

TITLE

RECOMBINANT BACTERIA HAVING IMPROVED SUCROSE UTILIZATION

FIELD OF THE INVENTION

The invention relates to the fields of microbiology and molecular biology. More specifically, recombinant bacteria having an improved ability to utilize sucrose are provided.

BACKGROUND OF THE INVENTION

Many commercially useful microorganisms use glucose as their main carbohydrate source. However, a disadvantage of the use of glucose by microorganisms developed for production of commercially desirable products is the high cost of glucose. The use of sucrose and mixed feedstocks containing sucrose and other sugars as carbohydrate sources for microbial production systems would be more commercially desirable because these materials are readily available at a lower cost.

A production microorganism can function more efficiently when it can utilize any sucrose present in a mixed feedstock. Therefore, when a production microorganism does not have the ability to utilize sucrose efficiently as a major carbon source, it cannot operate as efficiently. For example, bacterial cells typically show preferential sugar use, with glucose being the most preferred. In artificial media containing mixtures of sugars, glucose is typically metabolized to its entirety ahead of other sugars. Moreover, many bacteria lack the ability to utilize sucrose. For example, less than 50% of *Escherichia coli* strains have the ability to utilize sucrose. Thus, when a production microorganism cannot utilize sucrose as a carbohydrate source, it is desirable to engineer the microorganism so that it can utilize sucrose.

Recombinant bacteria that have been engineered to utilize sucrose by incorporation of sucrose utilization genes have been reported. For example, Livshits et al. (U.S. Patent No. 6,960,455) describe the

production of amino acids using *Escherichia coli* strains containing genes encoding a metabolic pathway for sucrose utilization. Additionally, Olson et al. (*Appl. Microbiol. Biotechnol.* 74:1031-1040, 2007) describe *Escherichia coli* strains carrying genes responsible for sucrose
5 degradation, which produce L-tyrosine or L-phenylalanine using sucrose as a carbon source. Additionally, Eliot et al. (U.S. Patent Application Publication No. 2011/0136190) describe recombinant bacteria that are capable of producing glycerol and glycerol-derived products from sucrose. However, there is still a need for bacterial strains that have an improved
10 ability to utilize sucrose. Additionally, there is a need for bacterial strains having an improved capability of producing glycerol and glycerol-derived products using sucrose as carbon source.

SUMMARY OF THE INVENTION

15 One embodiment provides a recombinant bacterium comprising in its genome:

- (a) one or more nucleotide sequences encoding a polypeptide or a polypeptide complex having sucrose transporter activity;
- (b) a nucleotide sequence encoding a polypeptide having
20 fructokinase activity; and
- (c) a nucleotide sequence encoding a polypeptide having sucrose hydrolase activity;

wherein:

- (i) (a), (b) and (c) are each operably linked to the same or a
25 different promoter;
- (ii) (a), (b), and (c) are integrated into the genome between the *yihP* gene or its homolog and the *yihO* gene or its homolog; and
- (iii) said bacterium metabolizes sucrose at a greater rate than a bacterium comprising (a), (b), and (c) integrated at a different
30 location in the genome.

Another embodiment provides a process for making glycerol, 1,3-propanediol and/or 3-hydroxypropionic acid from sucrose comprising:

- a) culturing the recombinant bacterium disclosed herein in the presence of sucrose; and
- b) recovering the glycerol, 1,3-propanediol and/or 3-hydroxypropionic acid produced.

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BRIEF DESCRIPTION OF THE FIGURE AND SEQUENCE DESCRIPTIONS

The invention can be more fully understood from the following detailed description, figure, and the accompanying sequence descriptions,
10 which form a part of this application.

Figure 1 is a diagram showing chromosomal locations where the sucrose gene cluster was integrated. The chromosomal genes are shown in striped arrows. The sucrose genes are shown in open arrows. The direction of arrows indicates the direction of gene expression.

15 The following sequences conform with 37 C.F.R. 1.821 1.825 ("Requirements for Patent Applications Containing Nucleotide Sequences and/or Amino Acid Sequence Disclosures - the Sequence Rules") and consistent with World Intellectual Property Organization (WIPO) Standard ST.25 (2009) and the sequence listing requirements of the EPO and PCT
20 (Rules 5.2 and 49.5(a bis), and Section 208 and Annex C of the Administrative Instructions). The symbols and format used for nucleotide and amino acid sequence data comply with the rules set forth in 37 C.F.R. §1.822.

Table A
Summary of Gene and Protein SEQ ID Numbers

Gene	Coding Sequence SEQ ID NO:	Encoded Protein SEQ ID NO:
<i>GPD1</i> from <i>Saccharomyces cerevisiae</i>	1	2
<i>GPD2</i> from <i>Saccharomyces cerevisiae</i>	3	4
<i>GPP1</i> from <i>Saccharomyces cerevisiae</i>	5	6
<i>GPP2</i> from <i>Saccharomyces cerevisiae</i>	7	8
<i>dhaB1</i> from <i>Klebsiella pneumoniae</i>	9	10
<i>dhaB2</i> from <i>Klebsiella pneumoniae</i>	11	12
<i>dhaB3</i> from <i>Klebsiella pneumoniae</i>	13	14
<i>aldB</i> from <i>Escherichia coli</i>	15	16
<i>aldA</i> from <i>Escherichia coli</i>	17	18
<i>aldH</i> from <i>Escherichia coli</i>	19	20
<i>galP</i> from <i>Escherichia coli</i>	21	22
<i>cscB</i> from <i>Escherichia coli</i> EC3132	23	24
<i>cscB</i> from <i>Escherichia coli</i> ATCC®13281	25	26
<i>cscB</i> from <i>Bifidobacterium lactis</i>	27	28
<i>susT1</i> from <i>Streptococcus pneumoniae</i> strain TIGR4	29	30
<i>susT2</i> from <i>Streptococcus pneumoniae</i> strain TIGR4	31	32
<i>susX</i> from <i>Streptococcus pneumoniae</i> strain TIGR4	33	34
<i>malE</i> from <i>Streptococcus mutans</i>	35	36
<i>malF</i> from <i>Streptococcus mutans</i>	37	38
<i>malG</i> from <i>Streptococcus mutans</i>	39	40
<i>malK</i> from <i>Streptococcus mutans</i>	41	42
<i>scrK</i> from <i>Agrobacterium tumefaciens</i>	43	44
<i>scrK</i> from <i>Streptococcus mutans</i>	45	46
<i>cscK</i> from <i>Escherichia coli</i>	47	48
<i>cscK</i> from <i>Enterococcus faecalis</i>	49	50
<i>HXK1</i> from <i>Saccharomyces cerevisiae</i>	51	52
<i>HXK2</i> from <i>Saccharomyces cerevisiae</i>	53	54
<i>cscA</i> from <i>Escherichia coli</i> EC3132	55	56
<i>cscA</i> from <i>Escherichia coli</i> ATCC®13281	57	58
<i>bfrA</i> from <i>Bifidobacterium lactis</i> strain DSM 10140 ^T	59	60
<i>SUC2</i> from <i>Saccharomyces cerevisiae</i>	61	62
<i>scrB</i> from <i>Corynebacterium glutamicum</i>	63	64
sucrose phosphorylase gene from <i>Leuconostoc mesenteroides</i> DSM 20193	65	66
<i>sucP</i> <i>Bifidobacterium adolescentis</i> DSM 20083	67	68
<i>dhaT</i> from <i>Klebsiella pneumoniae</i>	69	70
<i>yihP</i> from <i>Escherichia coli</i>	77	78
<i>yihQ</i> from <i>Escherichia coli</i>	79	80

<i>yihO</i> from <i>Escherichia coli</i>	81	82
<i>ompL</i> from <i>Escherichia coli</i>	83	84
<i>cscB</i> variant 408STOP	93	94
<i>cscB</i> variant L61P	95	96
<i>cscB</i> variant F159L	97	98
<i>cscB</i> variant G162C	99	100
<i>cscB</i> variant P169H	101	102
<i>cscB</i> variant L61W	103	104
<i>cscB</i> variant L61H	105	106
<i>cscB</i> variant L61F	107	108
<i>cscB</i> variant 403STOP	109	110
<i>scrK</i> From <i>Escherichia coli</i>	111	112
<i>scrK</i> from <i>Klebsiella pneumoniae</i>	113	114

SEQ ID NO:71 is the nucleotide sequence of the coding region of the *dhaX* gene from *Klebsiella pneumoniae*.

SEQ ID NO:72 is the nucleotide sequence of plasmid pSYCO101.

5 SEQ ID NO:73 is the nucleotide sequence of plasmid pSYCO103.

SEQ ID NO:74 is the nucleotide sequence of plasmid pSYCO106.

SEQ ID NO:75 is the nucleotide sequence of plasmid pSYCO109.

SEQ ID NO:76 is the nucleotide sequence of plasmid pSYCO400/AGRO.

10 SEQ ID NO:85 is the nucleotide sequence encoding putative permease YP_690957 of *Shigella flexneri*.

SEQ ID NO:86 is the nucleotide sequence encoding GPH family transport protein NP_462898 of *Salmonella enterica*.

15 SEQ ID NO:87 is the nucleotide sequence encoding hypothetical protein ENCANT_09547 of *Enterobacter cancerogenus* ATCC® 35316.

SEQ ID NO:88 is the nucleotide sequence encoding hypothetical protein CKO_03136 of *Citrobacter koseri* ATCC® BAA-895.

SEQ ID NO:89 is the nucleotide sequence encoding putative permease YP_690958 of *Shigella flexneri*.

20 SEQ ID NO:90 is the nucleotide sequence encoding GPH family transport protein NP_462897 of *Salmonella enterica*.

SEQ ID NO:91 is the nucleotide sequence encoding hypothetical protein ENCANT_09546 of *Enterobacter cancerogenus* ATCC® 35316.

SEQ ID NO:92 is the nucleotide sequence encoding hypothetical protein CKO_03137 of *Citrobacter koseri* ATCC® BAA-895.

SEQ ID NOs:115-122 are the nucleotide sequences of primers used in the Examples herein.

5 SEQ ID NO:123 is the nucleotide sequence of the *cscAKB* gene cluster *Escherichia coli* ATCC®13281.

SEQ ID NO:124 is nucleotide sequence of plasmid pBHR-cscBKA.

DETAILED DESCRIPTION

10 The disclosure of each reference set forth herein is hereby incorporated by reference in its entirety.

As used herein and in the appended claims, the singular forms "a", "an", and "the" include plural reference unless the context clearly dictates otherwise. Thus, for example, reference to "a cell" includes one or more
15 cells and equivalents thereof known to those skilled in the art, and so forth.

In the context of this disclosure, a number of terms and abbreviations are used. The following definitions are provided.

"Open reading frame" is abbreviated as "ORF".

"Polymerase chain reaction" is abbreviated as "PCR".

20 "American Type Culture Collection" is abbreviated as "ATCC".

The term "recombinant glycerol-producing bacterium" refers to a bacterium that has been genetically engineered to be capable of producing glycerol and/or glycerol-derived products such as 1,3-propanediol and 3-hydroxypropionic acid.

25 The term "polypeptide or polypeptide complex having sucrose transporter activity" refers to a polypeptide or polypeptide complex that is capable of mediating the transport of sucrose into microbial cells. Examples of polypeptides having sucrose transporter activity include, but are not limited to, sucrose:H⁺ symporters. Examples of polypeptide
30 complexes having sucrose transporter activity include, but are not limited to, ABC-type transporters. Sucrose:H⁺ symporters are encoded by, for example, the *cscB* gene found in *E. coli* strains such as EC3132 (Jahreis

et al., *J. Bacteriol.* 184:5307-5316, 2002) or ATCC®13281 (Olson et al., *Appl. Microbiol. Biotechnol.* 74:1031-1040, 2007), and *Bifidobacterium lactis* strain DSM 10140^T (Ehrmann et al., *Curr. Microbiol.* 46(6):391-397, 2003). An example of an ABC-type transporter with activity towards
5 sucrose is the complex encoded by the genes *susT1*, *susT2* and *susX* in *Streptococcus pneumoniae* strain TIGR4 (Iyer and Camilli, *Molecular Microbiology* 66:1-13, 2007). Polypeptides or polypeptide complexes having sucrose transporter activity may also have activity towards other saccharides. An example is the maltose transporter complex of
10 *Streptococcus mutans* encoded by *malEFGK* (Kilic et al., *FEMS Microbiol Lett.* 266:218, 2007).

The term “variant sucrose transporter polypeptide” refers to a polypeptide having sucrose transporter activity that has an amino acid sequence that differs from the sequence of a wild-type sucrose transporter
15 polypeptide. The difference in the sequence of the variant sucrose transporter polypeptide may be any one of the following: (i) an amino acid substitution in at least one position of the wild-type sequence, (ii) the sequence of the variant sucrose transporter polypeptide may be shortened from that of the wild-type sequence, or (iii) the sequence of the variant
20 sucrose transporter polypeptide may be shortened from that of the wild-type sequence and contain an amino acid substitution in at least one position of the wild-type sequence.

The term “polypeptide having fructokinase activity” refers to a polypeptide that has the ability to catalyze the conversion of D-fructose
25 + ATP to fructose-phosphate + ADP. Typical of fructokinase is EC 2.7.1.4. Enzymes that have some ability to phosphorylate fructose, whether or not this activity is their predominant activity, may be referred to as a fructokinase. Abbreviations used for genes encoding fructokinases and proteins having fructokinase activity include, for
30 example, “*Frk*”, “*scrK*”, “*cscK*”, “*FK*”, and “*KHK*”. Fructokinase is encoded by the *scrK* gene in *Agrobacterium tumefaciens* and *Streptococcus mutans*; and by the *cscK* gene in certain *Escherichia coli*

strains.

The term “polypeptide having sucrose hydrolase activity” refers to a polypeptide that has the ability to catalyze the hydrolysis of sucrose to produce glucose and fructose. Such polypeptides are often referred to as “invertases” or “ β -fructofuranosidases”. Typical of these enzymes is EC 3.2.1.26. Examples of genes encoding polypeptides having sucrose hydrolase activity are the *cscA* gene found in *E. coli* strains EC3132 (Jahreis et al. *supra*) or ATCC®13281 (Olson et al., *supra*), the *bfrA* gene from *Bifidobacterium lactis* strain DSM 10140^T, and the *SUC2* gene from *Saccharomyces cerevisiae* (Carlson and Botstein, *Cell* 28:145, 1982). A polypeptide having sucrose hydrolase activity may also have sucrose phosphate hydrolase activity. An example of such a peptide is encoded by *scrB* in *Corynebacterium glutamicum* (Engels et al., *FEMS Microbiol Lett.* 289:80-89, 2008). A polypeptide having sucrose hydrolase activity may also have sucrose phosphorylase activity. Typical of such an enzyme is EC 2.4.1.7. Examples of genes encoding sucrose phosphorylases having sucrose hydrolase activity are found in *Leuconostoc mesenteroides* DSM 20193 (Goedl et al., *Journal of Biotechnology* 129:77-86, 2007) and *Bifidobacterium adolescentis* DSM 20083 (van den Broek et al., *Appl. Microbiol. Biotechnol.* 65:219-227, 2004), among others.

The terms “glycerol derivative” and “glycerol-derived products” are used interchangeably herein and refer to a compound that is synthesized from glycerol or in a pathway that includes glycerol. Examples of such products include 3-hydroxypropionic acid, methylglyoxal, 1,2-propanediol, and 1,3-propanediol.

The term “microbial product” refers to a product that is microbially produced, i.e., the result of a microorganism metabolizing a substance. The product may be naturally produced by the microorganism, or the microorganism may be genetically engineered to produce the product.

The terms “phosphoenolpyruvate-sugar phosphotransferase system”, “PTS system”, and “PTS” are used interchangeably herein and

refer to the phosphoenolpyruvate-dependent sugar uptake system.

The terms “phosphocarrier protein HPr” and “PtsH” refer to the phosphocarrier protein encoded by *ptsH* in *E. coli*. The terms “phosphoenolpyruvate-protein phosphotransferase” and “PtsI” refer to the phosphotransferase, EC 2.7.3.9, encoded by *ptsI* in *E. coli*. The terms “glucose-specific IIA component”, and “Crr” refer to enzymes designated as EC 2.7.1.69, encoded by *crr* in *E. coli*. PtsH, PtsI, and Crr comprise the PTS system.

The term “PTS minus” refers to a microorganism that does not contain a PTS system in its native state or a microorganism in which the PTS system has been inactivated through the inactivation of a PTS gene.

The terms “glycerol-3-phosphate dehydrogenase” and “G3PDH” refer to a polypeptide responsible for an enzyme activity that catalyzes the conversion of dihydroxyacetone phosphate (DHAP) to glycerol 3-phosphate (G3P). *In vivo* G3PDH may be NAD- or NADP-dependent. When specifically referring to a cofactor specific glycerol-3-phosphate dehydrogenase, the terms “NAD-dependent glycerol-3-phosphate dehydrogenase” and “NADP-dependent glycerol-3-phosphate dehydrogenase” will be used. As it is generally the case that NAD-dependent and NADP-dependent glycerol-3-phosphate dehydrogenases are able to use NAD and NADP interchangeably (for example by the enzyme encoded by *gpsA*), the terms NAD-dependent and NADP-dependent glycerol-3-phosphate dehydrogenase will be used interchangeably. The NAD-dependent enzyme (EC 1.1.1.8) is encoded, for example, by several genes including *GPD1*, also referred to herein as *DAR1* (coding sequence set forth in SEQ ID NO:1; encoded protein sequence set forth in SEQ ID NO:2), or *GPD2* (coding sequence set forth in SEQ ID NO:3; encoded protein sequence set forth in SEQ ID NO:4), or *GPD3*. The NADP-dependent enzyme (EC 1.1.1.94) is encoded, for example, by *gpsA*.

The terms “glycerol 3-phosphatase”, “sn-glycerol 3-phosphatase”, “D,L-glycerol phosphatase”, and “G3P phosphatase” refer to a polypeptide

having an enzymatic activity that is capable of catalyzing the conversion of glycerol 3-phosphate and water to glycerol and inorganic phosphate. G3P phosphatase is encoded, for example, by *GPP1* (coding sequence set forth in SEQ ID NO:5; encoded protein sequence set forth in SEQ ID NO:6), or *GPP2* (coding sequence set forth in SEQ ID NO:7; encoded protein sequence set forth in SEQ ID NO:8).

The term "glycerol dehydratase" or "dehydratase enzyme" refers to a polypeptide having enzyme activity that is capable of catalyzing the conversion of a glycerol molecule to the product, 3-hydroxypropionaldehyde (3-HPA).

For the purposes of the present invention the dehydratase enzymes include a glycerol dehydratase (E.C. 4.2.1.30) and a diol dehydratase (E.C. 4.2.1.28) having preferred substrates of glycerol and 1,2-propanediol, respectively. Genes for dehydratase enzymes have been identified in *Klebsiella pneumoniae*, *Citrobacter freundii*, *Clostridium pasteurianum*, *Salmonella typhimurium*, *Klebsiella oxytoca*, and *Lactobacillus reuteri*, among others. In each case, the dehydratase is composed of three subunits: the large or "α" subunit, the medium or "β" subunit, and the small or "γ" subunit. The genes are also described in, for example, Daniel *et al.* (*FEMS Microbiol. Rev.* 22, 553 (1999)) and Toraya and Mori (*J. Biol. Chem.* 274, 3372 (1999)). Genes encoding the large or "α" (alpha) subunit of glycerol dehydratase include *dhaB1* (coding sequence set forth in SEQ ID NO:9, encoded protein sequence set forth in SEQ ID NO:10), *gldA* and *dhaB*; genes encoding the medium or "β" (beta) subunit include *dhaB2* (coding sequence set forth in SEQ ID NO:11, encoded protein sequence set forth in SEQ ID NO:12), *gldB*, and *dhaC*; genes encoding the small or "γ" (gamma) subunit include *dhaB3* (coding sequence set forth in SEQ ID NO:13, encoded protein sequence set forth in SEQ ID NO:14), *gldC*, and *dhaE*. Other genes encoding the large or "α" subunit of diol dehydratase include *pduC* and *pddA*; other genes encoding the medium or "β" subunit include *pduD* and *pddB*; and other

genes encoding the small or “ γ ” subunit include *pduE* and *pddC*.

Glycerol and diol dehydratases are subject to mechanism-based suicide inactivation by glycerol and some other substrates (Daniel *et al.*, *FEMS Microbiol. Rev.* 22, 553 (1999)). The term “dehydratase reactivation factor” refers to those proteins responsible for reactivating the dehydratase activity. The terms “dehydratase reactivating activity”, “reactivating the dehydratase activity” and “regenerating the dehydratase activity” are used interchangeably and refer to the phenomenon of converting a dehydratase not capable of catalysis of a reaction to one capable of catalysis of a reaction or to the phenomenon of inhibiting the inactivation of a dehydratase or the phenomenon of extending the useful half-life of the dehydratase enzyme *in vivo*. Two proteins have been identified as being involved as the dehydratase reactivation factor (see, e.g., U.S. Patent No. 6,013,494 and references therein; Daniel *et al.*, *supra*; Toraya and Mori, *J. Biol. Chem.* 274, 3372 (1999); and Tobimatsu *et al.*, *J. Bacteriol.* 181, 4110 (1999)). Genes encoding one of the proteins include, for example, *orfZ*, *dhaB4*, *gdrA*, *pduG* and *ddrA*. Genes encoding the second of the two proteins include, for example, *orfX*, *orf2b*, *gdrB*, *pduH* and *ddrB*.

The terms “1,3-propanediol oxidoreductase”, “1,3-propanediol dehydrogenase” and “DhaT” are used interchangeably herein and refer to the polypeptide(s) having an enzymatic activity that is capable of catalyzing the interconversion of 3-HPA and 1,3-propanediol provided the gene(s) encoding such activity is found to be physically or transcriptionally linked to a dehydratase enzyme in its natural (i.e., wild type) setting; for example, the gene is found within a *dha* regulon as is the case with *dhaT* from *Klebsiella pneumoniae*. Genes encoding a 1,3-propanediol oxidoreductase include, but are not limited to, *dhaT* from *Klebsiella pneumoniae*, *Citrobacter freundii*, and *Clostridium pasteurianum*. Each of these genes encode a polypeptide belonging to the family of type III alcohol dehydrogenases, which exhibits a conserved iron-binding motif, and has a preference for the NAD⁺/NADH

linked interconversion of 3-HPA and 1,3-propanediol (Johnson and Lin, *J. Bacteriol.* 169, 2050 (1987); Daniel *et al.*, *J. Bacteriol.* 177, 2151 (1995); and Leurs *et al.*, *FEMS Microbiol. Lett.* 154, 337 (1997)).

Enzymes with similar physical properties have been isolated from
5 *Lactobacillus brevis* and *Lactobacillus buchneri* (Veiga da Dunha and Foster, *Appl. Environ. Microbiol.* 58, 2005 (1992)).

The term “*dha* regulon” refers to a set of associated polynucleotides or open reading frames encoding polypeptides having various biological activities, including but not limited to a dehydratase
10 activity, a reactivation activity, and a 1,3-propanediol oxidoreductase. Typically a *dha* regulon comprises the open reading frames *dhaR*, *orfY*, *dhaT*, *orfX*, *orfW*, *dhaB1*, *dhaB2*, *dhaB3*, and *orfZ* as described in U.S. Patent No. 7,371,558.

The terms “aldehyde dehydrogenase” and “Ald” refer to a
15 polypeptide that catalyzes the conversion of an aldehyde to a carboxylic acid. Aldehyde dehydrogenases may use a redox cofactor such as NAD, NADP, FAD, or PQQ. Typical of aldehyde dehydrogenases is EC 1.2.1.3 (NAD-dependent); EC 1.2.1.4 (NADP-dependent); EC 1.2.99.3 (PQQ-dependent); or EC 1.2.99.7 (FAD-dependent). An example of an NADP-
20 dependent aldehyde dehydrogenase is AldB (SEQ ID NO:16), encoded by the *E. coli* gene *aldB* (coding sequence set forth in SEQ ID NO:15). Examples of NAD-dependent aldehyde dehydrogenases include AldA (SEQ ID NO:18), encoded by the *E. coli* gene *aldA* (coding sequence set forth in SEQ ID NO:17); and AldH (SEQ ID NO:20), encoded by the *E. coli*
25 gene *aldH* (coding sequence set forth in SEQ ID NO:19).

The terms “glucokinase” and “Glc” are used interchangeably herein and refer to a protein that catalyzes the conversion of D-glucose + ATP to glucose 6-phosphate + ADP. Typical of glucokinase is EC 2.7.1.2. Glucokinase is encoded by *glk* in *E. coli*.

30 The terms “phosphoenolpyruvate carboxylase” and “Ppc” are used interchangeably herein and refer to a protein that catalyzes the conversion of phosphoenolpyruvate + H₂O + CO₂ to phosphate +

oxaloacetic acid. Typical of phosphoenolpyruvate carboxylase is EC 4.1.1.31. Phosphoenolpyruvate carboxylase is encoded by *ppc* in *E. coli*.

5 The terms “glyceraldehyde-3-phosphate dehydrogenase” and “GapA” are used interchangeably herein and refer to a protein having an enzymatic activity capable of catalyzing the conversion of glyceraldehyde 3-phosphate + phosphate + NAD⁺ to 3-phospho-D-glyceroyl-phosphate + NADH + H⁺. Typical of glyceraldehyde-3-phosphate dehydrogenase is EC 1.2.1.12. Glyceraldehyde-3-phosphate
10 dehydrogenase is encoded by *gapA* in *E. coli*.

The terms “aerobic respiration control protein” and “ArcA” are used interchangeably herein and refer to a global regulatory protein. The aerobic respiration control protein is encoded by *arcA* in *E. coli*.

15 The terms “methylglyoxal synthase” and “MgsA” are used interchangeably herein and refer to a protein having an enzymatic activity capable of catalyzing the conversion of dihydroxyacetone phosphate to methylglyoxal + phosphate. Typical of methylglyoxal synthase is EC 4.2.3.3. Methylglyoxal synthase is encoded by *mgsA* in *E. coli*.

20 The terms “phosphogluconate dehydratase” and “Edd” are used interchangeably herein and refer to a protein having an enzymatic activity capable of catalyzing the conversion of 6-phospho-gluconate to 2-keto-3-deoxy-6-phospho-gluconate + H₂O. Typical of phosphogluconate dehydratase is EC 4.2.1.12. Phosphogluconate dehydratase is encoded by *edd* in *E. coli*.

25 The term “YciK” refers to a putative enzyme encoded by *yciK* which is translationally coupled to *btuR*, the gene encoding Cob(I)alamin adenosyltransferase in *E. coli*.

The term “cob(I)alamin adenosyltransferase” refers to an enzyme capable of transferring a deoxyadenosyl moiety from ATP to the reduced
30 corrinoid. Typical of cob(I)alamin adenosyltransferase is EC 2.5.1.17. Cob(I)alamin adenosyltransferase is encoded by the gene “*btuR*” in *E. coli*, “*cobA*” in *Salmonella typhimurium*, and “*cobO*” in *Pseudomonas*

denitrificans.

The terms “galactose-proton symporter” and “GalP” are used interchangeably herein and refer to a protein having an enzymatic activity capable of transporting a sugar and a proton from the periplasm to the cytoplasm. D-glucose is a preferred substrate for GalP. Galactose-proton symporter is encoded by *galP* in *Escherichia coli* (coding sequence set forth in SEQ ID NO:21, encoded protein sequence set forth in SEQ ID NO:22).

The term “non-specific catalytic activity” refers to the polypeptide(s) having an enzymatic activity capable of catalyzing the interconversion of 3-HPA and 1,3-propanediol and specifically excludes 1,3-propanediol oxidoreductase(s). Typically these enzymes are alcohol dehydrogenases. Such enzymes may utilize cofactors other than NAD⁺/NADH, including but not limited to flavins such as FAD or FMN. A gene for a non-specific alcohol dehydrogenase (*yqhD*) is found, for example, to be endogenously encoded and functionally expressed within *E. coli* K-12 strains.

The terms “1.6 long GI promoter”, “1.20 short/long GI Promoter”, and “1.5 long GI promoter” refer to polynucleotides or fragments containing a promoter from the *Streptomyces lividans* glucose isomerase gene as described in U.S. Patent No. 7,132,527. These promoter fragments include a mutation which decreases their activities as compared to the wild type *Streptomyces lividans* glucose isomerase gene promoter.

The terms “function” and “enzyme function” are used interchangeably herein and refer to the catalytic activity of an enzyme in altering the rate at which a specific chemical reaction occurs without itself being consumed by the reaction. It is understood that such an activity may apply to a reaction in equilibrium where the production of either product or substrate may be accomplished under suitable conditions.

The terms “polypeptide” and “protein” are used interchangeably herein.

The terms "carbon substrate" and "carbon source" are used interchangeably herein and refer to a carbon source capable of being metabolized by the recombinant bacteria disclosed herein and, particularly, carbon sources comprising sucrose. The carbon source may
5 further comprise monosaccharides, other disaccharides, oligosaccharides; or polysaccharides.

The terms "host cell" and "host bacterium" are used interchangeably herein and refer to a bacterium capable of receiving foreign or heterologous genes and capable of expressing those genes to
10 produce an active gene product.

The term "production microorganism" as used herein refers to a microorganism, including, but not limited to, those that are recombinant, used to make a specific product such as 1,3-propanediol, glycerol, 3-hydroxypropionic acid, polyunsaturated fatty acids, and the like.

15 As used herein, "nucleic acid" means a polynucleotide and includes a single or double-stranded polymer of deoxyribonucleotide or ribonucleotide bases. Nucleic acids may also include fragments and modified nucleotides. Thus, the terms "polynucleotide", "nucleic acid sequence", "nucleotide sequence" or "nucleic acid fragment" are used
20 interchangeably herein and refer to a polymer of RNA or DNA that is single- or double-stranded, optionally containing synthetic, non-natural or altered nucleotide bases. Nucleotides (usually found in their 5'-monophosphate form) are referred to by their single letter designation as follows: "A" for adenylate or deoxyadenylate (for RNA or DNA,
25 respectively), "C" for cytidylate or deoxycytidylate, "G" for guanylate or deoxyguanylate, "U" for uridylate, "T" for deoxythymidylate, "R" for purines (A or G), "Y" for pyrimidines (C or T), "K" for G or T, "H" for A or C or T, "I" for inosine, and "N" for any nucleotide.

A polynucleotide may be a polymer of RNA or DNA that is single- or
30 double-stranded, that optionally contains synthetic, non-natural or altered nucleotide bases. A polynucleotide in the form of a polymer of DNA may be comprised of one or more segments of cDNA, genomic DNA, synthetic

DNA, or mixtures thereof.

“Gene” refers to a nucleic acid fragment that expresses a specific protein, and which may refer to the coding region alone or may include regulatory sequences preceding (5' non-coding sequences) and following (3' non-coding sequences) the coding sequence. “Native gene” refers to a gene as found in nature with its own regulatory sequences. “Chimeric gene” refers to any gene that is not a native gene, comprising regulatory and coding sequences that are not found together in nature. Accordingly, a chimeric gene may comprise regulatory sequences and coding sequences that are derived from different sources, or regulatory sequences and coding sequences derived from the same source, but arranged in a manner different than that found in nature. “Endogenous gene” refers to a native gene in its natural location in the genome of an organism. A “foreign” gene refers to a gene that is introduced into the host organism by gene transfer. Foreign genes can comprise genes inserted into a non-native organism, genes introduced into a new location within the native host, or chimeric genes.

The term “native nucleotide sequence” refers to a nucleotide sequence that is normally found in the host microorganism.

The term “non-native nucleotide sequence” refers to a nucleotide sequence that is not normally found in the host microorganism.

The term “native polypeptide” refers to a polypeptide that is normally found in the host microorganism.

The term “non-native polypeptide” refers to a polypeptide that is not normally found in the host microorganism.

The terms “encoding” and “coding” are used interchangeably herein and refer to the process by which a gene, through the mechanisms of transcription and translation, produces an amino acid sequence.

The term “coding sequence” refers to a nucleotide sequence that codes for a specific amino acid sequence.

“Suitable regulatory sequences” refer to nucleotide sequences

located upstream (5' non-coding sequences), within, or downstream (3' non-coding sequences) of a coding sequence, and which influence the transcription, RNA processing or stability, or translation of the associated coding sequence. Regulatory sequences may include promoters, enhancers, silencers, 5' untranslated leader sequence (e.g., between the transcription start site and the translation initiation codon), introns, polyadenylation recognition sequences, RNA processing sites, effector binding sites and stem-loop structures.

The term "expression cassette" refers to a fragment of DNA comprising the coding sequence of a selected gene and regulatory sequences preceding (5' non-coding sequences) and following (3' non-coding sequences) the coding sequence that are required for expression of the selected gene product. Thus, an expression cassette is typically composed of: 1) a promoter sequence; 2) a coding sequence (i.e., ORF) and, 3) a 3' untranslated region (e.g., a terminator) that, in eukaryotes, usually contains a polyadenylation site. The expression cassette(s) is usually included within a vector, to facilitate cloning and transformation. Different organisms, including bacteria, yeast, and fungi, can be transformed with different expression cassettes as long as the correct regulatory sequences are used for each host.

"Transformation" refers to the transfer of a nucleic acid molecule into a host organism, resulting in genetically stable inheritance. The nucleic acid molecule may be a plasmid that replicates autonomously, for example, or it may integrate into the genome of the host organism. Host organisms transformed with the nucleic acid fragments are referred to as "recombinant" or "transformed" organisms or "transformants". "Stable transformation" refers to the transfer of a nucleic acid fragment into a genome of a host organism, including both nuclear and organellar genomes, resulting in genetically stable inheritance. In contrast, "transient transformation" refers to the transfer of a nucleic acid fragment into the nucleus, or DNA-containing organelle, of a host organism resulting in gene expression without integration or stable inheritance.

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

The terms “subfragment that is functionally equivalent” and “functionally equivalent subfragment” are used interchangeably herein. These terms refer to a portion or subsequence of an isolated nucleic acid fragment in which the ability to alter gene expression or produce a certain phenotype is retained whether or not the fragment or subfragment encodes an active enzyme. Chimeric genes can be designed for use in suppression by linking a nucleic acid fragment or subfragment thereof, whether or not it encodes an active enzyme, in the sense or antisense orientation relative to a promoter sequence.

The term “conserved domain” or “motif” means a set of amino acids conserved at specific positions along an aligned sequence of evolutionarily related proteins. While amino acids at other positions can vary between homologous proteins, amino acids that are highly conserved at specific positions indicate amino acids that are essential in the structure, the stability, or the activity of a protein.

The terms “substantially similar” and “corresponds substantially” are used interchangeably herein. They refer to nucleic acid fragments wherein changes in one or more nucleotide bases do not affect the ability of the nucleic acid fragment to mediate gene expression or produce a certain phenotype. These terms also refer to modifications of the nucleic acid fragments of the instant invention such as deletion or insertion of one or more nucleotides that do not substantially alter the functional properties of the resulting nucleic acid fragment relative to the initial, unmodified fragment. It is therefore understood, as those skilled in the art will

appreciate, that the invention encompasses more than the specific exemplary sequences. Moreover, the skilled artisan recognizes that substantially similar nucleic acid sequences encompassed by this invention are also defined by their ability to hybridize (under moderately stringent conditions, e.g., 0.5X SSC (standard sodium citrate), 0.1% SDS (sodium dodecyl sulfate), 60 °C) with the sequences exemplified herein, or to any portion of the nucleotide sequences disclosed herein and which are functionally equivalent to any of the nucleic acid sequences disclosed herein. Stringency conditions can be adjusted to screen for moderately similar fragments, such as homologous sequences from distantly related organisms, to highly similar fragments, such as genes that duplicate functional enzymes from closely related organisms. Post-hybridization washes determine stringency conditions.

The term "selectively hybridizes" includes reference to hybridization, under stringent hybridization conditions, of a nucleic acid sequence to a specified nucleic acid target sequence to a detectably greater degree (e.g., at least 2-fold over background) than its hybridization to non-target nucleic acid sequences and to the substantial exclusion of non-target nucleic acids. Selectively hybridizing sequences are two nucleotide sequences wherein the complement of one of the nucleotide sequences typically has about at least 80% sequence identity, or 90% sequence identity, up to and including 100% sequence identity (i.e., fully complementary) to the other nucleotide sequence.

The term "stringent conditions" or "stringent hybridization conditions" includes reference to conditions under which a probe will selectively hybridize to its target sequence. Probes are typically single stranded nucleic acid sequences which are complementary to the nucleic acid sequences to be detected. Probes are "hybridizable" to the nucleic acid sequence to be detected. Generally, a probe is less than about 1000 nucleotides in length, optionally less than 500 nucleotides in length.

Hybridization methods are well defined. Typically the probe and sample are mixed under conditions which will permit nucleic acid

hybridization. This involves contacting the probe and sample in the presence of an inorganic or organic salt under the proper concentration and temperature conditions. Optionally a chaotropic agent may be added. Nucleic acid hybridization is adaptable to a variety of assay formats. One
5 of the most suitable is the sandwich assay format. A primary component of a sandwich-type assay is a solid support. The solid support has adsorbed to it or covalently coupled to it an immobilized nucleic acid probe that is unlabeled and complementary to one portion of the sequence.

Stringent conditions are sequence-dependent and will be different
10 in different circumstances. By controlling the stringency of the hybridization and/or washing conditions, target sequences can be identified which are 100% complementary to the probe (homologous probing). Alternatively, stringency conditions can be adjusted to allow some mismatching in sequences so that lower degrees of similarity are
15 detected (heterologous probing).

Typically, stringent conditions will be those in which the salt concentration is less than about 1.5 M Na ion, typically about 0.01 to 1.0 M Na ion concentration (or other salts) at pH 7.0 to 8.3 and the temperature is at least about 30 °C for short probes (e.g., 10 to 50 nucleotides) and at
20 least about 60 °C for long probes (e.g., greater than 50 nucleotides). Stringent conditions may also be achieved with the addition of destabilizing agents such as formamide. Exemplary low stringency conditions include hybridization with a buffer solution of 30 to 35% formamide, 1 M NaCl, 1% SDS (sodium dodecyl sulfate) at 37 °C, and a
25 wash in 1X to 2X SSC (20X SSC = 3.0 M NaCl/0.3 M trisodium citrate) at 50 to 55 °C. Exemplary moderate stringency conditions include hybridization in 40 to 45% formamide, 1 M NaCl, 1% SDS at 37 °C, and a wash in 0.5X to 1X SSC at 55 to 60 °C. Exemplary high stringency conditions include hybridization in 50% formamide, 1 M NaCl, 1% SDS at
30 37 °C, and a wash in 0.1X SSC at 60 to 65 °C.

Specificity is typically the function of post-hybridization washes, the critical factors being the ionic strength and temperature of the final wash

solution. For DNA-DNA hybrids, the thermal melting point (T_m) can be approximated from the equation of Meinkoth et al., *Anal. Biochem.*

138:267-284 (1984): $T_m = 81.5\text{ }^{\circ}\text{C} + 16.6 (\log M) + 0.41 (\%GC) - 0.61 (\%$

5 form) - 500/L; where M is the molarity of monovalent cations, %GC is the percentage of guanosine and cytosine nucleotides in the DNA, % form is the percentage of formamide in the hybridization solution, and L is the length of the hybrid in base pairs. The T_m is the temperature (under defined ionic strength and pH) at which 50% of a complementary target sequence hybridizes to a perfectly matched probe. T_m is reduced by
10 about 1 $^{\circ}\text{C}$ for each 1% of mismatching; thus, T_m , hybridization and/or wash conditions can be adjusted to hybridize to sequences of the desired identity. For example, if sequences with $\geq 90\%$ identity are sought, the T_m can be decreased 10 $^{\circ}\text{C}$. Generally, stringent conditions are selected to be about 5 $^{\circ}\text{C}$ lower than T_m for the specific sequence and its complement
15 at a defined ionic strength and pH. However, severely stringent conditions can utilize a hybridization and/or wash at 1, 2, 3, or 4 $^{\circ}\text{C}$ lower than the T_m ; moderately stringent conditions can utilize a hybridization and/or wash at 6, 7, 8, 9, or 10 $^{\circ}\text{C}$ lower than the T_m ; low stringency conditions can utilize a hybridization and/or wash at 11, 12, 13, 14, 15, or 20 $^{\circ}\text{C}$ lower than the
20 T_m . Using the equation, hybridization and wash compositions, and desired T_m , those of ordinary skill will understand that variations in the stringency of hybridization and/or wash solutions are inherently described. If the desired degree of mismatching results in a T_m of less than 45 $^{\circ}\text{C}$ (aqueous solution) or 32 $^{\circ}\text{C}$ (formamide solution) it is preferred to increase the SSC
25 concentration so that a higher temperature can be used. An extensive guide to the hybridization of nucleic acids is found in Tijssen, *Laboratory Techniques in Biochemistry and Molecular Biology--Hybridization with Nucleic Acid Probes*, Part I, Chapter 2 "Overview of principles of hybridization and the strategy of nucleic acid probe assays", Elsevier, New
30 York (1993); and *Current Protocols in Molecular Biology*, Chapter 2, Ausubel et al., Eds., Greene Publishing and Wiley-Interscience, New York (1995). Hybridization and/or wash conditions can be applied for at least

10, 30, 60, 90, 120, or 240 minutes.

“Sequence identity” or “identity” in the context of nucleic acid or polypeptide sequences refers to the nucleic acid bases or amino acid residues in two sequences that are the same when aligned for maximum
5 correspondence over a specified comparison window.

Thus, “percentage of sequence identity” refers to the value determined by comparing two optimally aligned sequences over a comparison window, wherein the portion of the polynucleotide or polypeptide sequence in the comparison window may comprise additions
10 or deletions (i.e., gaps) as compared to the reference sequence (which does not comprise additions or deletions) for optimal alignment of the two sequences. The percentage is calculated by determining the number of positions at which the identical nucleic acid base or amino acid residue occurs in both sequences to yield the number of matched positions,
15 dividing the number of matched positions by the total number of positions in the window of comparison and multiplying the results by 100 to yield the percentage of sequence identity. Useful examples of percent sequence identities include, but are not limited to, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, or 95%, or any integer percentage from 50% to 100%.
20 These identities can be determined using any of the programs described herein.

Sequence alignments and percent identity or similarity calculations may be determined using a variety of comparison methods designed to detect homologous sequences including, but not limited to, the MegAlign™
25 program of the LASERGENE bioinformatics computing suite (DNASTAR Inc., Madison, WI). Within the context of this application it will be understood that where sequence analysis software is used for analysis, that the results of the analysis will be based on the “default values” of the program referenced, unless otherwise specified. As used herein “default
30 values” will mean any set of values or parameters that originally load with the software when first initialized.

The “Clustal V method of alignment” corresponds to the alignment

method labeled Clustal V (described by Higgins and Sharp, *CABIOS*. 5:151-153 (1989); Higgins, D.G. et al., *Comput. Appl. Biosci.* 8:189-191 (1992)) and found in the MegAlign™ program of the LASERGENE bioinformatics computing suite (DNASTAR Inc., Madison, WI). For multiple alignments, the default values correspond to GAP PENALTY=10 and GAP LENGTH PENALTY=10. Default parameters for pairwise alignments and calculation of percent identity of protein sequences using the Clustal V method are KTUPLE=1, GAP PENALTY=3, WINDOW=5 and DIAGONALS SAVED=5. For nucleic acids these parameters are KTUPLE=2, GAP PENALTY=5, WINDOW=4 and DIAGONALS SAVED=4. After alignment of the sequences using the Clustal V program, it is possible to obtain a “percent identity” by viewing the “sequence distances” table in the same program.

The “Clustal W method of alignment” corresponds to the alignment method labeled Clustal W (described by Higgins and Sharp, *supra*; Higgins, D.G. et al., *supra*) and found in the MegAlign™ v6.1 program of the LASERGENE bioinformatics computing suite (DNASTAR Inc., Madison, WI). Default parameters for multiple alignment correspond to GAP PENALTY=10, GAP LENGTH PENALTY=0.2, Delay Divergen Seqs(%)=30, DNA Transition Weight=0.5, Protein Weight Matrix=Gonnet Series, DNA Weight Matrix=IUB. After alignment of the sequences using the Clustal W program, it is possible to obtain a “percent identity” by viewing the “sequence distances” table in the same program.

“BLASTN method of alignment” is an algorithm provided by the National Center for Biotechnology Information (NCBI) to compare nucleotide sequences using default parameters.

It is well understood by one skilled in the art that many levels of sequence identity are useful in identifying polypeptides, from other species, wherein such polypeptides have the same or similar function or activity. Useful examples of percent identities include, but are not limited to, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 85%, 90%, or 95%, or any integer percentage from 50% to 100%. Indeed, any integer amino acid

identity from 50% to 100% may be useful in describing the present invention, such as 51%, 52%, 53%, 54%, 55%, 56%, 57%, 58%, 59%, 60%, 61%, 62%, 63%, 64%, 65%, 66%, 67%, 68%, 69%, 70%, 71%, 72%, 73%, 74%, 75%, 76%, 77%, 78%, 79%, 80%, 81%, 82%, 83%, 84%, 85%,
5 86%, 87%, 88%, 89%, 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98% or 99%. Also, of interest is any full-length or partial complement of this isolated nucleotide fragment.

Thus, the invention encompasses more than the specific exemplary nucleotide sequences disclosed herein. For example, alterations in the
10 gene sequence which reflect the degeneracy of the genetic code are contemplated. Also, it is well known in the art that alterations in a gene which result in the production of a chemically equivalent amino acid at a given site, but do not affect the functional properties of the encoded protein are common. Substitutions are defined for the discussion herein
15 as exchanges within one of the following five groups:

1. Small aliphatic, nonpolar or slightly polar residues: Ala, Ser, Thr (Pro, Gly);
2. Polar, negatively charged residues and their amides: Asp, Asn, Glu, Gln;
- 20 3. Polar, positively charged residues: His, Arg, Lys;
4. Large aliphatic, nonpolar residues: Met, Leu, Ile, Val (Cys);
and
5. Large aromatic residues: Phe, Tyr, Trp.

Thus, a codon for the amino acid alanine, a hydrophobic amino acid, may
25 be substituted by a codon encoding another less hydrophobic residue (such as glycine) or a more hydrophobic residue (such as valine, leucine, or isoleucine). Similarly, changes which result in substitution of one negatively charged residue for another (such as aspartic acid for glutamic acid) or one positively charged residue for another (such as lysine for
30 arginine) can also be expected to produce a functionally equivalent product. In many cases, nucleotide changes which result in alteration of the N-terminal and C-terminal portions of the protein molecule would also

not be expected to alter the activity of the protein.

Each of the proposed modifications is well within the routine skill in the art, as is determination of retention of biological activity of the encoded products. Moreover, the skilled artisan recognizes that substantially
5 similar sequences encompassed by this invention are also defined by their ability to hybridize under stringent conditions, as defined above.

Preferred substantially similar nucleic acid fragments of the instant invention are those nucleic acid fragments whose nucleotide sequences are at least 70% identical to the nucleotide sequence of the nucleic acid
10 fragments reported herein. More preferred nucleic acid fragments are at least 90% identical to the nucleotide sequence of the nucleic acid fragments reported herein. Most preferred are nucleic acid fragments that are at least 95% identical to the nucleotide sequence of the nucleic acid fragments reported herein.

15 A "substantial portion" of an amino acid or nucleotide sequence is that portion comprising enough of the amino acid sequence of a polypeptide or the nucleotide sequence of a gene to putatively identify that polypeptide or gene, either by manual evaluation of the sequence by one skilled in the art, or by computer-automated sequence comparison and
20 identification using algorithms such as BLAST (Basic Local Alignment Search Tool; Altschul, S. F., et al., *J. Mol. Biol.*, 215:403-410 (1993)). In general, a sequence of ten or more contiguous amino acids or thirty or more nucleotides is necessary in order to putatively identify a polypeptide or nucleic acid sequence as homologous to a known protein or gene.
25 Moreover, with respect to nucleotide sequences, gene-specific oligonucleotide probes comprising 20-30 contiguous nucleotides may be used in sequence-dependent methods of gene identification (e.g., Southern hybridization) and isolation (e.g., *in situ* hybridization of bacterial colonies or bacteriophage plaques). In addition, short oligonucleotides of
30 12-15 bases may be used as amplification primers in PCR in order to obtain a particular nucleic acid fragment comprising the primers. Accordingly, a "substantial portion" of a nucleotide sequence comprises

enough of the sequence to specifically identify and/or isolate a nucleic acid fragment comprising the sequence. The instant specification teaches the complete amino acid and nucleotide sequence encoding particular proteins. The skilled artisan, having the benefit of the sequences as reported herein, may now use all or a substantial portion of the disclosed sequences for purposes known to those skilled in this art.

The term “complementary” describes the relationship between two sequences of nucleotide bases that are capable of Watson-Crick base-pairing when aligned in an anti-parallel orientation. For example, with respect to DNA, adenosine is capable of base-pairing with thymine and cytosine is capable of base-pairing with guanine. Accordingly, the instant invention may make use of isolated nucleic acid molecules that are complementary to the complete sequences as reported in the accompanying Sequence Listing and the specification as well as those substantially similar nucleic acid sequences.

The term “isolated” refers to a polypeptide or nucleotide sequence that is removed from at least one component with which it is naturally associated.

“Promoter” refers to a DNA sequence capable of controlling the expression of a coding sequence or functional RNA. The promoter sequence consists of proximal and more distal upstream elements, the latter elements often referred to as enhancers. Accordingly, an “enhancer” is a DNA sequence that can stimulate promoter activity, and may be an innate element of the promoter or a heterologous element inserted to enhance the level or tissue-specificity of a promoter. Promoters may be derived in their entirety from a native gene, or be composed of different elements derived from different promoters found in nature, or even comprise synthetic DNA segments. It is understood by those skilled in the art that different promoters may direct the expression of a gene in different tissues or cell types, or at different stages of development, or in response to different environmental conditions. It is further recognized that since in most cases the exact boundaries of regulatory sequences have not been

completely defined, DNA fragments of some variation may have identical promoter activity. Promoters that cause a gene to be expressed in most cell types at most times are commonly referred to as “constitutive promoters”.

5 “3’ non-coding sequences”, “transcription terminator” and “termination sequences” are used interchangeably herein and refer to DNA sequences located downstream of a coding sequence, including polyadenylation recognition sequences and other sequences encoding regulatory signals capable of affecting mRNA processing or gene
10 expression. The polyadenylation signal is usually characterized by affecting the addition of polyadenylic acid tracts to the 3’ end of the mRNA precursor.

 The term “operably linked” refers to the association of nucleic acid sequences on a single nucleic acid fragment so that the function of one is
15 affected by the other. For example, a promoter is operably linked with a coding sequence when it is capable of affecting the expression of that coding sequence (i.e., the coding sequence is under the transcriptional control of the promoter). Coding sequences can be operably linked to regulatory sequences in a sense or antisense orientation. In another
20 example, the complementary RNA regions of the invention can be operably linked, either directly or indirectly, 5’ to the target mRNA, or 3’ to the target mRNA, or within the target mRNA, or a first complementary region is 5’ and its complement is 3’ to the target mRNA.

 Standard recombinant DNA and molecular cloning techniques used
25 herein are well known in the art and are described more fully in Sambrook, J., Fritsch, E.F. and Maniatis, T. Molecular Cloning: A Laboratory Manual; Cold Spring Harbor Laboratory: Cold Spring Harbor, NY (1989). Transformation methods are well known to those skilled in the art and are described *infra*.

30 “PCR” or “polymerase chain reaction” is a technique for the synthesis of large quantities of specific DNA segments and consists of a series of repetitive cycles (Perkin Elmer Cetus Instruments, Norwalk, CT).

Typically, the double-stranded DNA is heat denatured, the two primers complementary to the 3' boundaries of the target segment are annealed at low temperature and then extended at an intermediate temperature. One set of these three consecutive steps is referred to as a "cycle".

5 A "plasmid" or "vector" is an extra chromosomal element often carrying genes that are not part of the central metabolism of the cell, and usually in the form of circular double-stranded DNA fragments. Such elements may be autonomously replicating sequences, genome integrating sequences, phage or nucleotide sequences, linear or circular,
10 of a single- or double-stranded DNA or RNA, derived from any source, in which a number of nucleotide sequences have been joined or recombined into a unique construction which is capable of introducing an expression cassette(s) into a cell.

 The term "genetically altered" refers to the process of changing
15 hereditary material by genetic engineering, transformation and/or mutation.

 The term "recombinant" refers to an artificial combination of two otherwise separated segments of sequence, e.g., by chemical synthesis or by the manipulation of isolated segments of nucleic acids by genetic
20 engineering techniques. "Recombinant" also includes reference to a cell or vector, that has been modified by the introduction of a heterologous nucleic acid or a cell derived from a cell so modified, but does not encompass the alteration of the cell or vector by naturally occurring events (e.g., spontaneous mutation, natural transformation, natural transduction,
25 natural transposition) such as those occurring without deliberate human intervention.

 The term "variant bacterium" refers to a wild-type bacterium that has undergone a spontaneous mutation, natural transformation, natural transduction, or natural transposition; or has been modified by
30 mutagenesis.

 The terms "recombinant construct", "expression construct", "chimeric construct", "construct", and "recombinant DNA construct", are

used interchangeably herein. A recombinant construct comprises an artificial combination of nucleic acid fragments, e.g., regulatory and coding sequences that are not found together in nature. For example, a recombinant construct may comprise regulatory sequences and coding sequences that are derived from different sources, or regulatory sequences and coding sequences derived from the same source, but arranged in a manner different than that found in nature. Such a construct may be used by itself or may be used in conjunction with a vector. If a vector is used, then the choice of vector is dependent upon the method that will be used to transform host cells as is well known to those skilled in the art. For example, a plasmid vector can be used. The skilled artisan is well aware of the genetic elements that must be present on the vector in order to successfully transform, select and propagate host cells comprising any of the isolated nucleic acid fragments of the invention.

The skilled artisan will also recognize that different independent transformation events may result in different levels and patterns of expression (Jones et al., *EMBO J.* 4:2411-2418 (1985); De Almeida et al., *Mol. Gen. Genetics* 218:78-86 (1989)), and thus that multiple events may need be screened in order to obtain lines displaying the desired expression level and pattern. Such screening may be accomplished by Southern analysis of DNA, Northern analysis of mRNA expression, immunoblotting analysis of protein expression, or phenotypic analysis, among others.

The term "expression", as used herein, refers to the production of a functional end-product (e.g., an mRNA or a protein [either precursor or mature]).

The term "introduced" means providing a nucleic acid (e.g., expression construct) or protein into a cell. Introduced includes reference to the incorporation of a nucleic acid into a eukaryotic or prokaryotic cell where the nucleic acid may be incorporated into the genome of the cell, and includes reference to the transient provision of a nucleic acid or protein to the cell. Introduced includes reference to stable or transient

transformation methods, as well as sexually crossing. Thus, “introduced” in the context of inserting a nucleic acid fragment (e.g., a recombinant construct/expression construct) into a cell, means “transfection” or “transformation” or “transduction” and includes reference to the
5 incorporation of a nucleic acid fragment into a eukaryotic or prokaryotic cell where the nucleic acid fragment may be incorporated into the genome of the cell (e.g., chromosome, plasmid, plastid or mitochondrial DNA), converted into an autonomous replicon, or transiently expressed (e.g., transfected mRNA).

10 The term “homologous” refers to proteins or polypeptides of common evolutionary origin with similar catalytic function. The invention may include bacteria producing homologous proteins via recombinant technology.

Disclosed herein are recombinant bacteria comprising in their
15 genome one or more nucleotide sequences encoding a polypeptide or a polypeptide complex having sucrose transporter activity; a nucleotide sequence encoding a polypeptide having fructokinase activity; and a nucleotide sequence encoding a polypeptide having sucrose hydrolase activity. These nucleotide sequences are each operably linked to the
20 same or a different promoter. Additionally, the nucleotide sequences are integrated into the genome between the *yihP* gene or its homolog and the *yihO* gene or its homolog, as shown in Figure 1. Integration at this particular site in the genome results in a greater rate of sucrose metabolism by the recombinant bacterium compared to integration at
25 other sites in the genome, for example, at *aldH* (coding sequence set forth in SEQ ID NO:19), as shown in Examples 5 and 7-10 herein.

The *yihP* gene of *Escherichia coli* (coding sequence set forth in SEQ ID NO:77) encodes a putative inner membrane transport protein (SEQ ID NO:78) that appears to be part of a sugar utilization locus. The
30 upstream *yihQ* gene (coding sequence set forth in SEQ ID NO:79) encodes an α -glycosidase (SEQ ID NO:80). The downstream *yihO* gene (coding sequence set forth in SEQ ID NO:81) and *ompL* gene (coding

sequence set forth in SEQ ID NO:83) encode a putative inner membrane transport protein (SEQ ID NO:82) and an outer membrane porin (SEQ ID NO:84), respectively. The *aldH* gene (coding sequence set forth in SEQ ID NO:19, synonym of *puuC*) encodes a γ -glutamyl- γ -aminobutyraldehyde dehydrogenase (SEQ ID NO:20) that is part of the putrescine utilization pathway. The downstream *puuB* and *puuE* genes encode γ -glutamylputrescine oxidase and 4-aminobutyrate aminotransferase, respectively.

Homologs of the *Escherichia coli yihP* and *yihO* genes in other host bacteria may be identified using methods known in the art. For example, homologs of *yihP* and *yihO* genes can be identified using sequence analysis software, such as BLASTN, to search publically available nucleic acid sequence databases. Additionally, the isolation of homologous genes using sequence-dependent protocols is well known in the art. Examples of sequence-dependent protocols include, but are not limited to, methods of nucleic acid hybridization, and methods of DNA and RNA amplification as exemplified by various uses of nucleic acid amplification technologies (e.g. polymerase chain reaction (PCR), Mullis et al., U.S. Patent No. 4,683,202; ligase chain reaction (LCR), Tabor, S. et al., *Proc. Acad. Sci. USA* 82, 1074, 1985); or strand displacement amplification (SDA), Walker, et al., *Proc. Natl. Acad. Sci. U.S.A.*, 89: 392, (1992)). For example, the nucleotide sequence encoding the polypeptides described above may be employed as a hybridization probe for the identification of homologs.

Examples of homologs of *yihP* include, but are not limited to, putative permease YP_690957 of *Shigella flexneri* (coding sequence set forth in SEQ ID NO:85), GPH family transport protein NP_462898 of *Salmonella enterica* (coding sequence set forth in SEQ ID NO:86), hypothetical protein ENTCAN_09547 of *Enterobacter cancerogenus* ATCC® 35316 (coding sequence set forth in SEQ ID NO:87), and hypothetical protein CKO_03136 of *Citrobacter koseri* ATCC® BAA-895 (coding sequence set forth in SEQ ID NO:88). Examples of homologs of

yihO include, but are not limited to, putative permease YP_690958 of *Shigella flexneri* (coding sequence set forth in SEQ ID NO:89), GPH family transport protein NP_462897 of *Salmonella enterica* (coding sequence set forth in SEQ ID NO:90), hypothetical protein ENTCAN_09546 of

5 *Enterobacter cancerogenus* ATCC® 35316 (coding sequence set forth in SEQ ID NO:91), and hypothetical protein CKO_03137 of *Citrobacter koseri* ATCC® BAA-895 (coding sequence set forth in SEQ ID NO:92). These *yihP* and *yihO* homologs are adjacent to each other in each of the host chromosomes, as in *E. coli*.

10 Suitable host bacteria for use in the construction of the recombinant bacteria disclosed herein include, but are not limited to organisms of the genera: *Escherichia*, *Streptococcus*, *Agrobacterium*, *Bacillus*, *Corynebacterium*, *Lactobacillus*, *Clostridium*, *Gluconobacter*, *Citrobacter*, *Enterobacter*, *Klebsiella*, *Aerobacter*, *Methylobacter*, *Salmonella*,

15 *Streptomyces*, and *Pseudomonas*.

In one embodiment the host bacterium is selected from the genera: *Escherichia*, *Klebsiella*, *Citrobacter*, and *Aerobacter*.

In another embodiment, the host bacterium is *Escherichia coli*.

In some embodiments, the host bacterium is PTS minus. In these

20 embodiments, the host bacterium is PTS minus in its native state, or may be rendered PTS minus through inactivation of a PTS gene as described below.

In production microorganisms, it is sometimes desirable to unlink the transport of sugars and the use of phosphoenolpyruvate (PEP) for

25 phosphorylation of the sugars being transported.

The term “down-regulated” refers to reduction in, or abolishment of, the activity of active protein(s), as compared to the activity of the wildtype protein(s). The PTS may be inactivated (resulting in a “PTS minus” organism) by down-regulating expression of one or more of the

30 endogenous genes encoding the proteins required in this type of transport. Down-regulation typically occurs when one or more of these genes has a “disruption”, referring to an insertion, deletion, or targeted mutation within

a portion of that gene, that results in either a complete gene knockout such that the gene is deleted from the genome and no protein is translated or a protein has been translated such that it has an insertion, deletion, amino acid substitution or other targeted mutation. The location of the disruption in the protein may be, for example, within the N-terminal portion of the protein or within the C-terminal portion of the protein. The disrupted protein will have impaired activity with respect to the protein that was not disrupted, and can be non-functional. Down-regulation that results in low or lack of expression of the protein, could also result via manipulating the regulatory sequences, transcription and translation factors and/or signal transduction pathways or by use of sense, antisense or RNAi technology, etc.

Sucrose transporter polypeptides or polypeptide complexes are polypeptides or polypeptide complexes that are capable of mediating the transport of sucrose into microbial cells. Sucrose transport polypeptides and polypeptide complexes are known, as described above. Examples of polypeptides having sucrose transporter activity include, but are not limited to, CscB from *E. coli* wild-type strain EC3132 (set forth in SEQ ID NO:24), encoded by gene *cscB* (coding sequence set forth in SEQ ID NO:23); CscB from *E. coli* ATCC®13281 (set forth in SEQ ID NO:26), encoded by gene *cscB* (coding sequence set forth in SEQ ID NO:25); and CscB from *Bifidobacterium lactis* (set forth in SEQ ID NO:28), encoded by gene *cscB* (coding sequence set forth in SEQ ID NO:27). Examples of polypeptide complexes having sucrose transporter activity include, but are not limited to, the sucrose ABC-type transporter complex from *Streptococcus pneumoniae* strain TIGR4 comprising three polypeptide subunits set forth in SEQ ID NOs:30, 32, and 34, encoded by genes *susT1* (coding sequence set forth in SEQ ID NO:29), *susT2* (coding sequence set forth in SEQ ID NO:31), and *susX* (coding sequence set forth in SEQ ID NO: 33); and the maltose transporter complex of *Streptococcus mutans* comprising four polypeptide subunits set forth in SEQ ID NOs:36, 38, 40, and 42, encoded by genes *malE* (coding sequence set forth in SEQ ID NO:35),

malF (coding sequence set forth in SEQ ID NO:37), *malG* (coding sequence set forth in SEQ ID NO:39), and *malK* (coding sequence set forth in SEQ ID NO:41), respectively.

5 In one embodiment, the polypeptide having sucrose transporter activity has at least 95% sequence identity, based on the Clustal W method of alignment, to an amino acid sequence as set forth in SEQ ID NO:24, SEQ ID NO:26, or SEQ ID NO:28.

10 In another embodiment, the sucrose transporter polypeptide is a variant of the wild-type sucrose transporter polypeptide CscB from *E. coli* ATCC®13281 (set forth in SEQ ID NO:26, nucleotide coding sequence set forth in SEQ ID NO:25) that enables faster sucrose utilization in bacteria. These variant sucrose transporter polypeptides were isolated from variant *E. coli* strains that exhibited faster growth on sucrose, or were identified by saturation mutagenesis, as described in copending and commonly owned
15 U.S. Patent Application No. 13/210,488. The variant sucrose transporter polypeptides have an amino acid sequence that has at least 95% identity to an amino acid sequence as set forth in SEQ ID NO:26 based on a Clustal W method of alignment and having at least one amino acid change selected from the group consisting of:

- 20 (i) leucine to proline at position 61;
(ii) phenylalanine to leucine at position 159;
(iii) glycine to cysteine at position 162;
(iv) proline to histidine at position 169;
(v) leucine to tryptophan at position 61;
25 (vi) leucine to histidine at position 61;
(vii) leucine to phenylalanine at position 61; and
(viii) leucine to tyrosine at position 61.

In another embodiment, the variant sucrose transporter polypeptides have an amino acid sequence that has at least 95% identity
30 to an amino acid sequence as set forth in SEQ ID NO:94 (coding sequence set forth in SEQ ID NO: 93) based on a Clustal W method of

alignment and having a length of 402 to 407 amino acids from the N-terminus.

In another embodiment, the variant sucrose transporter polypeptides have an amino acid sequence that has at least 95% identity to an amino acid sequence as set forth in SEQ ID NO:94 based on a Clustal W method of alignment, having a length of 402 to 407 amino acids from the N-terminus, and having at least one of the amino acid changes listed above.

In another embodiment, the variant sucrose transporter polypeptides have an amino acid sequence selected from the group consisting of: SEQ ID NO:94, SEQ ID NO:96, SEQ ID NO:98, SEQ ID NO:100, SEQ ID NO:102, SEQ ID NO:104, SEQ ID NO:106, SEQ ID NO:108, and SEQ ID NO:110.

In another embodiment, the polypeptide complex having sucrose transporter activity comprises: a first subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:30; a second subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:32; and a third subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:34.

In another embodiment, the polypeptide complex having sucrose transporter activity comprises: a first subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:36; a second subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:38; a third subunit having at least 95% sequence identity, based on a Clustal W method of alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:40; and a fourth subunit having at least 95% sequence identity, based on a Clustal W method of

alignment, when compared to an amino acid sequence as set forth in SEQ ID NO:42.

In another embodiment, the polypeptide having sucrose transporter activity corresponds substantially to the amino acid sequence set forth in
 5 SEQ ID NO:26 or SEQ ID NO:96.

Polypeptides having fructokinase activity include fructokinases (designated EC 2.7.1.4) and various hexose kinases having fructose phosphorylating activity (EC 2.7.1.3 and EC 2.7.1.1). Fructose phosphorylating activity may be exhibited by hexokinases and
 10 ketohexokinases. Representative genes encoding polypeptides from a variety of microorganisms, which may be used to construct the recombinant bacteria disclosed herein, are listed in Table 1. One skilled in the art will know that proteins that are substantially similar to a protein which is able to phosphorylate fructose (such as encoded by the genes
 15 listed in Table 1) may also be used.

Table 1
Sequences Encoding Enzymes with Fructokinase Activity

Source	Gene Name	EC Number	Nucleotide SEQ ID NO:	Protein SEQ ID NO:
<i>Agrobacterium tumefaciens</i>	<i>scrK</i> (fructokinase)	2.7.1.4	43	44
<i>Streptococcus mutans</i>	<i>scrK</i> (fructokinase)	2.7.1.4	45	46
<i>Escherichia coli</i>	<i>scrK</i> (fructokinase)	2.7.1.4	111	112
<i>Klebsiella pneumoniae</i>	<i>scrK</i> (fructokinase)	2.7.1.4	113	114
<i>Escherichia coli</i>	<i>cscK</i> (fructokinase)	2.7.1.4	47	48
<i>Enterococcus faecalis</i>	<i>cscK</i> (fructokinase)	2.7.1.4	49	50
<i>Saccharomyces cerevisiae</i>	<i>HXK1</i> (hexokinase)	2.7.1.1	51	52
<i>Saccharomyces cerevisiae</i>	<i>HXK2</i> (hexokinase)	2.7.1.1	53	54

In one embodiment, the polypeptide having fructokinase activity has at least 95% sequence identity, based on the Clustal W method of alignment, to an amino acid sequence as set forth in SEQ ID NO:44, SEQ ID NO:46, SEQ ID NO:48, SEQ ID NO:50, SEQ ID NO:52, SEQ ID NO:54, 5 SEQ ID NO:112, or SEQ ID NO:114.

In another embodiment, the polypeptide having fructokinase activity corresponds substantially to the sequence set forth in SEQ ID NO:48

Polypeptides having sucrose hydrolase activity have the ability to catalyze the hydrolysis of sucrose to produce fructose and glucose.

10 Polypeptides having sucrose hydrolase activity are known, as described above, and include, but are not limited to CscA from *E. coli* wild-type strain EC3132 (set forth in SEQ ID NO:56), encoded by gene *cscA* (coding sequence set forth in SEQ ID NO:55), CscA from *E. coli* ATCC®13821 (set forth in SEQ ID NO:58), encoded by gene *cscA* (coding sequence set 15 forth in SEQ ID NO:57); BfrA from *Bifidobacterium lactis* strain DSM 10140^T (set forth in SEQ ID NO:60), encoded by gene *bfrA* (coding sequence set forth in SEQ ID NO:59); Suc2p from *Saccharomyces cerevisiae* (set forth in SEQ ID NO:62), encoded by gene *SUC2* (coding sequence set forth in SEQ ID NO:61); ScrB from *Corynebacterium* 20 *glutamicum* (set forth in SEQ ID NO:64), encoded by gene *scrB* (coding sequence set forth in SEQ ID NO:63); sucrose phosphorylase from *Leuconostoc mesenteroides* DSM 20193 (set forth in SEQ ID NO:66), coding sequence of encoding gene set forth in SEQ ID NO:65; and sucrose phosphorylase from *Bifidobacterium adolescentis* DSM 20083 25 (set forth in SEQ ID NO:68), encoded by gene *sucP* (coding sequence set forth in SEQ ID NO:67).

In one embodiment, the polypeptide having sucrose hydrolase activity has at least 95% sequence identity, based on the Clustal W method of alignment, to an amino acid sequence as set forth in SEQ ID 30 NO:56, SEQ ID NO:58, SEQ ID NO:60, SEQ ID NO:62, SEQ ID NO:64, SEQ ID NO:66, or SEQ ID NO:68.

In another embodiment, the polypeptide having sucrose hydrolase activity corresponds substantially to the amino acid sequence set forth in SEQ ID NO:58.

The coding sequence of genes encoding polypeptides or
5 polypeptide complexes having sucrose transporter activity, polypeptides having fructokinase activity, and polypeptides having sucrose hydrolase activity may be used to isolate nucleotide sequences encoding homologous polypeptides from the same or other microbial species. For example, homologs of the genes may be identified using methods known
10 in the art, as described above.

One of ordinary skill in the art will appreciate that genes encoding these polypeptides isolated from other sources may also be used in the recombinant bacteria disclosed herein. Additionally, variations in the nucleotide sequences encoding the polypeptides may be made without
15 affecting the amino acid sequence of the encoded polypeptide due to codon degeneracy, and that amino acid substitutions, deletions or additions that produce a substantially similar protein may be included in the encoded protein.

The nucleotide sequences encoding polypeptides or polypeptide
20 complexes having sucrose transporter activity, polypeptides having fructokinase activity, and polypeptides having sucrose hydrolase activity may be isolated using PCR (see, e.g., U.S. Patent No. 4,683,202) and primers designed to bound the desired sequence, if this sequence is known. Other methods of gene isolation are well known to one skilled in
25 the art such as by using degenerate primers or heterologous probe hybridization. The nucleotide sequences can also be chemically synthesized or purchased from vendors such as DNA2.0 Inc. (Menlo Park, CA). Additionally, the entire wild type *csc* operon may be isolated from the genomic DNA of *E. coli* strain ATCC®13281 or a variant *csc*
30 operon may be isolated from a variant bacterium and integrated into the genome of the host bacterium between the *yihP* gene or its homolog and the *yihO* gene or its homolog, as described in detail in Examples 1

and 3 herein.

The nucleotide sequences encoding the polypeptides described above are introduced into the host bacterium by integrating one or more copies of the coding sequences into the host genome between the *yihP* gene or its homolog and the *yihO* gene or its homolog using site-specific recombination systems known in the art, such as for example, as described in Examples 1-4 and 7-10 herein. The introduced coding regions in the genome may be expressed from at least one highly active promoter. An integrated coding region may either be introduced as a part of a chimeric gene having its own promoter, or it may be integrated adjacent to a highly active promoter that is endogenous to the genome or in a highly expressed operon. Suitable promoters include, but are not limited to, *CYC1*, *HIS3*, *GAL1*, *GAL10*, *ADH1*, *PGK*, *PHO5*, *GAPDH*, *ADC1*, *TRP1*, *URA3*, *LEU2*, *ENO*, and *lac*, *ara*, *tet*, *trp*, *IP_L*, *IP_R*, *T7*, *tac*, and *trc* (useful for expression in *Escherichia coli*) as well as the *amy*, *apr*, *npr* promoters and various phage promoters useful for expression in *Bacillus*. The promoter may also be the *Streptomyces lividans* glucose isomerase promoter or a variant thereof, described by Payne et al. (U.S. Patent No. 7,132,527).

In one embodiment, the recombinant bacteria disclosed herein are capable of producing glycerol. Biological processes for the preparation of glycerol using carbohydrates or sugars are known in yeasts and in some bacteria, other fungi, and algae. Both bacteria and yeasts produce glycerol by converting glucose or other carbohydrates through the fructose-1,6-bisphosphate pathway in glycolysis. In the method of producing glycerol disclosed herein, host bacteria may be used that naturally produce glycerol. In addition, bacteria may be engineered for production of glycerol and glycerol derivatives. The capacity for glycerol production from a variety of substrates may be provided through the expression of the enzyme activities glycerol-3-phosphate dehydrogenase (G3PDH) and/or glycerol-3-phosphatase as described in U.S. Patent No. 7,005,291. Genes encoding these proteins

- that may be used for expressing the enzyme activities in a host bacterium are described in U.S. Patent No. 7,005,291. Suitable examples of genes encoding polypeptides having glycerol-3-phosphate dehydrogenase activity include, but are not limited to, *GPD1* from
- 5 *Saccharomyces cerevisiae* (coding sequence set forth in SEQ ID NO:1, encoded protein sequence set forth in SEQ ID NO:2) and *GPD2* from *Saccharomyces cerevisiae* (coding sequence set forth in SEQ ID NO:3, encoded protein sequence set forth in SEQ ID NO:4). Suitable examples of genes encoding polypeptides having glycerol-3-
- 10 phosphatase activity include, but are not limited to, *GPP1* from *Saccharomyces cerevisiae* (coding sequence set forth in SEQ ID NO:5, encoded protein sequence set forth in SEQ ID NO:6) and *GPP2* from *Saccharomyces cerevisiae* (coding sequence set forth in SEQ ID NO:7, encoded protein sequence set forth in SEQ ID NO:8).
- 15 Increased production of glycerol may be attained through reducing expression of target endogenous genes. Down-regulation of endogenous genes encoding glycerol kinase and glycerol dehydrogenase activities further enhance glycerol production as described in U.S. Patent No. 7,005,291. Increased channeling of carbon to glycerol may be
- 20 accomplished by reducing the expression of the endogenous gene encoding glyceraldehyde 3-phosphate dehydrogenase, as described in U.S. Patent No. 7,371,558. Down-regulation may be accomplished by using any method known in the art, for example, the methods described above for down-regulation of genes of the PTS system.
- 25 Glycerol provides a substrate for microbial production of useful products. Examples of such products, i.e., glycerol derivatives include, but are not limited to, 3-hydroxypropionic acid, methylglyoxal, 1,2-propanediol, and 1,3-propanediol.
- In another embodiment, the recombinant bacteria disclosed herein
- 30 are capable of producing 1,3-propanediol. The glycerol derivative 1,3-propanediol is a monomer having potential utility in the production of polyester fibers and the manufacture of polyurethanes and cyclic

compounds. 1,3-Propanediol can be produced by a single microorganism by bioconversion of a carbon substrate other than glycerol or dihydroxyacetone, as described in U.S. Patent No. 5,686,276. In this bioconversion, glycerol is produced from the carbon substrate, as
5 described above. Glycerol is converted to the intermediate 3-hydroxypropionaldehyde by a dehydratase enzyme, which can be encoded by the host bacterium or can be introduced into the host by recombination. The dehydratase can be glycerol dehydratase (E.C. 4.2.1.30), diol dehydratase (E.C. 4.2.1.28) or any other enzyme able to
10 catalyze this conversion. A suitable example of genes encoding the “ α ” (alpha), “ β ” (beta), and “ γ ” (gamma) subunits of a glycerol dehydratase include, but are not limited to *dhaB1* (coding sequence set forth in SEQ ID NO:9), *dhaB2* (coding sequence set forth in SEQ ID NO:11), and *dhaB3* (coding sequence set forth in SEQ ID NO:13), respectively, from *Klebsiella*
15 *pneumoniae*. The further conversion of 3-hydroxypropionaldehyde to 1,3-propanediol can be catalyzed by 1,3-propanediol dehydrogenase (E.C. 1.1.1.202) or other alcohol dehydrogenases. A suitable example of a gene encoding a 1,3-propanediol dehydrogenase is *dhaT* from *Klebsiella pneumoniae* (coding sequence set forth in SEQ ID NO:69, encoded
20 protein sequence set forth in SEQ ID NO:70).

Bacteria can be recombinantly engineered to provide more efficient production of glycerol and the glycerol derivative 1,3-propanediol. For example, U.S. Patent No. 7,005,291 discloses transformed microorganisms and a method for production of glycerol and 1,3-
25 propanediol with advantages derived from expressing exogenous activities of one or both of glycerol-3-phosphate dehydrogenase and glycerol-3-phosphate phosphatase while disrupting one or both of endogenous activities glycerol kinase and glycerol dehydrogenase.

U.S. Patent No. 6,013,494 describes a process for the production of
30 1,3-propanediol using a single microorganism comprising exogenous glycerol-3-phosphate dehydrogenase, glycerol-3-phosphate phosphatase, dehydratase, and 1,3-propanediol oxidoreductase (e.g., *dhaT*). U.S.

Patent No. 6,136,576 discloses a method for the production of 1,3-propanediol comprising a recombinant microorganism further comprising a dehydratase and protein X (later identified as being a dehydratase reactivation factor peptide).

5 U.S. Patent No. 6,514,733 describes an improvement to the process where a significant increase in titer (grams product per liter) is obtained by virtue of a non-specific catalytic activity (distinguished from 1,3-propanediol oxidoreductase encoded by *dhaT*) to convert 3-hydroxypropionaldehyde to 1,3-propanediol. Additionally, U.S. Patent No.
10 7,132,527 discloses vectors and plasmids useful for the production of 1,3-propanediol.

Increased production of 1,3-propanediol may be achieved by further modifications to a host bacterium, including down-regulating expression of some target genes and up-regulating, expression of other target genes, as
15 described in U.S. Patent No. 7,371,558. For utilization of glucose as a carbon source in a PTS minus host, expression of glucokinase activity may be increased.

Additional genes whose increased or up-regulated expression increases 1,3-propanediol production include genes encoding:

- 20
- phosphoenolpyruvate carboxylase typically characterized as EC 4.1.1.31
 - cob(I)alamin adenosyltransferase, typically characterized as EC 2.5.1.17
 - non-specific catalytic activity that is sufficient to catalyze the
25 interconversion of 3-HPA and 1,3-propanediol, and specifically excludes 1,3-propanediol oxidoreductase(s), typically these enzymes are alcohol dehydrogenases

Genes whose reduced or down-regulated expression increases 1,3-propanediol production include genes encoding:

- 30
- aerobic respiration control protein
 - methylglyoxal synthase
 - acetate kinase

- phosphotransacetylase
- aldehyde dehydrogenase A
- aldehyde dehydrogenase B
- triosephosphate isomerase
- 5 • phosphogluconate dehydratase

In another embodiment, the recombinant bacteria disclosed herein are capable of producing 3-hydroxypropionic acid. 3-Hydroxypropionic acid has utility for specialty synthesis and can be converted to commercially important intermediates by known art in the chemical industry, e.g., acrylic acid by dehydration, malonic acid by oxidation, esters by esterification reactions with alcohols, and 1,3-propanediol by reduction. 3-Hydroxypropionic acid may be produced biologically from a fermentable carbon source by a single microorganism, as described in copending and commonly owned U.S. Patent Application No. 61/187476.

15 In one representative biosynthetic pathway, a carbon substrate is converted to 3-hydroxypropionaldehyde, as described above for the production of 1,3-propanediol. The 3-hydroxypropionaldehyde is converted to 3-hydroxypropionic acid by an aldehyde dehydrogenase. Suitable examples of aldehyde dehydrogenases include, but are not limited to, AldB (SEQ ID NO:16), encoded by the *E. coli* gene *aldB* (coding sequence set forth in SEQ ID NO:15); AldA (SEQ ID NO:18), encoded by the *E. coli* gene *aldA* (coding sequence set forth in SEQ ID NO:17); and AldH (SEQ ID NO:20), encoded by the *E. coli* gene *aldH* (coding sequence set forth in SEQ ID NO:19).

25 Many of the modifications described above to improve 1,3-propanediol production by a recombinant bacterium can also be made to improve 3-hydroxypropionic acid production. For example, the elimination of glycerol kinase prevents glycerol, formed from G3P by the action of G3P phosphatase, from being re-converted to G3P at the expense of ATP.

30 Also, the elimination of glycerol dehydrogenase (for example, *gldA*) prevents glycerol, formed from DHAP by the action of NAD-dependent glycerol-3-phosphate dehydrogenase, from being converted to

dihydroxyacetone. Mutations can be directed toward a structural gene so as to impair or improve the activity of an enzymatic activity or can be directed toward a regulatory gene, including promoter regions and ribosome binding sites, so as to modulate the expression level of an enzymatic activity.

Up-regulation or down-regulation may be achieved by a variety of methods which are known to those skilled in the art. It is well understood that up-regulation or down-regulation of a gene refers to an alteration in the level of activity present in a cell that is derived from the protein encoded by that gene relative to a control level of activity, for example, by the activity of the protein encoded by the corresponding (or non-altered) wild-type gene.

Specific genes involved in an enzyme pathway may be up-regulated to increase the activity of their encoded function(s). For example, additional copies of selected genes may be introduced into the host cell on multicopy plasmids such as pBR322. Such genes may also be integrated into the chromosome with appropriate regulatory sequences that result in increased activity of their encoded functions. The target genes may be modified so as to be under the control of non-native promoters or altered native promoters. Endogenous promoters can be altered *in vivo* by mutation, deletion, and/or substitution.

Alternatively, it may be useful to reduce or eliminate the expression of certain genes relative to a given activity level. Methods of down-regulating (disrupting) genes are known to those of skill in the art.

Down-regulation can occur by deletion, insertion, or alteration of coding regions and/or regulatory (promoter) regions. Specific down-regulations may be obtained by random mutation followed by screening or selection, or, where the gene sequence is known, by direct intervention by molecular biology methods known to those skilled in the art. A particularly useful, but not exclusive, method to effect down-regulation is to alter promoter strength.

Furthermore, down-regulation of gene expression may be used to

either prevent expression of the protein of interest or result in the expression of a protein that is non-functional. This may be accomplished for example, by 1) deleting coding regions and/or regulatory (promoter) regions, 2) inserting exogenous nucleic acid sequences into coding regions and/regulatory (promoter) regions, and 3) altering coding regions and/or regulatory (promoter) regions (for example, by making DNA base pair changes). Specific disruptions may be obtained by random mutation followed by screening or selection, or, in cases where the gene sequences in known, specific disruptions may be obtained by direct intervention using molecular biology methods known to those skilled in the art. A particularly useful method is the deletion of significant amounts of coding regions and/or regulatory (promoter) regions.

Methods of altering recombinant protein expression are known to those skilled in the art, and are discussed in part in Baneyx, *Curr. Opin. Biotechnol.* (1999) 10:411; Ross, et al., *J. Bacteriol.* (1998) 180:5375; deHaseth, et al., *J. Bacteriol.* (1998) 180:3019; Smolke and Keasling, *Biotechnol. Bioeng.* (2002) 80:762; Swartz, *Curr. Opin. Biotech.* (2001) 12:195; and Ma, et al., *J. Bacteriol.* (2002) 184:5733.

Recombinant bacteria containing the necessary changes in gene expression for metabolizing sucrose in the production of microbial products including glycerol and glycerol derivatives, as described above, may be constructed using techniques well known in the art, some of which are exemplified in the Examples herein.

The construction of the recombinant bacteria disclosed herein may be accomplished using a variety of vectors and transformation and expression cassettes suitable for the cloning, transformation and expression of coding regions that confer the ability to utilize sucrose in the production of glycerol and its derivatives in a suitable host microorganism. Suitable vectors are those which are compatible with the bacterium employed. Suitable vectors can be derived, for example, from a bacterium, a virus (such as bacteriophage T7 or a M-13 derived phage), a cosmid, a yeast or a plant. Protocols for obtaining and using such vectors

are known to those skilled in the art (Sambrook *et al.*, *supra*).

Initiation control regions, or promoters, which are useful to drive expression of coding regions for the instant invention in the desired host bacterium are numerous and familiar to those skilled in the art. Virtually
5 any promoter capable of driving expression is suitable for use herein. For example, any of the promoters listed above may be used.

Termination control regions may also be derived from various genes native to the preferred hosts. Optionally, a termination site may be unnecessary; however, it is most preferred if included.

10 For effective expression of the instant polypeptides, nucleotide sequences encoding the polypeptides are linked operably through initiation codons to selected expression control regions such that expression results in the formation of the appropriate messenger RNA.

Particularly useful in the present invention are the vectors
15 pSYCO101, pSYCO103, pSYCO106, and pSYCO109, described in U.S. Patent No. 7,371,558, and pSYCO400/AGRO, described in U.S. Patent No. 7,524,660. The essential elements of these vectors are derived from the *dha* regulon isolated from *Klebsiella pneumoniae* and from *Saccharomyces cerevisiae*. Each vector contains the open reading
20 frames *dhaB1*, *dhaB2*, *dhaB3*, *dhaX* (coding sequence set forth in SEQ ID NO:71), *orfX*, *DAR1*, and *GPP2* arranged in three separate operons. The nucleotide sequences of pSYCO101, pSYCO103, pSYCO106, pSYCO109, and pSYCO400/AGRO are set forth in SEQ ID NO:72, SEQ ID NO:73, SEQ ID NO:74, SEQ ID NO:75, and SEQ ID NO:76,
25 respectively. The differences between the vectors are illustrated in the chart below [the prefix “p-” indicates a promoter; the open reading frames contained within each “()” represent the composition of an operon]:
pSYCO101 (SEQ ID NO:72):

30 p-trc (Dar1_GPP2) in opposite orientation compared to the other 2 pathway operons,
p-1.6 long GI (*dhaB1_dhaB2_dhaB3_dhaX*), and
p-1.6 long GI (*orfY_orfX_orfW*).

pSYCO103 (SEQ ID NO:73):

p-trc (Dar1_GPP2) same orientation compared to the other 2
pathway operons,

p-1.5 long GI (dhaB1_dhaB2_dhaB3_dhaX), and

5 p-1.5 long GI (orfY_orfX_orfW).

pSYCO106 (SEQ ID NO:74):

p-trc (Dar1_GPP2) same orientation compared to the other 2
pathway operons,

p-1.6 long GI (dhaB1_dhaB2_dhaB3_dhaX), and

10 p-1.6 long GI (orfY_orfX_orfW).

pSYCO109 (SEQ ID NO:75):

p-trc (Dar1_GPP2) same orientation compared to the other 2
pathway operons,

p-1.6 long GI (dhaB1_dhaB2_dhaB3_dhaX), and

15 p-1.6 long GI (orfY_orfX).

pSYCO400/AGRO (SEQ ID NO:76):

p-trc (Dar1_GPP2) same orientation compared to the other 2
pathway operons,

p-1.6 long GI (dhaB1_dhaB2_dhaB3_dhaX), and

20 p-1.6 long GI (orfY_orfX).

p-1.20 short/long GI (scrK) opposite orientation compared to the
pathway operons.

Once suitable expression cassettes are constructed, they are used
to transform appropriate host bacteria. Introduction of the cassette

25 containing the coding regions into the host bacterium may be
accomplished by known procedures such as by transformation (e.g., using
calcium-permeabilized cells, or electroporation) or by transfection using a
recombinant phage virus (Sambrook et al., *supra*). Expression cassettes
may be maintained on a stable plasmid in a host cell. In addition,
30 expression cassettes may be integrated into the genome of the host
bacterium through homologous or random recombination using vectors
and methods well known to those skilled in the art. Site-specific

recombination systems may also be used for genomic integration of expression cassettes.

In addition to the cells exemplified, cells having single or multiple mutations specifically designed to enhance the production of microbial products including glycerol and/or its derivatives may also be used. Cells that normally divert a carbon feed stock into non-productive pathways, or that exhibit significant catabolite repression may be mutated to avoid these phenotypic deficiencies.

Methods of creating mutants are common and well known in the art. A summary of some methods is presented in U.S. Patent No. 7,371,558. Specific methods for creating mutants using radiation or chemical agents are well documented in the art. See, for example, Thomas D. Brock in *Biotechnology: A Textbook of Industrial Microbiology*, Second Edition (1989) Sinauer Associates, Inc., Sunderland, MA., or Deshpande, Mukund V., *Appl. Biochem. Biotechnol.* 36, 227 (1992).

After mutagenesis has occurred, mutants having the desired phenotype may be selected by a variety of methods. Random screening is most common where the mutagenized cells are selected for the ability to produce the desired product or intermediate. Alternatively, selective isolation of mutants can be performed by growing a mutagenized population on selective media where only resistant colonies can develop. Methods of mutant selection are highly developed and well known in the art of industrial microbiology. See, for example, Brock, *Supra*; DeMancilha *et al.*, *Food Chem.* 14, 313 (1984).

Fermentation media in the present invention comprise sucrose as a carbon substrate. Other carbon substrates such as glucose and fructose may also be present.

In addition to the carbon substrate, a suitable fermentation medium contains, for example, suitable minerals, salts, cofactors, buffers and other components, known to those skilled in the art, suitable for the growth of the cultures and promotion of the enzymatic pathway necessary for production of glycerol and its derivatives, for example 1,3-propanediol.

Particular attention is given to Co(II) salts and/or vitamin B₁₂ or precursors thereof in production of 1,3-propanediol.

Adenosyl-cobalamin (coenzyme B₁₂) is an important cofactor for dehydratase activity. Synthesis of coenzyme B₁₂ is found in prokaryotes, some of which are able to synthesize the compound *de novo*, for example, *Escherichia blattae*, *Klebsiella* species, *Citrobacter* species, and *Clostridium* species, while others can perform partial reactions. *E. coli*, for example, cannot fabricate the corrin ring structure, but is able to catalyze the conversion of cobinamide to corrinoid and can introduce the 5'-deoxyadenosyl group. Thus, it is known in the art that a coenzyme B₁₂ precursor, such as vitamin B₁₂, needs be provided in *E. coli* fermentations. Vitamin B₁₂ may be added continuously to *E. coli* fermentations at a constant rate or staged as to coincide with the generation of cell mass, or may be added in single or multiple bolus additions.

Although vitamin B₁₂ is added to the transformed *E. coli* described herein, it is contemplated that other bacteria, capable of *de novo* vitamin B₁₂ biosynthesis will also be suitable production cells and the addition of vitamin B₁₂ to these bacteria will be unnecessary.

Typically bacterial cells are grown at 25 to 40 °C in an appropriate medium containing sucrose. Examples of suitable growth media for use herein are common commercially prepared media such as Luria Bertani (LB) broth, Sabouraud Dextrose (SD) broth or Yeast medium (YM) broth. Other defined or synthetic growth media may also be used, and the appropriate medium for growth of the particular bacterium will be known by someone skilled in the art of microbiology or fermentation science. The use of agents known to modulate catabolite repression directly or indirectly, e.g., cyclic adenosine 2':3'-monophosphate, may also be incorporated into the reaction media. Similarly, the use of agents known to modulate enzymatic activities (e.g., methyl viologen) that lead to enhancement of 1,3-propanediol production may be used in conjunction

with or as an alternative to genetic manipulations with 1,3-propanediol production strains.

Suitable pH ranges for the fermentation are between pH 5.0 to pH 9.0, where pH 6.0 to pH 8.0 is typical as the initial condition.

5 Reactions may be performed under aerobic, anoxic, or anaerobic conditions depending on the requirements of the recombinant bacterium. Fed-batch fermentations may be performed with carbon feed, for example, carbon substrate, limited or excess.

10 Batch fermentation is a commonly used method. Classical batch fermentation is a closed system where the composition of the medium is set at the beginning of the fermentation and is not subject to artificial alterations during the fermentation. Thus, at the beginning of the fermentation, the medium is inoculated with the desired bacterium and fermentation is permitted to occur adding nothing to the system.

15 Typically, however, "batch" fermentation is batch with respect to the addition of carbon source, and attempts are often made at controlling factors such as pH and oxygen concentration. In batch systems, the metabolite and biomass compositions of the system change constantly up to the time the fermentation is stopped. Within batch cultures, cells
20 moderate through a static lag phase to a high growth log phase and finally to a stationary phase where growth rate is diminished or halted. If untreated, cells in the stationary phase will eventually die. Cells in log phase generally are responsible for the bulk of production of end product or intermediate.

25 A variation on the standard batch system is the Fed-Batch system. Fed-Batch fermentation processes are also suitable for use herein and comprise a typical batch system with the exception that the substrate is added in increments as the fermentation progresses. Fed-Batch systems are useful when catabolite repression is apt to inhibit the metabolism of
30 the cells and where it is desirable to have limited amounts of substrate in the media. Measurement of the actual substrate concentration in Fed-Batch systems is difficult and is therefore estimated on the basis of

the changes of measurable factors such as pH, dissolved oxygen and the partial pressure of waste gases such as CO₂. Batch and Fed-Batch fermentations are common and well known in the art and examples may be found in Brock, *supra*.

5 Continuous fermentation is an open system where a defined fermentation medium is added continuously to a bioreactor and an equal amount of conditioned medium is removed simultaneously for processing. Continuous fermentation generally maintains the cultures at a constant high density where cells are primarily in log phase growth.

10 Continuous fermentation allows for the modulation of one factor or any number of factors that affect cell growth or end product concentration. For example, one method will maintain a limiting nutrient such as the carbon source or nitrogen level at a fixed rate and allow all other parameters to moderate. In other systems, a number of factors affecting growth can be altered continuously while the cell concentration, measured by the turbidity of the medium, is kept constant. Continuous systems strive to maintain steady state growth conditions, and thus the cell loss due to medium being drawn off must be balanced against the cell growth rate in the fermentation. Methods of modulating nutrients and growth factors for continuous fermentation processes as well as techniques for maximizing the rate of product formation are well known in the art of industrial microbiology and a variety of methods are detailed by Brock, *supra*.

25 It is contemplated that the present invention may be practiced using batch, fed-batch or continuous processes and that any known mode of fermentation would be suitable. Additionally, it is contemplated that cells may be immobilized on a substrate as whole cell catalysts and subjected to fermentation conditions for production of glycerol and glycerol derivatives, such as 1,3-propanediol.

30 In one embodiment, a process for making glycerol, 1,3-propanediol, and/or 3-hydroxypropionic acid from sucrose is provided. The process comprises the steps of culturing a recombinant bacterium, as described

above, in the presence of sucrose, and optionally recovering the glycerol, 1,3-propanediol, and/or 3-hydroxypropionic acid produced. The product may be recovered using methods known in the art. For example, solids may be removed from the fermentation medium by centrifugation, filtration, decantation, or the like. Then, the product may be isolated from the fermentation medium, which has been treated to remove solids as described above, using methods such as distillation, liquid-liquid extraction, or membrane-based separation.

10

EXAMPLES

The present invention is further defined in the following Examples. It should be understood that these Examples, while indicating preferred embodiments of the invention, are given by way of illustration only. From the above discussion and these Examples, one skilled in the art can ascertain the essential characteristics of this invention, and without departing from the spirit and scope thereof, can make various changes and modifications of the invention to adapt it to various uses and conditions.

20

GENERAL METHODS

Standard recombinant DNA and molecular cloning techniques used herein are well known in the art and are described by Sambrook, J. and Russell, D., *Molecular Cloning: A Laboratory Manual*, Third Edition, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY (2001); and by Silhavy, T. J., Bennis, M. L. and Enquist, L. W., *Experiments with Gene Fusions*, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY (1984); and by Ausubel, F. M. et. al., *Short Protocols in Molecular Biology*, 5th Ed. Current Protocols, John Wiley and Sons, Inc., N.Y., 2002.

Materials and methods suitable for the maintenance and growth of microbial cultures are well known in the art. Techniques suitable for use in the following examples may be found as set out in *Manual of Methods for General Bacteriology* (Phillipp Gerhardt, R. G. E. Murray, Ralph N.

Costilow, Eugene W. Nester, Willis A. Wood, Noel R. Krieg and G. Briggs Phillips, Eds.), American Society for Microbiology: Washington, D.C. (1994)); or in *Manual of Industrial Microbiology and Biotechnology*, 3rd Edition (Richard H. Baltz, Julian E. Davies, and Arnold L. Demain Eds.),
5 ASM Press, Washington, DC, 2010. All reagents, restriction enzymes and materials described for the growth and maintenance of bacterial cells may be obtained from Aldrich Chemicals (Milwaukee, WI), BD Diagnostic Systems (Sparks, MD), Life Technologies (Rockville, MD), New England Biolabs (Beverly, MA), or Sigma Chemical Company (St. Louis, MO).

10 The meaning of abbreviations is as follows: "sec" means second(s), "min" means minute(s), "h" means hour(s), "nm" means nanometer(s), "μL" means microliter(s), "mL" means milliliter(s), "L" means liter(s), "mM" means millimolar, "M" means molar, "g" means gram(s), "μg" means microgram(s), "ng" means nanogram(s), "bp" means base pair(s),
15 "kbp" means kilobase pair(s), "rpm" means revolutions per minute, "ATCC" means American Type Culture Collection, Manassas, VA, "OD" means optical density, "g" means the gravitation constant, "HPLC" means high performance liquid chromatography.

Table 2
Primers used in the Examples

Primer	Sequence	SEQ ID NO:
aldH cscA	TAGACGTGAAACAGGAGTCATAATGAATTT TCATCATCTGGGATCCCTTGCCCGCTGTTG	115
aldH cscB	CATTTTCAGGCCTCCAGGCTTATCCAGATGG TTTTTCAGTTCTGAATTCGCAGGACCGTGATA	116
aldH_check _up	TGAGCGAATCCCGATGAGCTTACT	117
aldH_check _dn	ATACGTTTCGCGGATGATCTCACCA	118
yihP cscA	ACCATTGTGGCGATGGGTTGCTTCTACAG CCTGAACGAGAGGATCCCTTGCCCGCTGT TG	119
yihP cscB	TTACGGGCTTCTATCTCTTCCACAATGCGG ACATACATCTGAATTCGCAGGACCGTGATA	120
yihPA For	TGC TGG GCG ATC TGC TCA ACT ATT	121
yihPB Rev	TAA TCC CGC CAT AGT AAG CAG GCA	122

5

EXAMPLES 1-4

Integration of Sucrose Gene Clusters in the *E. coli* Chromosome

These Examples describe the integration of sucrose gene clusters in two locations within the genome of *E. coli*, at the *aldH* gene or between the *yihP* gene and the *yihO* gene, to enable sucrose utilization.

10 Wild type or variant *cscAKB* gene clusters from *E. coli* ATCC®13281 were introduced into PDO producing strain TTab pSYCO400/AGRO to enable PDO production from sucrose. *E. coli* strain TTab pSYCO400/AGRO, a PTS minus strain, was constructed as follows. Strain TTab was generated by deletion of the *aldB* gene from strain TT

15 aldA, described in U.S. Patent No. 7,371,558 (Example 17). Briefly, an *aldB* deletion was made by first replacing 1.5 kbp of the coding region of *aldB* in *E. coli* strain MG1655 with the FRT-CmR-FRT cassette of the pKD3 plasmid (Datsenko and Wanner, *Proc. Natl. Acad. Sci. USA* 97:6640-6645, 2000). A replacement cassette was amplified with the

20 primer pair SEQ ID NO:58 and SEQ ID NO:59 using pKD3 as the template. The primer SEQ ID NO:58 contains 80 bp of homology to the 5'-

end of *aldB* and 20 bp of homology to pKD3. Primer SEQ ID NO:59 contains 80 bp of homology to the 3' end of *aldB* and 20 bp homology to pKD3. The PCR products were gel-purified and electroporated into MG1655/pKD46 competent cells (U.S. Patent No. 7,371,558).

- 5 Recombinant strains were selected on LB plates with 12.5 mg/L of chloramphenicol. The deletion of the *aldB* gene was confirmed by PCR, using the primer pair SEQ ID NO:60 and SEQ ID NO:61. The wild-type strain gave a 1.5 kbp PCR product while the recombinant strain gave a characteristic 1.1 kbp PCR product. A P1 lysate was prepared and used
- 10 to move the mutation to the TT *aldA* strain to form the TT *aldA*Δ*aldB*::Cm strain. A chloramphenicol-resistant clone was checked by genomic PCR with the primer pair SEQ ID NO:60 and SEQ ID NO:61 to ensure that the mutation was present. The chloramphenicol resistance marker was removed using the FLP recombinase (Datsenko and Wanner, *supra*) to
- 15 create TTab. Strain TTab was then transformed with pSYCO400/AGRO (set forth in SEQ ID NO:55), described in U.S. Patent No. 7,524,660 (Example 4), to generate strain TTab pSYCO400/AGRO.

As described in the cited references, strain TTab is a derivative of *E. coli* strain FM5 (ATCC® No. 53911) containing the following

- 20 modifications:

deletion of *glpK*, *gldA*, *ptsHI*, *corr*, *edd*, *arcA*, *mgsA*, *qor*, *ackA*, *pta*, *aldA* and *aldB* genes;

upregulation of *galP*, *glk*, *btuR*, *ppc*, and *yqhD* genes; and

downregulation of *gapA* gene.

- 25 Plasmid pSYCO400/AGRO contains genes encoding a glycerol production pathway (*DAR1* and *GPP2*) and genes encoding a glycerol dehydratase and associated reactivating factor (*dhaB123*, *dhaX*, *orfX*, *orfY*), as well as a gene encoding a fructokinase (*scrK*).

The wild type or a variant sucrose gene cluster from *E. coli*

- 30 ATCC®13281 was integrated at the *aldH* gene or the *yihP* gene in TTab pSYCO400/AGRO by the Lambda Red method. Figure 1 shows the chromosomal regions where the sucrose gene cluster was integrated.

The wild type *cscAKB* gene cluster (SEQ ID NO: 123) was amplified from plasmid pBHR-cscBKA (SEQ ID NO:124), which was constructed as described in Example 1 of U.S. Patent Application Publication No.

2011/0136190 A1. The variant sucrose gene cluster containing a leucine
5 to proline substitution at codon 61 (L61P) in the *cscB* gene (SEQ ID NO:95) was amplified from an isolate of a TTab pSYCO400/AGRO strain transformed with the *cscAKB* gene cluster from *E. coli* ATCC®13281 at the *aldH* gene, which exhibited enhanced growth on sucrose.

Integration at the *aldH* gene was achieved using aldH cscA primer
10 (SEQ ID NO:115) and aldH cscB primer (SEQ ID NO:116) containing flanking homology for both regions outside of the *aldH* gene in the chromosome. Integration of the sucrose gene cluster at the *aldH* gene replaced the *aldH* gene with the sucrose gene cluster. Integration
between the *yihP* gene and the *yihO* gene was achieved using yihP cscA
15 primer (SEQ ID NO:119) and yihP cscB primer (SEQ ID NO:120) containing flanking homology for the *yihP* gene. The sucrose gene cluster was inserted at a site close to the C-terminal end of *yihP* without removing the *yihP* sequence from the chromosome. Plasmid pBHR-cscBKA,
linearized by PstI digest, was used as the PCR template for the wild type
20 cluster. Cells containing the L61P substitution in *cscB* of the sucrose gene cluster were used as the PCR template for the variant cluster. High fidelity PfuUltra ® II Fusion HS DNA polymerase (Stratagene; La Jolla, CA) was used in the PCR reaction. PCR was performed using the following cycling conditions: 95 °C for 2 min; 35 cycles of 95 °C for 30 sec, 60 °C for 30 sec,
25 and 72 °C for 4 min; and then 72 °C for 7 min. The resulting PCR product was stored at 4 °C. The PCR product was purified using a QIAquick PCR Purification kit (Qiagen, Valencia, CA). The PCR product was
electroporated into the TTab pSYCO400/AGRO strain containing the
pKD46 plasmid (Red recombinase plasmid, GenBank Acc. No.
30 AY048746), encoding lambda recombinases, following the lambda red recombination procedure (Datsenko, K.A. and Wanner, B.L., 2000, *Proc. Natl. Acad. Sci. USA* 97: 6640-6645). The transformation mixture was

plated on MOPS minimal plates containing 10 g/L sucrose and 100 µg/mL spectinomycin. The MOPS minimal plates contained 1XMOPS buffer (Technova, Hollister, CA), 1.32 mM KH₂PO₄ (Technova), 50 µg/L uracil and 1.5 g/L Bacto agar. Plates were incubated at 37 °C for 2-3 days.

- 5 Colonies grown on minimal sucrose plates were picked and purified by streaking on LB spectinomycin plates. Integration of the sucrose gene cluster at the *aldH* gene was confirmed by PCR using primer aldH_check_up (SEQ ID NO: 117) and primer aldH_check_dn (SEQ ID NO:118). Integration of the sucrose gene cluster between the *yihP* gene and the *yihO* gene was confirmed by PCR using primer yihPA For (SEQ ID NO: 121) and primer yihPB Rev (SEQ ID NO:122). The integrated sucrose gene cluster was confirmed by sequencing to ensure that the isolated strains contained no unexpected mutation. The strains constructed are summarized in Table 3.

15

Table 3
Recombinant *E. coli* Strains Containing an Integrated
Sucrose Gene Cluster

Example	Strain	cscAKB	Location in Genome
1	PDO3083	wild type	between <i>yihP</i> and <i>yihO</i>
2, Comparative	PDO3084	wild type	<i>aldH</i>
3	PDO3096	L61P variant	between <i>yihP</i> and <i>yihO</i>
4, Comparative	PDO3097	L61P variant	<i>aldH</i>

20

EXAMPLE 5
Growth Rates of Recombinant *E. coli* Strains

This Example demonstrates the enhanced growth on sucrose of the *E. coli* strains having a sucrose gene cluster integrated between the *yihP*

gene and the *yihO* gene compared to *E. coli* strains having the sucrose gene cluster integrated at the *aldH* gene.

The maximum growth rates of the integrated *E. coli* strains in sucrose containing minimal medium was determined using the Bioscreen C instrument (Bioscreen, Helsinki, Finland). Two isolates from each integrated strain were picked for the assay. The *E. coli* strains were individually grown in 3 mL of LA medium (1% tryptone, 0.5% yeast extract, 0.05% sodium chloride) containing 100 µg/mL spectinomycin at 37 °C for 16 hours. For the Bioscreen assay, the fresh overnight cultures were diluted 1:100 into MOPS minimal medium containing 2.5 g/L, 5 g/L or 10 g/L sucrose and 100 µg/mL spectinomycin in a Bioscreen honeycomb plate. Vitamin B₁₂ was added to the medium to a concentration of 0.1 mg/L. Blank wells containing the growth medium were also included. The honeycomb plate was placed into the Bioscreen C instrument according to the manufacturer's instructions. The plate was incubated at 33 °C with constant shaking and the OD was recorded every 15 min. The maximum growth rate ($\mu_{\max}$) was estimated using the following procedure. First, the background was removed by subtracting the averaged OD values in the blank wells from the OD values of non-blank wells. Then, the growth rate parameter was estimated using a sliding window consisting of 8 data points (covering 2 hours of growth) by fitting the data points to an exponential curve using non-linear regression. In each sliding window, the estimated growth rate was recorded only if the fit was good (i.e., $R^2 > 0.95$). The largest value from all the recorded growth rates was the $\mu_{\max}$. The $\mu_{\max}$ of both isolates of each strain are given in Table 4. Strains containing integration of the sucrose gene cluster between the *yihP* gene and the *yihO* gene showed faster growth on sucrose than strains containing the cluster at the *aldH* gene, particularly at low sucrose levels.

EXAMPLE 6

Production of PDO and Glycerol by Recombinant *E. coli* Strains

Grown on Sucrose

This Example describes the production of PDO and glycerol by the
5 *E. coli* strains described in Examples 1-4 when grown on sucrose.

The molar yield for production of PDO and glycerol was determined in shake flask studies. Fresh overnight cultures of the *E. coli* isolates were inoculated into 12.5 mL MOPS medium containing 10 g/L sucrose plus 100 ng/mL Vitamin B12 and 100 µg/mL spectinomycin to an initial OD of
10 0.01. Cells were grown at 33 °C with shaking at 250 rpm for 44 hours. Cultures were centrifuged and the supernatants were added to 0.22 µm Spin-X centrifuge tube filters (Corning Inc., Corning, NY) and centrifuged at 10,000 g for 1 min. The filtrates were analyzed by HPLC using a Waters Alliance 2690 HPLC system (Waters Corp., Milford, MA) with an
15 Aminex HPX-87C HPLC carbohydrate analysis column (Bio-Rad Laboratories, Hercules, CA, Cat # 125-0095) heated to 85 °C in a separated Waters TCM heating chamber. A Bio-Rad carbo-C micro-guard column (Bio-Rad, Cat #125-0128) was used before the analysis column. The mobile phase was composed of 0.05 mM CaO (Sigma, #208159), 0.5
20 mM MES (Sigma, #M3671), 0.05 mM HNO₃ (EMD Chemicals, Gibbstown, NJ, Cat #NX0409), pH 5.3. The flow rate was 0.5 mL/min. Typically, the retention times of PDO and glycerol were 17.5 min and 19.3 min, respectively. The retention times of sucrose, glucose and fructose were 10.3 min, 12.5 min and 15.9 min, respectively.

25 *E. coli* strains containing the sucrose gene cluster integration between the *yihP* gene and the *yihO* gene showed slightly higher molar yield for production of PDO and glycerol (i.e., moles of PDO and glycerol per mole of sucrose) than the strains containing the sucrose gene cluster integrated at the *aldH* gene for both the wild type gene cluster and the
30 variant gene cluster, as shown in Table 4.

Table 4
Growth Rate and Molar Yield for the Production of PDO and
Glycerol by Recombinant *E. coli* Strains

TTab-derived strains	cscAKB*	Location	Growth rate ($\mu_{\max}$, hour ⁻¹) on sucrose			Molar yield (mol PDO+ Gly / mol sucrose)
			2.5g/L	5g/L	10g/L	
Example 1- isolate 7	wild type	between <i>yihP</i> and <i>yihO</i>	0.127	0.165	0.197	1.10
Example 1- isolate 8	wild type	between <i>yihP</i> and <i>yihO</i>	0.124	0.183	0.185	1.14
Example 2 Comparative, isolate 7	wild type	<i>aldH</i>	0.102	0.151	0.234	1.09
Example 2 Comparative, isolate 18	wild type	<i>aldH</i>	0.084	0.146	0.228	1.08
Example 3 – isolate 13	L61P variant	between <i>yihP</i> and <i>yihO</i>	0.251	0.258	0.255	1.26
Example 3 – isolate 14	L61P variant	between <i>yihP</i> and <i>yihO</i>	0.253	0.276	0.263	1.26
Example 4 Comparative, isolate 15	L61P variant	<i>aldH</i>	0.233	0.272	0.275	1.25
Example 4 Comparative, isolate 19	L61P variant	<i>aldH</i>	0.232	0.270	0.275	1.25

5

EXAMPLES 7-10

Integration of Sucrose Gene Clusters in a Wild Type *E. coli* Strain

These Examples describe the integration of sucrose gene clusters in a non-PDO producing wild type *E. coli*. Integration between the *yihP* gene and the *yihO* gene also resulted in faster growth in sucrose than integration at the *aldH* gene in this *E. coli* strain.

Integration of the wild type or the variant sucrose gene cluster at *aldH* or *yihP* gene in *E. coli* strain FM5 (ATCC® No. 53911) was done as described in Examples 1-4, except that *E. coli* strain FM5 was used as the host for integration. The colonies were also purified and cured of pKD46.

The integration site was confirmed by PCR and the integrated clusters were sequenced to ensure that no unexpected mutation occurred. Growth rates of the FM5 derived strains on sucrose were determined using the Bioscreen assay as described in Example 5. The results (i.e., the mean and standard deviation of triplicate determinations) are shown in Table 5. The strains having the sucrose gene cluster, both the wild type and the variant gene cluster, integrated between the *yihP* gene and the *yihO* gene exhibited higher growth rates than strains having the sucrose gene cluster integrated at the *aldH* gene.

10

Table 5

Growth Rates of *E. coli* strain FM5 Derived Strains Containing Sucrose Gene Clusters integrated at the *aldH* or between the *yihP* gene and the *yihO* gene

Example	Strain	cscAKB*	Location	Growth rate ($\mu_{\max}$, hour ⁻¹) on sucrose		
				1g/L	2.5g/L	10g/L
7, Comparative	PDO3257	wild type	<i>aldH</i>	0.107 ± 0.004	0.235 ± 0.001	0.444 ± 0.007
8	PDO3085	wild type	between <i>yihP</i> and <i>yihO</i>	0.133 ± 0.004	0.284 ± 0.008	0.456 ± 0.012
9, Comparative	PDO3094	L61P variant	<i>aldH</i>	0.229 ± 0.012	0.415 ± 0.004	0.448 ± 0.004
10	PDO3099	L61P variant	between <i>yihP</i> and <i>yihO</i>	0.259 ± 0.002	0.428 ± 0.003	0.439 ± 0.009

CLAIMS

What is claimed is:

1. A recombinant bacterium comprising in its genome:
 - (a) one or more nucleotide sequences encoding a polypeptide or a polypeptide complex having sucrose transporter activity;
 - (b) a nucleotide sequence encoding a polypeptide having fructokinase activity; and
 - (c) a nucleotide sequence encoding a polypeptide having sucrose hydrolase activity;wherein:
 - (i) (a), (b) and (c) are each operably linked to the same or a different promoter;
 - (ii) (a), (b), and (c) are integrated into the genome between the *yihP* gene or its homolog and the *yihO* gene or its homolog; and
 - (iii) said bacterium metabolizes sucrose at a greater rate than a bacterium comprising (a), (b), and (c) integrated at a different location in the genome.
2. The recombinant bacterium of claim 1, wherein the polypeptide having sucrose hydrolase activity is classified as EC 3.2.1.26 or EC 2.4.1.7.
3. The recombinant bacterium of claim 1, wherein the polypeptide having fructokinase activity is classified as EC 2.7.1.4, EC 2.7.1.3, or EC 2.7.1.1.
4. The recombinant bacterium of claim 1 wherein the bacterium is selected from the group consisting of the genera: *Escherichia*, *Klebsiella*, *Citrobacter*, and *Aerobacter*.
5. The recombinant bacterium of claim 4 wherein the bacterium is *Escherichia coli*.

6. The recombinant bacterium of claim 1 wherein the bacterium produces 1,3-propanediol, glycerol, and/or 3-hydroxypropionic acid.

- 5 7. A process for making glycerol, 1,3-propanediol and/or 3-hydroxypropionic acid from sucrose comprising:
- a) culturing the recombinant bacterium of claim 6 in the presence of sucrose; and
 - b) recovering the glycerol, 1,3-propanediol and/or 3-hydroxypropionic acid produced.
- 10