme may comprise an amino acid other than leucine at this position. In various embodiments, the position corresponding to position 111 of SEQ ID NO: 5 will not be Valine, the amino acid at the corresponding position of SEQ ID NO: 1. Other suitable substitutions at the position corresponding to position 111 may include glycine (G), alanine (A), isoleucine (I) or methionine (M). In some embodiments, the amino acid at the position corresponding to position 111 of SEQ ID NO: 5 has a side chain that is less hydrophobic and/or bulky than valine.

In various embodiments, the UGT comprises a methionine (M) amino acid at the position corresponding to position 183 of SEQ ID NO: 5. In various embodiments, the UGT comprises another suitable amino acid at this position, other than isoleucine, which is at the corresponding position of SEQ ID NO: 1. For example, the amino acid at this position may have a side chain that is less hydrophobic than isoleucine and/or may provide a hydrogen bond. Some exemplary substitutions at the position corresponding to position 183 of SEQ ID NO: 5 include alanine (A), valine (V), leucine (L), Cysteine (C), Serine (S), Threonine (T), Tyrosine (Y), Asparagine (N), Glutamine (Q), Aspartic Acid (D), and Glutamic acid (E).

In various embodiments, the 1-3 UGT comprises an Alanine (A) or Glycine (G) at the position corresponding to position 354 of SEQ ID NO: 5. In various embodiments, the amino acid at this position has a side chain that is less hydrophobic and/or less bulky than leucine, which is at the corresponding position of SEQ ID NO: 1.

In some embodiments, the 1-3 UGT enzyme comprises an insertion (with respect to UGT76G1, SEQ ID NO: 1) of from 5 to about 15 amino acids, such as from 6 to 12 amino acids, or about 6 or about 11 amino acids, after the position corresponding to position 155 of SEQ ID NO: 5. In some embodiments, the insertion is a flexible and hydrophilic sequence, that is predominately Glycine and Serine residues. In some embodiments, the sequence is GSGGSG (SEQ ID NO: 7) or GSGGSGGSG (SEQ ID NO: 8).

In various embodiments, the 1-3 UGT enzyme shows improved conversion of stevioside to Reb A, and improved conversion of RebD to RebM, as compared to UGT76G1-

L200A (SEQ ID NO: 3). This improved conversion is exhibited in a bioconversion assay where stevioside or RebD substrate is fed to microbial cells expressing the 1-3 UGT enzyme of this disclosure. Improved conversion can be demonstrated in reactions with cell lysates containing recombinantly expressed 1-3 UGT, or in vitro reactions with purified or partially purified 1-3 UGT. Such reactions are well known in the art. Alternatively, whole cell assays can be used. For example, an *E. coli* strain (Δ ushA, Δ galETKM, Δ pgi; overexpressed pgm, galU) expressing the 1-3 UGT enzyme is grown overnight in 96-well plates at 250 rpm at 37 °C. The cells are then transferred to a fresh production culture to 10% of the total volume. 0.5 mM substrate (*e.g.*, stevioside or Rebaudioside D) are included in the production culture. The production culture is then grown for 48 hours in 96-well plates at 250 rpm at 37 °C. Products can be quantified using a LC-MS QQQ.

In some embodiments, the identity of amino acids at positions corresponding to positions 183, 354, 54, and 111 of SEQ ID NO: 5, allows for further modification at other positions. For example, in some embodiments, the 1-3 UGT enzyme comprises an amino acid sequence that is at least about 60% identical to the amino acid sequence of SEQ ID NO: 5, 6, or 9, wherein the UGT enzyme comprises: a glycine (G) or threonine (T) at the position corresponding to position 54 of SEQ ID NO: 5; a leucine (L) or isoleucine (I) at the position corresponding to position 111 of SEQ ID NO: 5; a methionine (M) or leucine (L) at the position corresponding to position 183 of SEQ ID NO: 5; and an alanine (A), or glycine (G), or serine (S) at the position corresponding to position 354 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT enzyme comprises a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. In some embodiments, the 1-3 UGT has two or three of a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5, a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5, and a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5. These modifications can provide substantial improvements to the activity of the enzyme. In some embodiments, the amino acid sequence is at least about 70% identical to the amino acid sequence of SEQ ID NO: 5, 6, or 9, or at least about 80% identical to the amino acid sequence

of SEQ ID NO: 5, 6, or 9, or at least about 90% identical to the amino acid sequence of SEQ ID NO: 5, 6, or 9, or at least about 95% to the amino acid sequence of SEQ ID NO: 5, 6, or 9.

5 In some embodiments, the 1-3 UGT enzyme comprises a glycine (G) amino acid at the position corresponding to position 54 of SEQ ID NO: 5, a leucine (L) amino acid at the position corresponding to position 111 of SEQ ID NO: 5; and a methionine (M) amino acid at the position corresponding to position 183 of SEQ ID NO: 5.

10 In some embodiments, the 1-3 UGT enzyme comprises a glycine (G) amino acid at the position corresponding to position 54 of SEQ ID NO: 5, and a leucine (L) amino acid at the position corresponding to position 111 of SEQ ID NO: 5.

In some embodiments, the 1-3 UGT enzyme comprises a glycine (G) amino acid at the position corresponding to position 54 of SEQ ID NO: 5, and a methionine (M) amino acid at the position corresponding to position 183 of SEQ ID NO: 5.

15 In some embodiments, the 1-3 UGT enzyme comprises a leucine (L) amino acid at the position corresponding to position 111 of SEQ ID NO: 5 and a methionine (M) amino acid at the position corresponding to position 183 of SEQ ID NO: 5.

20 In these or other embodiments, the 1-3 UGT enzyme has a deletion of one or more amino acids at positions E225 to T232, with respect to the amino acid sequence of SEQ ID NO: 6. For example, the UGT may have a deletion of at least two, at least three, at least four, at least five, at least six, at least seven, or eight amino acids corresponding to amino acids E225-T232 of SEQ ID NO: 6.

25 In these or other embodiments, the 1-3 UGT enzyme further includes one or more of amino acid substitutions at positions corresponding to position 72, position 305, position 345, and position 428. For example, 1-3 UGT enzyme may have a substitution of glutamine (Q) or asparagine (N) at the position corresponding to position 72 of SEQ ID NO: 6. In some embodiments, the 1-3 UGT enzyme has a substitution of a neutral hydrophilic amino acid, such as cysteine (C), Serine (S), or Threonine (T) at the position corresponding to position 305 of SEQ ID NO: 6. In some embodiments, the 1-3 UGT enzyme has a substitution of phenylalanine (F) or Tryptophan (W) at the position corresponding to position 345 of SEQ

ID NO: 6. In some embodiments, the 1-3 UGT enzyme has a substitution of isoleucine (I), valine (V), or alanine (A) at the position corresponding to position 428 of SEQ ID NO: 6. In some embodiments, the 1-3 UGT enzyme has 2, 3, or 4 of the following substitutions with respect to SEQ ID NO: 6: S72Q, A305C, Y345F, and L428I.

5 In some embodiments, the 1-3 UGT enzyme comprises an insertion (with respect to 76G1) of from 5 to about 15 amino acids, such as from about 6 to about 12 amino acids, or about 6 or about 11 amino acids, after the position corresponding to positions 155 of SEQ ID NO: 5. In some embodiments, the insertion is a flexible and hydrophilic sequence, such as an amino acid sequence that is predominately Glycine and Serine residues. In some
10 embodiments, the sequence is GSGGSG (SEQ ID NO: 7) or GSGGSGGSG (SEQ ID NO: 8).

 In still other aspects and embodiments, the 1-3 UGT enzyme is not a circular permutant of UGT76G1, that is, the enzyme comprises an amino acid sequence that has at least about 75% sequence identity to the amino acid sequence of SEQ ID NO:1. In such
15 embodiments, the enzyme may include one or more amino acid modifications described herein. Exemplary modifications of UGT76G1 (SEQ ID NO:1) include modifications with respect to SEQ ID NO:1 selected from: (i) a deletion of one or more amino acids corresponding to E74 to T81, (ii) a substitution at the position corresponding to position 357, which is optionally glycine, (iii) a substitution at the position corresponding to position 414,
20 and which is optionally leucine, (iv) a substitution at the position corresponding to position 29, and which is optionally methionine, (v) a substitution at the position corresponding to position 402, which is optionally glutamine, (vi) a substitution at the position corresponding to position 154, which is optionally cysteine, (vii) a substitution at the position corresponding to position 194, and which is optionally phenylalanine, (viii) a substitution at
25 the position corresponding to position 277, and which is optionally isoleucine, (ix) a substitution at the position corresponding to position 208, and which is optionally glutamine, (x) a substitution at the position corresponding to position 140, and which is optionally proline, and (xi) a substitution at the position corresponding to position 259, and which is optionally glutamic acid.

For example, in some embodiments, the UGT enzyme comprises a deletion of at least two, or at least three, at least four, at least five, at least six, at least seven, or all eight amino acids corresponding to E74 to T81 of SEQ ID NO:1. In various embodiments, the enzyme further comprises a substitution of alanine at the position corresponding to position 200 of SEQ ID NO: 1. In some embodiments, the enzyme has at least two, three, or four of: 357G, 414L, 29M, 402Q, 154C, 194F, 277I, 208Q, 140P, and 259E, each numbered according to SEQ ID NO:1.

In such embodiments, the enzyme may have is at least about 80% sequence identity, or at least about 85% sequence identity, or at least about 90% sequence identity, or at least about 95% sequence identity, or at least about 98% sequence identity to the amino acid sequence of SEQ ID NO:1. For example, the enzyme may have from 1 to 20, or from 1 to 10 amino acid modifications independently selected from amino acid substitutions, deletions, and insertions with respect to SEQ ID NO:1.

In still other aspects and embodiments, the 1-3 UGT enzyme is a circular permutant of SrUGT76G1 (see US 2017/0332673, which is hereby incorporated by reference in its entirety) and optionally having from 1 to 20 or from 1 to 15, or from 1 to 10 amino acid modifications independently selected from amino acid substitutions, deletions, and insertions with respect to the corresponding position of SEQ ID NO:1. Exemplary modifications with respect to positions of SEQ ID NO:1 can be selected from: (i) a deletion of one or more amino acids corresponding to E74 to T81 (as described herein), (ii) a substitution at the position corresponding to position 357, which is optionally glycine, (iii) a substitution at the position corresponding to position 414, and which is optionally leucine, (iv) a substitution at the position corresponding to position 29, and which is optionally methionine, (v) a substitution at the position corresponding to position 402, which is optionally glutamine, (vi) a substitution at the position corresponding to position 154, which is optionally cysteine, (vii) a substitution at the position corresponding to position 194, and which is optionally phenylalanine, (viii) a substitution at the position corresponding to position 277, and which is optionally isoleucine, (ix) a substitution at the position corresponding to position 208, and which is optionally glutamine, (x) a substitution at the position corresponding to position 140, and which is optionally proline, and (xi) a substitution at the position corresponding to position 259, and which is optionally glutamic

acid. In some embodiments, the UGT enzyme comprises a deletion of the amino acids corresponding to E74 to T81.

Changes to the amino acid sequence of an enzyme can alter its activity or have no measurable effect. Silent changes with no measurable effect are most likely to be conservative substitutions and small insertions or deletions on solvent-exposed surfaces that are located away from active sites and substrate-binding sites. In contrast, enzymatic activity is more likely to be affected by non-conservative substitutions, large insertions or deletions, and changes within active sites, substrate-binding sites, and at buried positions important for protein folding or conformation. Changes that alter enzymatic activity may increase or decrease the reaction rate or increase or decrease the affinity or specificity for a particular substrate. For example, changes that increase the size of a substrate-binding site may permit an enzyme to act on larger substrates and changes that position a catalytic amino acid side chain closer to a target site on a substrate may increase the enzymatic rate.

Knowledge of the three-dimensional structure of an enzyme and the location of relevant active sites, substrate-binding sites, and other interaction sites can facilitate the rational design of mutations and provide mechanistic insight into the phenotype of specific changes. Plant UGTs share a highly conserved secondary and tertiary structure while having relatively low amino acid sequence identity. Osmani et al, Substrate specificity of plant UDP-dependent glycosyltransferases predicted from crystal structures and homology modeling, *Phytochemistry* 70 (2009) 325–347. The sugar acceptor and sugar donor substrates of UGTs are accommodated in a cleft formed between the N- and C-terminal domains. Several regions of the primary sequence contribute to the formation of the substrate binding pocket including structurally conserved domains as well as loop regions differing both with respect to their amino acid sequence and sequence length.

Construction of UGT derivatives can be guided based on structure analysis and homology modeling. See, Soon Goo Lee, et al., Molecular Basis for Branched Steviol Glucoside Biosynthesis, *PNAS*, June 19, 2019.

For example, based on independent crystal structure preparation and analysis of SrUGT76G1_L200A and an amino acid sequence alignment of SrUGT76G1 to MbUGT3-1_1, it is predicted that the steviol core of stevioside is close (within 4 Å) to the following

residues of MbUGT3-1_1: I244, L280, W351, A354, I357, M362, and T438. Further, the C19 1-2 glycosylation is predicted to be close (within 4 Å) to T438. The steviol core of RebD is predicted to be close (within 4 Å) of the following hydrophobic side chains of MbUGT3-1_1: L239, M242, I244, L280, I353, A354, and I357. The C13 1-2' glycosylation is predicted to be close (within 4 Å) of the following hydrogen bonding side chains of MbUGT3-1_1: S301 and D77. Positioning and amino acid content of the V341-Q352 and K355-A367 helices of MbUGT3-1_1 may be important for catalysis as the mutation corresponding to L200A is in a loop between these helices. Positions L76 and/or D77 of MbUGT3-1_1 may interact with the C13 glycosylation of stevioside.

Substitutions of amino acids may be conservative substitutions or non-conservative substitutions. Conservative substitutions are defined where the old and new amino acids have similar characteristics such as size and charge. Naturally occurring residues are divided into groups based on common side chain properties:

(group 1) hydrophobic (aliphatic): methionine (Met), Alanine (Ala), Valine (Val), Leucine (Leu), Isoleucine (Ile);

(group 2) neutral hydrophilic: Cysteine (Cys), Serine (Ser), Threonine (Thr), Asparagine (Asn), Glutamine (Gln);

(group 3) acidic: Aspartic acid (Asp), Glutamic acid (Glu);

(group 4) basic: Histidine (His), Lysine (Lys), Arginine (Arg);

(group 5) residues that influence chain orientation: Glycine (Gly), Proline (Pro); and

(group 6) aromatic: Tryptophan (Trp), Tyrosine (Tyr), Phenylalanine (Phe).

Non-conservative substitutions will entail exchanging a member of one of these classes for another an amino acid of another class.

The amino acid sequence of the UGT enzyme can optionally include an alanine inserted or substituted at position 2 to decrease turnover in the cell. In various embodiments, the 1-3 UGT enzyme comprises an alanine amino acid residue inserted or substituted at position 2 with respect to SEQ ID NO: 5, 6, or 9, to provide additional stability *in vivo*.

Identity of amino acid sequences, i.e. the percentage of sequence identity, can be determined via sequence alignments. Such alignments can be carried out with several known algorithms, such as that described by Karlin and Altschul (Karlin & Altschul (1993) *Proc. Natl. Acad. Sci. USA* 90: 5873-5877), with hmalign (HMMER package) or with the
5 CLUSTAL algorithm (Thompson, J. D., Higgins, D. G. & Gibson, T. J. (1994) *Nucleic Acids Res.* 22, 4673-80). The grade of sequence identity (sequence matching) may be calculated using e.g. BLAST, BLAT or BlastZ (or BlastX). A similar algorithm is incorporated into the BLASTN and BLASTP programs of Altschul et al (1990) *J. Mol. Biol.* 215: 403-410. BLAST protein alignments may be performed with the BLASTP program, score = 50, word
10 length = 3. To obtain gapped alignments for comparative purposes, Gapped BLAST is utilized as described in Altschul et al (1997) *Nucleic Acids Res.* 25: 3389-3402. When utilizing BLAST and Gapped BLAST programs, the default parameters of the respective programs are used.

In other aspects, the invention provides polynucleotides encoding the 1-3 UGT
15 enzyme disclosed herein, as well as host cells comprising the same. The host cell may be a microorganism, a fungal cell, an algal cell, or a plant cell. The plant may be a stevia plant or, more particularly, a *Stevia rebaudiana* plant. Stevia plants naturally express the enzymes required to synthesize steviol and steviol glycosides, but they produce only trace amounts of highly glycosylated steviol glycosides such as RebM. In contrast, the RebM content of a
20 stevia or *Stevia rebaudiana* plant expressing a polynucleotide encoding the 1-3 UGT may be more than about 1%, or more than about 2%, or more than about 5%, or more than about 10% of the steviol glycoside content of the plant leaves. Furthermore, the RebA content of a stevia or *Stevia rebaudiana* plant expressing a polynucleotide encoding the 1-3 UGT may be more than about 5%, or more than about 10%, or more than about 15% of the steviol
25 glycoside content of the plant leaves.

The microbial host cell in various embodiments may be prokaryotic or eukaryotic. In some embodiments, the microbial host cell is a bacteria selected from *Escherichia spp.*, *Bacillus spp.*, *Corynebacterium spp.*, *Rhodobacter spp.*, *Zymomonas spp.*, *Vibrio spp.*, and *Pseudomonas spp.* For example, in some embodiments, the bacterial host cell is a species
30 selected from *Escherichia coli*, *Bacillus subtilis*, *Corynebacterium glutamicum*, *Rhodobacter capsulatus*, *Rhodobacter sphaeroides*, *Zymomonas mobilis*, *Vibrio natriegens*,

or *Pseudomonas putida*. In some embodiments, the bacterial host cell is *E. coli*. Alternatively, the microbial cell may be a yeast cell, such as but not limited to a species of *Saccharomyces*, *Pichia*, or *Yarrowia*, including *Saccharomyces cerevisiae*, *Pichia pastoris*, and *Yarrowia lipolytica*.

5 The polynucleotides encoding the 1-3 UGT enzymes may be integrated into the chromosome of the microbial cell, or alternatively, are expressed extrachromosomally. For example, the 1-3 UGT enzyme may be expressed from a bacterial artificial chromosome (BAC) or plasmid.

 Expression of UGT enzymes can be tuned for optimal activity, using, for example, gene modules (e.g., operons) or independent expression of the UGT enzymes. For example, expression of the genes or operons can be regulated through selection of promoters, such as inducible or constitutive promoters, with different strengths (e.g., strong, intermediate, or weak). Several non-limiting examples of promoters of different strengths include Trc, T5 and T7. Additionally, expression of genes or operons can be regulated through manipulation of the copy number of the gene or operon in the cell. In some embodiments, the cell expresses a single copy of each UGT enzyme. In some embodiments, expression of genes or operons can be regulated through manipulating the order of the genes within a module, where the genes transcribed first are generally expressed at a higher level. In some embodiments, expression of genes or operons is regulated through integration of one or more genes or operons into the chromosome.

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 Optimization of UGT expression can also be achieved through selection of appropriate promoters and ribosomal binding sites. In some embodiments, this may include the selection of high-copy number plasmids, or single-, low- or medium-copy number plasmids. The step of transcription termination can also be targeted for regulation of gene expression, through the introduction or elimination of structures such as stem-loops.

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 In some embodiments, the cell is a plant cell. For example, the polynucleotide can be heterologously expressed in a stevia plant under the control of a suitable promoter, such as a constitutive or inducible promoter.

 In the various embodiments, the host cell may express one or more additional UGT enzymes selected from C-13 UGT enzyme, a C-19 UGT enzyme, and a 1-2 UGT enzyme.

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In some embodiments, the host cell expresses (in addition to the 1-3 UGT enzyme) a heterologous C-13 UGT enzyme, a heterologous C-19 UGT enzyme, and a heterologous 1-2 UGT enzyme, and is thus capable of glycosylating steviol and steviol glycoside substrates to produce RebM.

5 **Figure 2** illustrates the structures of steviol and various steviol glycosides, and identifies enzymatic activities in biosynthetic pathways leading from steviol to RebM. Likewise, **Table 1** identifies substrates and products on biosynthetic pathways leading from steviol to RebM. For each substrate and product pair, **Table 1** describes the type of glycosylation and identifies enzymes with the requisite activity. Four types glycosylation
10 activity are required for production of RebM: primary glycosylation of the C13 and C19 carbons, and secondary glycosylation at the 2' or 3' positions of the primary glycan. The glycans are added one 6-carbon monosaccharide unit at a time. Thus, a primary glycan must be conjugated to the C13 or C19 of steviol or a steviol glycoside before a secondary glycan can be conjugated to that primary glycan. However, the order of glycosylation of steviol
15 glycosides is not otherwise restricted. **Table 2** identifies enzymes from various sources with the activities required on biosynthetic pathways leading from steviol to Reb M and provides references for their nucleotide and amino acid sequences. See U.S. Patent Application Publication 20170332673, which is hereby incorporated by reference in its entirety.

Table 1: Enzymes catalyzing reactions leading to Reb M.

Substrate	Product	Glycos.	Enzyme 1	Enzyme 2	Enzyme 3	Enzyme 4
Steviol	Steviolmonoside	C13	SrUGT85C2			
Steviol	C19-Glu-Steviol	C19	SrUGT74G1	MbUGTc19		
Steviolmonoside	Steviolbioside	1-2'	SrUGT91D1	SrUGT91D2	OsUGT1-2	MbUGT1-2
Steviolmonoside	Rubusoside	C19	SrUGT74G1	MbUGTc19		
C19-Glu-Steviol	Rubusoside	C13	SrUGT85C2			
Steviolbioside	Stevioside	C19	SrUGT74G1	MbUGTc19		
Steviolbioside	RebB	1-3'	SrUGT76G1	MbUGT1-3_1		
Stevioside	RebE	1-2'	SrUGT91D1	SrUGT91D2	OsUGT1-2	MbUGT1-2
Stevioside	Reb A	1-3'	SrUGT76G1	MbUGT1-3_1		
RebB	Reb A	C19	SrUGT74G1	MbUGTc19		

RebE	Reb D	1-3'	SrUGT76G1	MbUGT1-3_1		
Reb A	Reb D	1-2'	SrUGT91D1	SrUGT91D2	OsUGT1-2	MbUGT1-2
Reb D	Reb M	1-3'	SrUGT76G1	MbUGT1-3_1	MbUGT1-3_2	

Table 2: Enzyme/gene sequences for biosynthesis of steviol glycosides

Glycosylation type	Enzyme	Gene ID	Protein ID	Description
C13	SrUGT85C2	AY345978.1	AAR06916.1	
C19	SrUGT74G1	AY345982.1	AAR06920.1	
	MbUGTc19	-	-	US 2017/0332673
1-2'	SrUGT91D1	AY345980.1	AAR06918.1	
	SrUGT91D2	ACE87855.1	ACE87855.1	
	SrUGT91D2e	-	-	US 2011/038967
	OsUGT1-2	NM_001057542.1	NP_001051007.2	WO 2013/022989
	MbUGT1-2	-	-	US 2017/0332673
1-3'	SrUGT76G1	FB917645.1	CAX02464.1	
	MbUGT1-3_1			This disclosure
	MbUGT1-3_2			This disclosure

In some embodiments, the host cell produces steviol by expression of endogenous and/or heterologous enzymes for biosynthesis of steviol. The host cell may be engineered to co-express the 1-3 UGT with other UGT enzymes active on terpenoids and terpenoid glycosides, such as a C-13 UGT enzyme, a C-19 UGT enzyme, and a 1-2 UGT enzyme (see Tables 1-2). The microbial cell may additionally be engineered to co-express enzymes for steviol biosynthesis, such as enzymes of the MEP or MVA pathways, copalyl synthase and kaurene synthase (which can be present as a bifunctional enzyme in some embodiments), P450 enzymes such as kaurene oxidase and kaurenoic acid hydroxylase and P450 reductase enzymes. Table 3. Pathways and enzymes for biosynthesis of steviol are disclosed in US 20170332673, which is hereby incorporated by reference in its entirety.

Table 3: Summary of enzyme/gene sequences enabling biosynthesis of steviol.

No.	Enzyme	Species	Gene ID	Protein ID
1	TcGGPPS	Taxus canadensis	AF081514.1	AAD16018.1
2	AgGGPPS	Abies grandis	AF425235.2	AAL17614.2
3	AnGGPPS	Aspergillus nidulans	XM_654104.1	XP_659196.1
4	SmGGPPS	Streptomyces melanosporofaciens	AB448947.1	BAI44337.1
5	MbGGPPS	Marine bacterium 443	n/a	AAR37858.1

6	PhGGPPS	Paracoccus haeundaensis	n/a	AAAY28422.1
7	CtGGPPS	Chlorobium tepidum TLS	NC_002932.3	NP_661160.1
8	SsGGPPS	Synechococcus sp. JA-3-3Ab	n/a	ABC98596.1
9	Ss2GGPPS	Synechocystis sp. PCC 6803	n/a	BAA16690.1
10	TmGGPPS	Thermotoga maritima HB8	n/a	NP_227976.1
11	CgGGPPS	Corynebacterium glutamicum	n/a	NP_601376.2
12	TtGGPPS	Thermus thermophilus HB27	n/a	YP_143279.1
13	PcGGPPS	Pyrobaculum calidifontis JCM 11548	n/a	WP_011848845.1
14	SrCPS	Stevia rebaudiana	AF034545.1	AAB87091.1
15	EtCPS	Erwina tracheiphila	n/a	WP_020322919.1
16	SfCPS	Sinorhizobium fredii	n/a	WP_010875301.1
17	SrKS	Stevia rebaudiana	AF097311.1	AAD34295.1
18	EtKS	Erwina tracheiphila	n/a	WP_020322918.1
19	SfKS	Sinorhizobium fredii	n/a	WP_010875302.1
20	GfCPS/KS	Gibberella fujikuroi	AB013295.1	Q9UVY5.1
21	PpCPS/KS	Physcomitrella patens	AB302933.1	BAF61135.1
22	PsCPS/KS	Phaeosphaeria sp. L487	AB003395.1	O13284.1
23	AtKO	Arabidopsis thaliana	NM_122491.2	NP_197962.1
24	SrKO	Stevia rebaudiana	AY364317.1	AAQ63464.1
25	PpKO	Physcomitrella patens	AB618673.1	BAK19917.1
26	AtCPR	Arabidopsis thaliana	X66016.1	CAA46814.1
27	SrCPR	Stevia rebaudiana	DQ269454.4	ABB88839.2
28	AtKAH	Arabidopsis thaliana	NM_122399.2	NP_197872.1
29	SrKAH1	Stevia rebaudiana	DQ398871.3	ABD60225.1
30	SrKAH2	Stevia rebaudiana	n/a	n/a

In some aspects, the invention provides a method for transferring a monosaccharide group to a substrate. The method comprises contacting an NDP-sugar (e.g., UDP-monosaccharide) and the substrate with the 1-3 UGT enzyme described herein, or a host cell expressing the 1-3 UGT enzyme or a lysate thereof. Various substrates can be glycosylated according to this disclosure, including but not limited to terpenoids. In some embodiments, the substrate is a terpenoid substrate, and can be a diterpenoid, such as steviol and/or steviol glycosides. In some embodiments, the substrate comprises stevioside and/or RebD. In various embodiments, the monosaccharide is glucose, galactose, fructose, rhamnose, or xylose. In some embodiments, the monosaccharide is glucose. In some embodiments, the method takes place in vitro with recombinant 1-3 UGT, and includes exogenously added NDP-sugar (e.g., UDP-glucose or ADP-glucose) reagent. In other embodiments, the 1-3

UGT is expressed recombinantly in a cell, and the NDP-glucose is available endogenously. In these embodiments, substrate can be fed to the cells, and is available in the cell for the glycosyltransferase reactions.

Whole cell conversion (i.e., a “biotransformation reaction”) requires that substrate (e.g., glycoside intermediates) and product are transported into and out of the cell, respectively, and that the cell provides UDP-glucose cofactor regeneration. This is in contrast to processes that use enzymes from cell lysis or secretion outside the cell, which requires an exogenous NDP-glucose supply or NDP-glucose precursor or NDP-glucose regeneration mechanism or NDP-glucose regeneration enzyme system. In embodiments of the present invention, catalysis (glycosylation) is carried out within live microbial cells. UDP-glucose cofactor recycling takes place using the native cellular metabolism without requiring externally provided enzymes or the feeding of expensive substrates. In accordance with some embodiments, glycoside intermediates are transported into the cell, and product is transported out of the cell.

US 2017/0332673 describes *E. coli* strains that overexpress MEP pathway enzymes, along with a downstream steviol biosynthesis pathway, and UGT enzymes to drive production of RebM from glucose. However, these strains do not perform biocatalysis of fed steviol glycoside intermediates to RebM, which may be, in part, due to the inability of the host cell to import the steviol glycoside substrate. In some embodiments, genetic modifications to the microbial cell allow for glycosylated intermediates to be translocated into the cell, while advanced glycosylated products are secreted into the medium.

In some embodiments, the microbial cell has one or more genetic modifications that increase UDP-glucose availability. In some embodiments, without wishing to be bound by theory, these modifications may also stress the cell for glucose availability, leading to the increased expression of endogenous transporters to import steviol glycosides into the cell. Wild-type UDP-glucose levels in exponentially growing *E. coli* is about 2.5 mM (Bennett BD, et al., Absolute metabolite concentrations and implied enzyme active site occupancy in *Escherichia coli*. *Nat Chem Biol.* 2009;5(8):593-9). In some embodiments, genetic modifications to the host cell are engineered to increase UDP-glucose, e.g., to at least 5 mM,

or at least 10 mM, in exponentially growing cells (e.g., that do not have recombinant expression of UGT enzymes).

In some embodiments, the microbial cell has a deletion, inactivation, or reduced activity or expression of a gene encoding an enzyme that consumes UDP-glucose. For example, the microbial cell may have a deletion, inactivation, or reduced activity of *ushA* (UDP-sugar hydrolase) and/or one or more of *galE*, *galT*, *galK*, and *galM* (which are responsible for UDP-galactose biosynthesis from UDP-glucose), or ortholog thereof in the microbial species. In some embodiments, *galETKM* genes are inactivated, deleted, or substantially reduced in expression.

In these or other embodiments, the microbial cell has a deletion, inactivation, or reduced activity or expression of a gene encoding an enzyme that consumes a precursor to UDP-glucose. For example, in some embodiments, the microbial cell has a deletion, inactivation, or reduced activity or expression of *pgi* (glucose-6 phosphate isomerase), or ortholog thereof in the microbial species of the host cell.

In these or other embodiments, the cell has an overexpression or increased activity of one or more genes encoding an enzyme involved in converting glucose-6-phosphate to UDP-glucose. For example, *pgm* (phosphoglucomutase) and/or *galU* (UTP-glucose-1-phosphate uridylyltransferase) (or ortholog or derivative thereof) can be overexpressed, or modified to increase enzyme productivity. See, US 2020/0087692, which is hereby incorporated by reference in its entirety.

In some embodiments, the substrate is a plant extract, which is optionally a stevia leaf extract. In various embodiments, a microbial cell expressing the 1-3 UGT may be fed with steviol or a lower order steviol glycoside for the production of higher order steviol glycosides, including Reb D and Reb M. Advanced intermediates from stevia leaf extract are readily available from existing industrial extraction of steviol glycosides. As shown in **Table 4**, available leaf extract contains primarily the pathway intermediates stevioside and Rebaudioside A (RebA). In various embodiments, the stevia leaf extract is an extraction of steviol glycosides. In some embodiments, the extract comprises one or more of stevioside, steviolbioside, and Rebaudioside A, as prominent components. A prominent component generally makes up at least about 10% of the steviol glycosides in the extract, but in some

embodiments, may make up at least about 20%, or at least about 25%, or at least about 30% of the steviol glycosides in the extract.

Table 4: Steviol Glycoside Composition of Available Stevia Leaf Extract

%	Batch 1	Batch 2	Batch 3
Rebaudioside A	38.2	10.5	30.3
Stevioside	8.5	9.0	18.4
Rebaudioside C	12.9	4.2	16.6
Rebaudioside B	4.3	7.1	1.2
Rubusoside	5.0	2.2	2.0
Rebaudioside F	2.0	2.7	2.1
Steviolbioside	0.3	3.7	0.3
Rebaudioside D	0.2	2.1	0.9
Dulcoside A	0.9	0.4	0.5

5 In various embodiments, the 1-3 UGT converts a lower order steviol glycoside to a higher order steviol glycoside. For example, the UGT enzyme may have 1-3' UGT activity for the conversion of steviobioside to RebB, rubusoside to RebG, stevioside to Reb A, Reb A to RebI, RebG to Reb4, RebE to Reb D, and/or Reb D to Reb M. Alternatively, the UGT may be used in combination with another 1-3 UGT enzyme or enzymes having a preference
 10 of specificity for certain substrates. For example, one UGT may preferentially act as a 1-3 UGT on C13 glycosyl substrates whereas another UGT enzyme preferentially acts as a 1-3 UGT on C19 glycosyl substrates.

In some embodiments, a microbial cell expressing the 1-3 UGT enzyme is fed with RebD, and converts at least about 15%, or at least about 20%, or at least about 25%, or at
 15 least about 30%, or at least about 50%, or at least about 75%, or at least about 90% of the Reb D to Reb M. In various embodiments, such conversions are allowed to take place for at least about 8 hours, or at least about 24 hours in some embodiments. For example, the conversion may be allowed to take place in the culture for from 8 hours to about 72 hours. In some embodiments, the conversion may be allowed to take place for about 24 hours to
 20 about 60 hours. In some embodiments, the microbial cell converts at least about 40%, or at least about 50%, or at least about 75%, or at least about 90% of the Reb D to Reb M in about 48 hours or less or about 24 hours or less.

In some embodiments, the microbial cell is fed with stevioside and expresses the 1-3 UGT, and converts at least about 15%, or at least about 20%, or at least about 25%, or at

least about 30%, or at least about 50% of the stevioside to Reb A. In some embodiments, the enzyme converts at least about 75% or at least about 90% of the stevioside to RebA. In various embodiments, such conversions are allowed to take place for at least about 8 hours, or at least about 24 hours in some embodiments. For example, the conversion may be
5 allowed to take place in the culture for from 8 hours to about 72 hours. In some embodiments, the conversion may be allowed to take place for about 24 hours to about 60 hours. In some embodiments, the microbial cell converts at least about 40%, or at least about 50%, or at least about 75%, of the stevioside to RebA in about 48 hours or less or about 24 hours or less.

10 While the native UGT enzymes are generally plant enzymes (which often have optimal temperatures in the range of 20-24° C) or are derived from plant enzymes, the present disclosure in some embodiments enables production of the glycosylated product at high yield in microbial cells (e.g., bacterial cells such as *E. coli*), with enzyme productivity at temperatures above 24° C, such as from 24° C to 37° C, or from 27° C to 37° C, or from
15 30° C to 37° C. In some embodiments, culturing is conducted at from 30 to 34 °C.

In some embodiments, the process is scalable for large-scale production. For example, in some embodiments, the size of the culture is at least about 100 L, at least about 200 L, at least about 500 L, at least about 1,000 L, or at least about 10,000 L, or at least about 100,000 L, or at least about 500,000 L.

20 In various embodiments, methods further include recovering glycosylated product from the cell culture or from cell lysates. In some embodiments, the culture produces at least about 100 mg/L, or at least about 200 mg/L, or at least about 500 mg/L, or at least about 1 g/L, or at least about 2 g/L, or at least about 5 g/L, or at least about 10 g/L, or at least about 20 g/L, or at least about 30 g/L, or at least about 40 g/L, or at least about 50 g/L of the
25 glycosylated product, which in some embodiments is extracted from the culture media.

In some embodiments, the substrate is a terpenoid, such as a monoterpenoid, sesquiterpenoid, or triterpenoid. In some embodiments, the terpenoid is a triterpenoid, which is optionally mogrol or a mogroside. In some embodiments, the 1-3 UGT enzyme of the present disclosure has broad substrate activity towards glycosides, aliphatic and branched
30 alcohols, substituted phenols, flavonoids and gallates. See e.g. Dewitt, G. et al., Screening

of recombinant glycosyltransferases reveals the broad acceptor specificity of stevia UGT-76G1, *J. Biotechnology* 233 (2016) 49–55. Substrates of the UGT enzyme may include terpenoid glycosides (isoprenoids), including diterpenoid glycosides such as steviol glycosides and triterpenoid glycosides such as mogrosides.

5 In some embodiments, the method comprises growing the host cell in the presence of the substrate. The substrate may be fed to the culture, or in some embodiments, the substrate is synthesized by the host cell. In some embodiments, the substrate is steviol, and the host cell expresses a plurality of UGT enzymes to produce target steviol glycosides, such as RebM.

10 In some embodiments, the glycosylated products (*e.g.*, RebM) are purified from media components. Thus, in some embodiments, the methods comprise separating growth media from *E. coli* cells, and isolating the desired glycosylation products (*e.g.*, RebM) from the growth media. In some embodiments, product such as RebM is further extracted from the cellular material.

15 In some aspects, the invention provides methods for making a product comprising a glycosylated product, such as RebM. The method comprises incorporating the target steviol glycoside (produced according to this disclosure) into a product, such as a food, beverage, oral care product, sweetener, flavoring agent, or other product. Purified steviol glycosides, prepared in accordance with the present invention, may be used in a variety of products
20 including, but not limited to, foods, beverages, texturants (*e.g.*, starches, fibers, gums, fats and fat mimetics, and emulsifiers), pharmaceutical compositions, tobacco products, nutraceutical compositions, oral hygiene compositions, and cosmetic compositions. Non-limiting examples of flavors for which RebM can be used in combination include lime, lemon, orange, fruit, banana, grape, pear, pineapple, mango, bitter almond, cola, cinnamon,
25 sugar, cotton candy and vanilla flavors. Non-limiting examples of other food ingredients include flavors, acidulants, and amino acids, coloring agents, bulking agents, modified starches, gums, texturizers, preservatives, antioxidants, emulsifiers, stabilizers, thickeners and gelling agents.

 In some aspects, the invention provides methods for making a sweetener product
30 comprising a plurality of high-intensity sweeteners, said plurality including two or more of

a steviol glycoside, a mogroside, sucralose, aspartame, neotame, advantame, acesulfame potassium, saccharin, cyclamate, neohesperidin dihydrochalcone, gnetifolin E, and/or piceatannol 4'-O- β -D-glucopyranoside. The method may further comprise incorporating the sweetener product into a food, beverage, oral care product, sweetener, flavoring agent, or
5 other product, including those described above.

Target steviol glycoside(s), such as RebM, and sweetener compositions comprising the same, can be used in combination with various physiologically active substances or functional ingredients. Functional ingredients generally are classified into categories such as carotenoids, dietary fiber, fatty acids, saponins, antioxidants, nutraceuticals, flavonoids,
10 isothiocyanates, phenols, plant sterols and stanols (phytosterols and phytostanols); polyols; prebiotics, probiotics; phytoestrogens; soy protein; sulfides/thiols; amino acids; proteins; vitamins; and minerals. Functional ingredients also may be classified based on their health benefits, such as cardiovascular, cholesterol-reducing, and anti-inflammatory.

Further, target steviol glycoside(s), such as RebM, and sweetener compositions
15 obtained according to this invention, may be applied as a high intensity sweetener to produce zero calorie, reduced calorie or diabetic beverages and food products with improved taste characteristics. It may also be used in drinks, foodstuffs, pharmaceuticals, and other products in which sugar cannot be used. In addition, RebM and sweetener compositions can be used as a sweetener not only for drinks, foodstuffs, and other products dedicated for human
20 consumption, but also in animal feed and fodder with improved characteristics.

Examples of products in which target steviol glycoside(s) and sweetener compositions may be used include, but are not limited to, alcoholic beverages such as vodka, wine, beer, liquor, and sake, natural juices, carbonated soft drinks, diet drinks, zero calorie drinks, reduced calorie drinks and foods, yogurt drinks, instant juices, instant coffee,
25 powdered types of instant beverages, canned products, syrups, fermented soybean paste, soy sauce, vinegar, dressings, mayonnaise, ketchups, curry, soup, instant bouillon, powdered soy sauce, powdered vinegar, types of biscuits, rice biscuit, crackers, bread, chocolates, caramel, candy, chewing gum, jelly, pudding, preserved fruits and vegetables, fresh cream, jam, marmalade, flower paste, powdered milk, ice cream, sorbet, vegetables and fruits packed in
30 bottles, canned and boiled beans, meat and foods boiled in sweetened sauce, agricultural

vegetable food products, seafood, ham, sausage, fish ham, fish sausage, fish paste, deep fried fish products, dried seafood products, frozen food products, preserved seaweed, preserved meat, tobacco, medicinal products, and many others.

During the manufacturing of products such as foodstuffs, drinks, pharmaceuticals, cosmetics, table top products, and chewing gum, the conventional methods such as mixing, kneading, dissolution, pickling, permeation, percolation, sprinkling, atomizing, infusing and other methods may be used.

Aspects and embodiments of the invention are now described with reference to the following examples.

10

EXAMPLES

Aspects and embodiments of the invention are now described with reference to the following examples.

Example 1: Screening of Mutants for MbUGT1-3_1 (SEQ ID NO: 5)

15

Plasmids comprising polynucleotides encoding UGT MbUGT1-3_1 (SEQ ID NO: 5) and 95 selected mutants were transformed into *E. coli* cells (Δ ushA, Δ galETKM, Δ pgi; overexpressed pgm, galU). The resulting strains were seeded into a rich seed media and incubated overnight in 96-well plates at 250 rpm at 37 °C to make the seed cultures.

20

Production cultures were seeded with the seed cultures by adding 40 μ L of the seed to 360 μ L of fresh production media containing 0.5 mM Stevioside and 0.5 mM Rebaudioside D. The production culture was subsequently grown for 48 hours in 96-well plates at 250 rpm at 37 °C. Products were quantified using a LC-MS QQQ.

The 95 mutants screened include the following (amino acid position of these mutants is with respect to MbUGT1-3_1 (SEQ ID NO: 5):

25

i) Substitution:

F11L, K13R, T16E, V18L, E19A, G48T, S62A, D73P, L89W, V93L, Y94E, W99F, E100C, N106R, E115K, Y119T, Q122E, K130W, V133A, V133S, M136K, S153L, G164R, R165N, R166G, I169L, F200L, F204H, F204P, K206A, K208D, K208N, F219D,

F219S, L221P, R229A, I230F, L233I, G241A, R243M, P245S, I246L, R257D, E260A, L261K, L262Q, L264S, D269E, E271P, S273A, R294P, L296I, S301N, F304S, H309F, V310A, T327S, A333V, F336L, V341I, Y348T, Q352A, Q352D, Q352E, A354S, A354T, K355Y, L358I, M361Q, I362V, S375T, E383F, V387L, I388E, I388S, R389Q, L400F, L404F, A406S, D413E, V418C, P426A, S428K, S428G, V441I, D445E, D455N, Q457G, Q457K/S458Q, or Q457K.

ii) Substitution and deletion:

Q457K and delete S458 (Δ S458).

iii) Deletion:

Δ G159; Δ G159 Δ G161; or Δ G159 Δ S160 Δ G161.

iv) Insertion:

Insertion of S between position 158 and 159 or insertion of K between 456 and 457.

All of the 95 mutants of MbUGT1-3_1 were screened for their ability to produce RebA and RebI as well as RebM from Stevioside (substrate). **Table 5** shows the fold improvement of selected mutants of MbUGT1-3_1 to produce RebA and RebI (through 1-3 glucosylation at C-13-glucose) as well as RebM (through 1-3 glucosylation at C-19-glucose). In **Table 5**, column 2 generally corresponds to glycosylation at the C13-glucose of the substrate, while column 3 generally corresponds to glycosylation at the C19-glucose of the substrate. As shown, C-19 glycosylation is enhanced more than C-13 glycosylation. The mutant constructed with the mutations in Table 5 is referred to herein as MbUGT1-3_2 (SEQ ID NO: 6).

Table 5: MbUGT1-3_1 (lead mutations)

Mutation	(RebA+RebI)/(RebA+RebI+Stevioside)	RebM/(RebD+RebM+RebE)
Deletion G159_S160_G161 (Δ G159 Δ S160 Δ G161)	1.13	1.25
L262Q	1.12	1.19
R294P	1.22	1.21
D413E	1.15	1.17

Example 2: Bioconversion by 1-3' Glycosylating Enzymes

Plasmids comprising polynucleotides encoding three UGTs, SrUGT76G1-L200A (SEQ ID NO: 1), MbUGT1-3_0 (SEQ ID NO: 4), MbUGT1-3_1 (SEQ ID NO: 5), and MbUGT1-3_2 (SEQ ID NO: 6) were individually transformed into *E. coli* cells (Δ ushA, Δ galETKM, Δ pgi; overexpressed pgm, galU). The resulting strains were seeded into culture media containing 1 mM stevioside or 1 mM RebD. After growth, steviol glycosides were recovered from the culture media. Strains were grown overnight in 96-well plates at 250 rpm at 37 °C. The cells were then transferred to a fresh production culture to 10% of the total volume. Each of stevioside (0.5 mM) and Rebaudioside D (0.5 mM) were included in the production culture. The production culture was then grown for 48 hours in 96-well plates at 250 rpm at 37 °C. Products were quantified using a LC-MS QQQ.

Figure 4 shows the percent conversion of stevioside to RebA and the percent conversion of RebD to RebM. The percent conversion for both reactions was highest for MbUGT1-3_1 and MbUGT1-3_2, which have the amino acid sequences of SEQ ID NO: 5 and SEQ ID NO: 6, respectively. **Figure 5** shows the fold improvement of MbUGT1-3_1 and MbUGT1-3_2 compared to SrUGT76G1-L200A.

Example 3: Screening of Mutants for MbUGT1-3_2 (SEQ ID NO: 6)

Plasmids comprising polynucleotides encoding UGT MbUGT1-3_2 (SEQ ID NO: 6) and 96 selected mutants of MbUGT1-3_2 were transformed into *E. coli* cells (Δ ushA, Δ galETKM, Δ pgi; Δ araA, overexpressed pgm, galU, UGT1-2 enzyme). The resulting strains were seeded into a rich seed media and incubated overnight in 96-well plates at 250 rpm at 37 °C to make the seed cultures.

Production cultures were then seeded with the seed cultures by adding 40 μ L of the seed to 360 μ L of fresh production media containing 1 g/L stevioside/RebA leaf extract. The production culture was then grown for 48 hours in 96-well plates at 250 rpm at 37 °C. Products were quantified using a UPLC-DAD.

The mutants screened include the following (amino acid position is with respect to MbUGT1-3_1 (SEQ ID NO: 5):

i) Substitution:

5 T16G, V18L, E19A, D23E, R31K, C64S, I70V, L76N, P79M,
W99F, D114E, R125L, V133A, S150D, T202M, F204E, Y212F,
Y212H, R218L, D227S, E228S, I230F, I230Y, L233I,
G237S/P238A, P238S, L239E, L239G, A240S, A240V, M242A,
M242I, I246Y, I247F, A252I, D253E, L261K, L264E, A265D,
E271P, S273A, C274G, C274L, Y282W, N292K, S302G, L303M,
F306W, L312M, Q314L, L318W, P323L, E331A, K340R, S346V,
Y348F/S349D/N350T/W351L/Q352E/I353N,
10 Y348G/S349E/N350F/W351G/Q352E/I353K,
Y348T/S349N/N350E/W351P/Q352E/I353E,
W351F/Q352E/A354G, W351P, Q352D/A354G, Q352E, A354S,
I362L, A367N, E383S, E385A, H403Y, L404F, F419K, S428K,
L431I, D445E, D445I, A450L, or Q457G.

ii) Substitution and deletion:

D227T and Δ 228 to 234

iii) Deletion:

20 Δ G158 to G161; Δ G159 to G161; Δ S160 to Δ G161; Δ G161; Δ 228;
 Δ 228 to 229; Δ 228 to 230; Δ 228-231; Δ 228 to 232; Δ 228 to 233;
 Δ 228 to 234; Δ 228 to 235; Δ 228 to 236; Δ 228 to 237; Δ Y320 to
P323; Δ D325 to K326; or Δ K326.

iv) Insertion:

Insert LEA between F25 and L26;

iv) Replace:

Swap Y348-I353 with INPQG

Table 6 shows the ability of selected mutants of MbUGT1-3_2 (SEQ ID NO: 6) to produce RebM. Column 2 of Table 6 shows the fold improvement in the percentage of RebM in the reaction product.

30 Table 6: MbUGT1-3_2 lead mutations

Mutation	Fold Improvement %RebM
Delete E225-T232 (Δ E225 to T232)	11.1

S72Q	1.25
A305C	3.51
Y345F	3.97
L428I	2.48

The deletion of amino acids E225 to T232 produced a surprising 11 fold improvement in the production of RebM. Based on homology modeling, amino acids E225 to T232 appear to form a loop near the bound substrate. Deletion of amino acids E225-T232 may cause a shift in the substrate specificity of the UGT enzyme in favor of the RebD to RebM reaction. The sequence having a deletion of E225-T232 loop and S72Q, A305C, Y345F and L428I mutations with respect to MbUGT1-3_2 (SEQ ID NO: 6) is referred to as MbUGT1-3_3 (SEQ ID NO: 9).

Several deletions in the E225 to T232 region were tested, and these also showed enhancements in RebM production. Table 7 shows various beneficial deletions of the E225-T232 region (numbered according to SEQ ID NO:6)

Table 7: MbUGT1-3_2 Deletions

Mutation	Fold Improvement %RebM
Delete E225-T232	11.1
Delete E225-L230	3.2
Delete E225-H233	3.2
Delete E225-P231	3.1
Delete E225-N229	1.7
Delete E225-S228	1.6
Delete E225	1.6
Delete E225-I227	1.5
Delete E225-G234	1.5

SEQUENCES

SEQ ID NO:1
UGT76G1 [Stevia rebaudiana]

5 (SEQ ID NO:1)

MENKTETTVRRRRRIILFPVPFQGHINPILQLANVLYSKGFSITIFHTNFNKPKTSNYPHFTFRFILDNDPQD
ERISNLPTHGFLAGMRIPINEHGADELRRLELLMLASEEDEEVSLITDALWYFAQSVADSLNLRRLVMT
SSLFNFHAHVSLPQFDELGYLDPDDKTRLEEQASGFPMKVKDIKSAYSNWQILKEILGKMIKQTKASSGVIW
10 NSFKELEESELETVIREIPAPSFLIPLPKHLTASSSSLLDHDRTVFQWLDQQPPSSVLYVSFGSTSEVDEKDF
LEIARGLVDSKQSFLWVVRPGFVKGSTWVEPLPDGFLGERGRIVKWVPQQEVLAHGAIGAFWTHSGWNSTLES
VCEGVPMIFSDFGLDQPLNARYMSDVLKGVYLENGWERGEIANAIRRMVDEEGEYIRQNARVLKQKADVSL
MKGGSSYESLESLSVSYISSL

15 SEQ ID NO:2
MbUGT1-3
Reference: US 2017/0332673

MANWQILKEILGKMIKQTKASSGVIWNSFKELEESELETVIREIPAPSFLIPLPKHLTASSSSLLDHDRTVFQ
20 WLDQQPPSSVLYVSFGSTSEVDEKDFLEIARGLVDSKQSFLWVVRPGFVKGSTWVEPLPDGFLGERGRIVKWV
PQQEVLAHGAIGAFWTHSGWNSTLESVCEGVPMIFSDFGLDQPLNARYMSDVLKGVYLENGWERGEIANAIR
RVMVDEEGEYIRQNARVLKQKADVSLMKGGSSYESLESLSVSYISSLNKTETTVRRRRRIILFPVPFQGHINP
ILQLANVLYSKGFSITIFHTNFNKPKTSNYPHFTFRFILDNDPQDERISNLPTHGFLAGMRIPINEHGADEL
RRELELLMLASEEDEEVSLITDALWYFAQSVADSLNLRRLVMTSSSLFNFAHVSLPQFDELGYLDPDDKTR
25 LEEQASGFPMKVKDIKSAYS

SEQ ID NO:3
UGT76G1_L200A
Reference: US 2017/0332673

30 MAENKTETTVRRRRRIILFPVPFQGHINPILQLANVLYSKGFSITIFHTNFNKPKTSNYPHFTFRFILDNDPQ
DERISNLPTHGFLAGMRIPINEHGADELRRLELLMLASEEDEEVSLITDALWYFAQSVADSLNLRRLVMT
TSSSLFNFAHVSLPQFDELGYLDPDDKTRLEEQASGFPMKVKDIKSAYSNWQIAKEILGKMIKQTKASSGVI
WNSFKELEESELETVIREIPAPSFLIPLPKHLTASSSSLLDHDRTVFQWLDQQPPSSVLYVSFGSTSEVDEKD
35 FLEIARGLVDSKQSFLWVVRPGFVKGSTWVEPLPDGFLGERGRIVKWVPQQEVLAHGAIGAFWTHSGWNSTLE
SVCEGVPMIFSDFGLDQPLNARYMSDVLKGVYLENGWERGEIANAIRRMVDEEGEYIRQNARVLKQKADVS
LMKGGSSYESLESLSVSYISSL

40 SEQ ID NO:4
MbUGT1-3_0

MAKQSFLWVVRPGFVKGSTWVEPLPDGFLGERGRIVKWVPQQEVLAHGAIGAFWTHSGWNSTLESVCEGVPMI
FSDFGLDQPLNARYMSDVLKGVYLENGWERGEIANAIRRMVDEEGEYIRQNARVLKQKADVSLMKGGSSYE
SLESLSVSYISSLNKTETTVRRRRRIILFPVPFQGHINPILQLANVLYSKGFSITIFHTNFNKPKTSNYPHFT
45 FRFILDNDPQDERISNLPTHGFLAGMRIPINEHGADELRRLELLMLASEEDEEVSLITDALWYFAQSVAD
SLNLRRLVMTSSSLFNFAHVSLPQFDELGYLDPDDKTRLEEQASGFPMKVKDIKSAYSNWQIAKEILGKMI
KQTKASSGVIWNSFKELEESELETVIREIPAPSFLIPLPKHLTASSSSLLDHDRTVFQWLDQQPPSSVLYVSF
GSTSEVDEKDFLEIARGLVDS

50 SEQ ID NO: 5
MbUGT1-3_1

MAFLWVVRPGFVKGSTWVEPLPDGFLGERGRIVKWVPQQEVLAHGAIGAFWTHGGWNSTLESVCEGVPMIFSD
55 FGLDQPLNARYMSDVLKGVYLENGWERGEIANAIRRLMVDEEGEYIRQNARVLKQKADVSLMKGGSSYESLE
SLVSYISSLGSGSGSGRRRIILFPVPFQGHINPILQLANVLYSKGFSITIFHTNFNKPKTSNYPHFTFRF

5

SEQ ID NO: 6
MbUGT1-3_2

10

20

GSGGSG

25

GSGGSGGSG

30

35

CLAIMS

1. A uridine diphosphate-dependent glycosyltransferase (UGT) enzyme comprising an amino acid sequence that is at least 85% identical to the amino acid sequence of SEQ ID NO: 5 or SEQ ID NO: 6, wherein:
 - the enzyme has an insertion with respect to SEQ ID NO: 1 of a flexible and hydrophilic sequence of 6 to 12 Glycine and Serine residues after the position corresponding to position 155 of SEQ ID NO: 5; and
 - the enzyme comprises:
 - a glycine (G) at the position corresponding to position 54 of SEQ ID NO: 5;
 - a leucine (L) at the position corresponding to position 111 of SEQ ID NO: 5; and
 - a methionine (M) at the position corresponding to position 183 of SEQ ID NO: 5.
2. The enzyme of claim 1, wherein the amino acid sequence is at least 95% identical to SEQ ID NO: 5 or SEQ ID NO: 6.
3. The enzyme of claim 1, wherein the insertion is GSGGSG (SEQ ID NO: 7) or GSGGSGGSG (SEQ ID NO: 8).
4. The enzyme of claim 1, wherein the enzyme comprises a deletion of at least three amino acids corresponding to amino acids E225 to T232 with respect to the amino acid sequence of SEQ ID NO: 6.
5. The enzyme of claim 4, wherein the enzyme comprises a deletion of the amino acids corresponding to amino acids E225 to T232 of SEQ ID NO: 6.
6. The enzyme of claim 1, wherein the enzyme comprises an amino acid substitution at one or more positions corresponding to position 72, position 305, position 345, and position 428 of SEQ ID NO: 6.
7. The enzyme of claim 6, wherein the enzyme comprises one or more amino acid substitutions selected from: a glutamine (Q) at the position corresponding to position 72 of SEQ ID NO: 6; a cysteine (C) at the position corresponding to position 305 of SEQ ID NO: 6; a

phenylalanine (F) at the position corresponding to position 345 of SEQ ID NO: 6; and an isoleucine (I) at the position corresponding to position 428 of SEQ ID NO: 6.

8. The enzyme of claim 1, comprising an amino acid sequence of SEQ ID NO: 9.

9. A polynucleotide encoding the enzyme of any one of claim 1.

5 10. A recombinant microorganism comprising the polynucleotide of claim 9.

11. A method for transferring a monosaccharide group to a substrate comprising contacting a NDP-sugar and the substrate with the recombinant microorganism of claim 10.

12. A method for transferring a glycosyl group to a substrate comprising growing the recombinant microorganism of claim 10 in the presence of the substrate.