

DESCRIPTION

ENGINEERING OF THERMOTOLERANT *BACILLUS COAGULANS* FOR
PRODUCTION OF D(-)-LACTIC ACID

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application Serial Number 61/416,002, filed November 22, 2010, the disclosure of which is hereby incorporated by reference in its entirety, including all figures, tables and nucleic acid sequences.

GOVERNMENTAL SUPPORT

This invention was made with government support under Department of Energy grant number DE-FG36-04GO14019. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

Petroleum serves not only as the primary source of fuel but also as the raw material for production of various polymers used by the plastics industry. The finite nature of the petroleum reserves and the negative environmental impact from the use of petroleum has shifted attention towards alternate, renewable source of fuels and chemicals as replacements for petroleum (23). Fermentation of carbohydrates has been shown to produce various short chain hydroxy acids as well as other chemicals that can be polymerized to produce plastics with differing physical and chemical properties. Among these fermentation products, lactic acid stands out as a primary chemical that can be a starting material for manufacture of biodegradable, renewable plastics with minimal environmental impact; CO₂ neutral. Fermentation of sugars to lactic acid dates back to pre-historic times and commercial production of lactic acid using pure bacterial cultures started as early as 1895 (3). Although lactic acid is primarily used by food and pharmaceutical industries, lactic acid derived biopolymer production is expected to outstrip these uses provided the cost of production of lactic acid based polymer is comparable to the polymers derived from petrochemicals (8, 14, 18).

Lactic acid is condensed into lactide, purified and polymerized to polylactide (PLA), a thermoplastic (18, 22). By judicious mixing of the D(-)- and L(+)- lactic acid, polymers with various physical and thermochemical properties can be produced. Although lactic acid can be

synthesized from petroleum, the product is a mixture of the two isomers and is not suitable for PLA production. Optically pure lactic acid required for PLA production is produced only by microbial fermentation (14). Various lactic acid bacteria, *Lactobacillus*, *Lactococcus*, etc., produce L(+)-lactic acid at high yield and titer from fermentable sugars such as glucose and sucrose (6, 14). Their nutritional requirements are complex and their growth temperature range between 30°C and 35°C. Microorganisms that produce D(-)-lactic acid as the primary fermentation product has been described and is currently being used by industry (25, 34, 36) (12). Lactic acid fermentation by these microbial biocatalysts is currently conducted at 30-37 °C and raising the growth and fermentation temperature to 50-55 °C is expected to minimize contamination of large scale industrial fermentations (1). In order to reduce the cost of lactic acid production and also to eliminate the use of food carbohydrates as feedstock for lactic acid production, alternate sources of fermentable sugars and microbial biocatalysts are being developed. Lignocellulosic biomass is an attractive source of sugars; glucose, xylose, etc. However, the lactic acid bacteria used by the industry lacks the ability to ferment pentoses efficiently to lactic acid although there are several attempts to improve the xylose fermentation property of these lactic acid bacteria (25, 31).

Bacillus coagulans is a sporogenic lactic acid bacterium that grows at 50-55 °C and pH 5.0 and ferments both hexoses and pentoses (10, 27). This bacterium has been shown to produce L(+)-lactic acid at concentrations as high as 180 g/L in fed-batch fermentations from both glucose and xylose and is also an excellent candidate for simultaneous saccharification and fermentation of cellulose to optically pure lactic acid (26). *B. coagulans* is, generally, recalcitrant to genetic engineering and methods for producing pure lactic acid are needed (particularly using genetically engineered microorganisms that do not contain exogenous nucleic acid sequences). One aspect of the invention disclosed herein provides a general method for engineering this genetically recalcitrant bacterium. Using the disclosed method and growth-based selection, the fermentation product of *B. coagulans* strain P4-102B is changed from L(+)-lactic acid to D(-)-lactic acid. The engineered biocatalyst produced about 90 g/L of D(-)-lactic acid in less than 48 hours at 50°C.

BRIEF SUMMARY OF THE INVENTION

Genetically modified microorganisms having the ability to produce D(-)-lactic acid at temperatures between 30°C and 55°C are provided. In various embodiments, the microorganisms may have the chromosomal lactate dehydrogenase (*ldh*) gene and/or the

chromosomal acetolactate synthase (*alsS*) gene inactivated. Exemplary microorganisms for use in the disclosed methods are *Bacillus spp.*, such as *Bacillus coagulans*. Microorganisms produced according to the instant disclosure produce D(-)- lactic acid in amounts of at least 60g/L of culture medium, (e.g., at least 70g/L, 80g/L, 90g/L or 100g/L). Methods of making and using the disclosed genetically modified microorganisms are also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A-1B. Fermentation profile of *B. coagulans* strain QZ4 (Δldh) at pH 5.0 (Fig. 1A) and pH 7.0 (Fig. 1B). Fermentations were conducted in small fermenters with pH control in LB with glucose. Starting glucose concentration was 30 g/L at pH 5.0 and 50 g/L at pH 7.0.

Figures 2A-B. Fermentation profile of *B. coagulans* strain QZ5 (Δldh , $\Delta alsS$) at pH 5.0 (Fig. 2A) and pH 7.0 (Fig. 2B). Fermentations were in small fermenters with pH control by automatic addition of KOH in LB + glucose (30 g/L).

Figure 3. Growth-based selection of *B. coagulans* strain QZ5 in small fermenters in LB + glucose (30 g/L) at pH 5.0 leading to strain QZ13.

Figure 4. Growth-based selection of *B. coagulans* strain QZ13 in small fermenters in LB + glucose (50 g/L) at pH 7.0 leading to strain QZ14.

Figure 5. Growth-based selection of *B. coagulans* strain QZ14 in small fermenters in LB + glucose at pH 7.0 with increasing glucose concentration leading to strain QZ15. Medium also contained 20 g/L CaCO_3 . Starting glucose concentration was 50 g/L. After the third transfer glucose concentration was increased to 60 g/L. Glucose concentration of the medium was 100 g/L after the fifth transfer.

Figure 6. Fermentation profile of *B. coagulans* strain QZ19 at pH 7.0 in LB + glucose with 20 g/L CaCO_3 . L(+)-lactic acid or formate was not detectable in the fermentation broth.

Figure 7. Exemplary schematic for production of D(-)- lactic acid producing bacterial strains. Generally, the target bacterial strain/cell will be genetically modified to inactivate the activity of L-lactate dehydrogenase and acetolactate synthase, competing reactions at the pyruvate node. Cells will then be cultured under O_2 -limiting conditions at a pH of between 4.5 and 5.5. Cells producing higher cell yields and/or production of lactic acid as compared to the parent strain are selected for further development. Selected cells are then cultured under O_2 -limiting/anaerobic conditions at a pH between about 6.5 and 7.5.

Cells producing higher cell yields and/or production of lactic acid as compared to the original selected strain are selected for further development or use in the production of D(-)- lactic acid. In certain preferred aspects of the invention, the cells used for the production of D(-)- lactic acid produce at least 60g of lactic acid per liter of culture medium (preferably within about 48 hours).

BRIEF DESCRIPTION OF THE SEQUENCES

SEQ ID NO: 1 encodes lactate dehydrogenase gene of *B. coagulans* P4-102B.

SEQ ID NO: 2 encodes acetolactate synthase of *B. coagulans* P4-102B.

SEQ ID NO: 3 encodes pyruvate formate lyase (*pfl*) of *B. coagulans* P4-102B.

DETAILED DISCLOSURE OF THE INVENTION

One aspect of the subject application provides genetically modified microorganisms having the ability to produce D(-)-lactic acid. In various embodiments of this aspect of the invention, the microorganisms may have the chromosomal lactate dehydrogenase (*ldh*) gene, chromosomal pyruvate formate lyase (*pflB*) gene, pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or the chromosomal acetolactate synthase (*alsS*) gene inactivated and the microorganism is a *Bacillus spp.*, such as *Bacillus coagulans*. Microorganisms produced according to the instant disclosure produce D(-)- lactic acid in amounts of at least 60g/L of culture medium, (e.g., at least 70g/L, 80g/L, 90g/L or 100g/L). In certain aspects of the invention, the chromosomal lactate dehydrogenase (*ldh*) gene, chromosomal pyruvate formate lyase gene (*pflB*) and the chromosomal acetolactate synthase (*alsS*) gene inactivated. Other aspects provide microorganisms in which the chromosomal lactate dehydrogenase (*ldh*) gene and the chromosomal acetolactate synthase (*alsS*) gene inactivated. Other aspects of the invention provide for microorganisms having various combinations of inactivated enzymatic activity (see discussion below).

The term "gene" includes structural genes and regions that have specific regulatory functions such as promoters and operators. The term "gene" includes the open reading frame of the gene as well as the upstream and downstream regulatory sequences. The upstream regulatory region is also referred as the promoter region of the gene. The downstream regulatory region is also referred as the terminator sequence region. The inactivation of *ldh* and *alsS* may be accomplished by deletion of nucleotide sequences in chromosomal DNA which: (1) are involved in transcriptional regulation of the promoter,

operator, or the like of the *ldh*, *pflA*, *pflB*, *alsD* and/or *alsS* gene; (2) a frameshift introduced such that lactate dehydrogenase, pyruvate formate lyase, pyruvate formate lyase activating enzyme, alpha-acetolactate decarboxylase and/or acetolactate synthase is/are not expressed as an active protein; or (3) the entire structural gene, or a portion thereof, encoding lactate dehydrogenase, pyruvate formate lyase, pyruvate formate lyase activating enzyme, alpha-acetolactate decarboxylase and/or acetolactate synthase has been deleted. In certain preferred embodiments, microorganisms in which the entire gene encoding lactate dehydrogenase, pyruvate formate lyase, pyruvate formate lyase activating enzyme, alpha-acetolactate decarboxylase and/or acetolactate synthase has been deleted are provided. Exemplary sequences for the lactate dehydrogenase gene and acetolactate synthase gene, alpha-acetolactate decarboxylase gene are provided in SEQ ID NOs: 1 and 2, respectively. The coding sequence of pyruvate formate lyase and pyruvate formate lyase activating enzyme are provided in SEQ ID NO: 3.

The phrase "portion of a structural gene" or the entire structural gene, or "a portion thereof," may refer to a single nucleotide deletion in the structural gene portion. The deletion is preferably a deletion of five to ten nucleotides in the structural gene, more preferably ten to 50 nucleotides, and yet more preferably 50 to 100 nucleotides. In some aspects of the invention, the entire structural gene may be deleted. Other aspects of the invention provide for the deletion of lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*). The open reading frames of the genes encoding the aforementioned enzymes are indicated in the sequence listing. As discussed below, *ldh* and any combination of *pflA*, *pflB*, *alsS* and *alsD* can be deleted.

In one aspect, the mutation of the genes in the chromosome of the microorganism is accomplished without introducing genes or portions thereof from exogenous sources. Another aspect provides for the mutation of endogenous genes by the introduction of one or more point mutation(s) or by introducing one or more stop codon in the open reading frame of the endogenous gene that is being modified. In another aspect, the open reading frame of the endogenous gene can be deleted from the chromosomal DNA.

In certain aspects, an exogenous nucleotide sequence may be introduced to inactivate a target gene for the purpose of selecting a bacterial strain with a mutated gene having a desired phenotype. The exogenous nucleotide sequence introduced into the microbial genome

can be subsequently removed in a seamless fashion without leaving behind any residual exogenous nucleotide sequence.

In one embodiment, biocatalysts are selected for their ability to produce D(-)- lactic acid at high titer, yield and volumetric productivity. One embodiment provides a biocatalyst capable of producing at least 0.5 mole of D(-)- lactic acid for every one mole of carbon source (*e.g.*, glucose) consumed. Such biocatalysts may, optionally, have been selected using growth-based selection.

The term “titer” means the molar concentration of a particular compound in the fermentation broth. Thus in the fermentation process for the production of D(-)- lactic acid, a titer of 100 mM would mean that the fermentation broth at the time of measurement contained 100 mmoles of lactic acid per liter of the fermentation broth.

The term “yield” refers to the moles of particular compound produced per mole of the feedstock consumed during the fermentation process. Thus in the fermentative process for the production of D(-)- lactic acid using glucose as the feedstock, the term yield refers to the number of moles of D(-)- lactic acid produced per mole of glucose consumed.

The term “volumetric productivity” refers to the amount of particular compound in grams produced per unit volume per unit time. Thus a volumetric productivity value of 0.9 g L⁻¹ h⁻¹ for D(-)- lactic acid would mean that 0.9 gram of D(-)- lactic acid is accumulated in one liter of fermentation broth during an hour of growth. The volumetric productivity range of the genetically modified organisms disclosed herein can be up to 4 g L⁻¹ h⁻¹. for example, QZ19 can reach a volumetric productivity higher than 3 g L⁻¹ h⁻¹.

The terms “titer,” “yield,” and “volumetric productivity” as used in this disclosure also include “normalized titer,” “normalized yield,” and “normalized volumetric productivity.” In the determination of the normalized titer, normalized yield, and normalized volumetric productivity, the volume of the neutralizing reagents added to the fermentation vessel in order to maintain the pH of the growth medium is also taken into consideration.

The term “(w/v)” refers to the amount of a substance (in grams) per liter (g/L).

The terms “genetically engineered” or “genetically modified” as used herein refers to the practice of altering the expression of one or more enzymes in a microorganism by manipulating its genomic DNA. The terms “genetically modified microorganism(s)”, “genetically modified bacterial strain(s) (GMBS)” and “biocatalyst(s)” may be used interchangeably within this disclosure. In certain embodiments, various *Bacillus spp.*, *e.g.*, *Bacillus coagulans* strains, *Bacillus*

licheniformis strains, *Bacillus subtilis* strains, *Bacillus amyloliquifaciens* strains, *Bacillus megaterium* strains, *Bacillus macerans* strains, *Paenibacillus* spp. strains or *Geobacillus* spp. such as *Geobacillus stearothermophilus* strains can be genetically modified. Other *Bacillus* strain can be obtained from culture collections such as ATCC (American Type Culture Collection) and genetically engineered as set forth herein for the production of D(-)- lactic acid. In some embodiments of the invention, the *B. coagulans* strain Suy27-13 and/or *B. coagulans* strains containing the point mutation found in Suy27-13 may be specifically excluded from the scope of the claims.

Thus in one aspect, a process for the production of lactic acid in commercially significant quantities from the carbon compounds by genetically modified bacterial strains is provided. Microorganisms suitable for the production of D(-)- lactic acid can be cultured in one or two-step processes as disclosed herein. For any of the method steps, the genetically modified microorganisms may be maintained at a temperature between about 30°C and about 65°C. Various embodiments contemplate culturing the microorganisms at a temperature of about 30°C, 37°C or 55°C. Other embodiments contemplate culturing the microorganisms at a temperature between about 37°C and about 65°C, between about 37°C and about 55°C, between about 45°C and about 60°C or between about 45°C and about 50°C.

“Mutation” or “inactivation” refers to genetic modifications done to the gene including the open reading frame, upstream regulatory region and downstream regulatory region. The gene mutations result in a down regulation or complete inhibition of the transcription of the open reading frame (ORF) of the gene. Gene mutations can be achieved either by deleting the entire coding region of the gene (ORF) or a portion of the coding nucleotide sequence (ORF), by introducing a frame shift mutation within the coding region, by introducing a missense mutation, insertion of sequences that disrupt the activity of the protein encoded by the gene, by introducing a stop codon or any combination of the aforementioned gene mutations.

As used herein, the term “exogenous” is intended to mean that a molecule or an activity derived from outside of a cell is introduced into the host microbial organism. In the case of an exogenous nucleic acid molecule introduced into the microbial cell, the introduced nucleic acid may exist as an independent plasmid or may get integrated into the host chromosomal DNA. In certain embodiments, exogenous nucleic acid encoding a protein is not found in the biocatalysts disclosed herein. Other embodiments allow for biocatalysts containing exogenous genes. Where present, an exogenous gene (nucleic

acid sequence) may be introduced into the microbial cell in an expressible form with its own regulatory sequences such as promoter and terminator sequences. Alternatively, the exogenous nucleic acid molecule may get integrated into the host chromosomal DNA and may be under the control of the host regulatory sequences.

5 The term “endogenous” refers to the molecules and activity that are naturally (natively) present within the host cell. When used in reference to a biosynthetic activity, the term “exogenous” refers to an activity that is introduced into the host reference organism. The source can be, for example, a homologous or heterologous encoding nucleic acid that expresses the referenced activity following introduction into the host
10 microbial organism. If the nucleic acid coding for a protein is obtained from the same species of the microbial organism, it is referred as homologous DNA. If the nucleic acid is derived from a different microbial species, it is referred as heterologous DNA. Irrespective of the nature of the DNA, whether it is homologous or heterologous, when introduced into a host cell, the DNA as well as the activity derived from that introduced
15 DNA is referred to as exogenous. Therefore, exogenous expression of an encoding nucleic acid can utilize either or both heterologous and homologous encoding nucleic acid.

One aspect provides GMBS showing impressive titers, high yield and significant volumetric productivity for D(-)- lactic acid. The microorganisms disclosed herein can be
20 employed in a production process for producing D(-) – lactic acid using various sugars. In one embodiment, the genetic modifications involve only the manipulation of genes within the native genome of the microorganism. In that embodiment, no exogenous genetic material such as plasmids bearing antibiotic resistance genes or any other exogenous nucleotide sequences coding for certain enzyme proteins is present in the
25 bacterial strain for D(-)- lactic acid production.

The present invention combines the technique of specific genetic modifications with a process of growth-based selection to obtain strains showing high yield, titer and volumetric productivity for D(-)- lactic acid production. The genetically modified microbial strains produced by the disclosed methods may be subsequently grown in
30 under various conditions, such as low pH, for several generations to select a clone producing D(-)- lactic acid at levels higher than the original parental strain and/or which has a higher cell yield as compared to parental strain. An exemplary scheme in this

regard is shown in Figure 7. This process for the growth-based selection of a clone with the most preferred phenotype is referred as growth-based selection .

During growth-based selection, the genetically modified strain is repeatedly transferred into fresh medium for a period of time to obtain a clone that exhibits
5 fast/higher cell growth, rapid consumption of different carbon sources, ability to use multiple sugars simultaneously, ability to tolerate toxic chemicals in the carbon source and high production yield and productivity of the desired organic acid coupled with the low production of other organic acids. During growth-based selection, attention is paid to select the clone with the desirable phenotypes discussed above. A clone resulting from
10 the selection process showing a very good growth rate but that has not improved in the yield of the desired organic acid is not a desirable clone. In the practice of the disclosed methods, strains are selected by starting the culture of a genetically modified strain aerobically and conducting serial passaging of the strain under conditions that limit oxygen within the culture system (*e.g.*, fermenter). Genetically modified microorganisms capable of
15 growing under oxygen limiting conditions are selected for continued passaging until microaerobic or anaerobic conditions are reached. Microorganisms are then anaerobically cultured under increasing pH conditions and selected on the basis of D(-)-lactate production under the culture conditions. For any of the method steps, the genetically modified microorganisms may be maintained at a temperature between about 30°C and about 65°C.
20 Various embodiments contemplate culturing the microorganisms at a temperature of about 30°C, 37°C or 55°C. Other embodiments contemplate culturing the microorganisms at a temperature between about 37°C and about 65°C, between about 37°C and about 55°C, between about 45°C and about 60°C or between about 45°C and about 50°C.

Genetic manipulations can be done in several different stages accompanied by
25 growth-based selection in between the stages of genetic manipulations. The genomic manipulations involve either altering the endogenous DNA sequences or completely removing specific DNA sequences from the genomic DNA. The genetic manipulations may also involve inserting a foreign DNA sequence within the genomic DNA sequence of the microorganism. Certain embodiments, the genetic manipulations are
30 accomplished by means of removing specific DNA sequences from the genomic DNA of the microorganisms without introducing any foreign DNA. Certain genetic manipulations necessary to inactivate the expression of a gene coding for a particular protein product requires an insertion of a foreign DNA sequence into the genome of the microorganism

to select a clone with the desired genetic modification. For example, exogenous antibiotic marker genes can be used to insertionally inactivate the endogenous genes and to select the clone with the desired genotype. In one embodiment of the present invention, the introduced exogenous DNA sequences are ultimately removed from the genomic DNA of the microorganism so that the microorganism at the end of the genetic engineering process would have little or no exogenous DNA in its resulting genomic DNA, particularly no exogenous DNA genes (or portions thereof). Various genetic engineering techniques necessary for accomplishing the objectives of the preferred embodiment of the present invention are known in the art, including the use of plasmids exhibiting instability at elevated temperatures (see, for example, the material and methods discussed in the Examples of this application). Any cited scientific publications as well as patent documents are incorporated by reference in their entirety for the purpose of providing any necessary details for genetic engineering techniques useful for the present invention.

In one embodiment of the present invention, one or more of the genes coding for the proteins known to function in fermentative pathways are inactivated through one or more genetic manipulations or genetic engineering techniques as discussed above. Genes and enzymes that may be inactivated include: *ldh*, lactate dehydrogenase; and *alsS*, acetolactate synthase.

Accordingly, the following non-limiting embodiments are provided:

1. A bacterial cell comprising genetic modifications causing the inactivation of enzymatic activity for:

a) lactate dehydrogenase and optionally acetolactate synthase and/or pyruvate formate lyase;

b) lactate dehydrogenase and acetolactate synthase;

c) lactate dehydrogenase, acetolactate synthase and pyruvate formate lyase or

d) any of the following combinations of enzymatic activity: lactate dehydrogenase + pyruvate formate lyase; lactate dehydrogenase + pyruvate formate lyase activating enzyme; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase; lactate dehydrogenase + acetolactate synthase; lactate dehydrogenase + alpha-acetolactate decarboxylase; lactate dehydrogenase + acetolactate synthase + alpha-

acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + alpha-acetolactate decarboxylase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase + alpha-acetolactate decarboxylase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + alpha-acetolactate decarboxylase + acetolactate synthase.

2. The bacterial cell according to embodiment 1, further comprising genetic modifications causing the inactivation of a desired enzymatic activity.

3. The bacterial cell according to embodiment 1 or 2, further comprising genetic modifications introducing exogenous genes into said bacterial cell.

4. The bacterial cell according to embodiment 1 or 2, wherein said genetic modification comprises the mutation of a gene encoding lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*) or the deletion of all or a portion of a gene encoding lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*).

5. The bacterial cell according to embodiment 4, the mutation of said genes comprises the introduction of one or more point mutation(s) or the introduction of one or more stop codon in the open reading frame of the gene.

6. The bacterial cell according to embodiment 1-3, wherein said genetic modification comprises a point mutation or a deletion in the coding sequence/open reading frame(s) of lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*) or insertion of an exogenous sequence into the coding region/open reading frame(s) of lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*).

7. The bacterial cell according to any one of embodiments 1, 2, 4, 5 or 6, wherein said bacterial cell does not contain exogenous genes or portions thereof.

8. The bacterial cell according to any one of embodiments 1, 2, 4, 5 or 6, wherein enzymatic activity of L-lactate dehydrogenase, pyruvate formate lyase and/or acetolactate synthase is inactivated by homologous recombination, optionally using a plasmid sensitive to temperature.

9. The bacterial cell according to embodiment 8, wherein said genetic modification comprises complete or partial deletion of nucleotides encoding acetolactate synthase, lactate dehydrogenase and/or pyruvate formate lyase.

10. The bacterial cell according to any one of embodiments 1-9, wherein:

a) said bacterium is a *Bacillus* spp., such as *Bacillus coagulans*, *Bacillus licheniformis*, *Bacillus subtilis*, *Bacillus amyloliquifaciens*, *Bacillus pumilus*, *Bacillus circulans* or *Bacillus thiaminolyticus*; and

b) wherein *Bacillus coagulans* Suy27-13 may be optionally excluded from the scope of the claims.

11. A genetically modified bacterial cell according to any one of embodiments 1-10, wherein said genetically modified bacterial cell is QZ15 or QZ19.

12. A method of producing D(-)- lactic acid comprising culturing a genetically modified bacterial cell according to any one of embodiments 1-11 in a medium comprising a carbon source under conditions that allow for the production of D(-)- lactic acid.

5 13. The method according to embodiment 12, further comprising isolating or purifying the D(-)- lactic acid.

14. The method according to embodiment 13, wherein said bacterial strain is cultured under anaerobic conditions.

10 15. The method according to embodiments 12-14, wherein said medium comprises between 2% and 20% (w/v) carbon source.

16. A method of making a D(-)- lactic acid producing genetically modified bacterial cell comprising:

15 a) inactivation of lactate dehydrogenase and acetolactate synthase activity in said bacterial cell;

b) culturing said bacterial cell at a pH between 3.0 and 6.0 under aerobic and/or oxygen-limiting conditions in a medium containing a carbon source;

20 c) selecting a bacterial cell exhibiting increased cell yield and/or D(-)- lactic acid production as compared to the parental strain;

d) culturing the selected bacterial cell at a pH of between 6.5 and 8.0 under anaerobic conditions in a medium containing a carbon source; and

25 e) selecting a bacterial cell exhibiting increased cell yield and/or D(-)- lactic acid production as compared to the parental bacterial cell or the bacterial cell selected in step d).

17. The method according to embodiment 16, wherein step b) is performed at a pH of:

a) about 4.5 or 5.5; or

30 b) about 5.0.

18. The method according to embodiment 16, wherein step d) is performed at a pH of:

- a) about 6.5 to about 7.5; or
- b) about 7.0.

5 19. The method according to embodiments 16-18, wherein steps d) and e) are repeated in medium containing increasing amounts of a carbon source.

20. The method according to embodiments 16-18, wherein steps b) and c) are repeated in medium containing increasing amounts of a carbon source.

10 21. The method according to embodiments 16-18, wherein steps b) - e) are repeated in medium containing increasing amounts of a carbon source.

15 22. The method according to embodiments 12-21, wherein the carbon source is glucose, fructose, xylose, arabinose, galactose, mannose, rhamnose, sucrose, cellobiose, hemicelluloses, cellulose, glycerol or combination thereof.

23. The method according to embodiments 12-15, wherein said fermentation is conducted under anaerobic conditions at a pH of:

- 20 a) about 6.5 to about 7.5; or
- b) about 7.0.

25 24. The method according to embodiments 12-22, wherein said genetically modified bacterial cell produces at least 60g of lactic acid per liter, at least 80 g of lactic acid per liter, or at least 90 g of lactic acid per liter of fermentation medium within 48 hours of the start of fermentation.

25. The method according to embodiments 12-24, wherein the pH of medium used to culture said genetically modified bacterial cell is maintained by the automatic addition of acid or base.

30

26. The method according to embodiments 16-23, wherein said genetically modified bacterial cell is initially cultured under aerobic conditions and serially passaged

under conditions that reduce the amount of oxygen present in the culture system until microaerobic or anaerobic conditions are reached.

27. The method according to embodiments 16-23 or 26, wherein the bacterial cell
5 a *Bacillus* spp., such as *Bacillus coagulans*, *Bacillus licheniformis*, *Bacillus subtilis*, *Bacillus amyloliquifaciens*, *Bacillus pumilus*, *Bacillus circulans* or *Bacillus thiaminolyticus*; wherein *Bacillus coagulans* Suy27-13 may be optionally excluded.

28. The bacterial cell or method of any one of embodiments 1-10 and 12-27,
10 wherein the bacterial cell has one of the following combinations of gene inactivations: *ldh* + *pflB*; *ldh* + *pflA*; *ldh* + *pflA* + *pflB*; *ldh* + *alsS*; *ldh* + *alsD*; *ldh* + *alsS* + *alsD*; *ldh* + *pflB* + *alsS*; *ldh* + *pflB* + *alsD*; *ldh* + *pflA* + *alsS*; *ldh* + *pflA* + *alsD*; *ldh* + *pflA* + *pflB* + *alsS*; *ldh* + *pflA* + *pflB* + *alsD*; *ldh* + *pflA* + *alsD* + *alsS*; *ldh* + *pflB* + *alsD* + *alsS*; *ldh* + *pflA* + *pflB* + *alsD* + *alsS*; or inactivation of one of the following combinations of enzymatic activity:
15 lactate dehydrogenase + pyruvate formate lyase; lactate dehydrogenase + pyruvate formate lyase activating enzyme; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase; lactate dehydrogenase + acetolactate synthase; lactate dehydrogenase + alpha-acetolactate decarboxylase; lactate dehydrogenase + acetolactate synthase + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase + acetolactate
20 synthase; lactate dehydrogenase + pyruvate formate lyase + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + alpha-acetolactate decarboxylase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + alpha-acetolactate decarboxylase; lactate
25 dehydrogenase + pyruvate formate lyase activating enzyme + alpha-acetolactate decarboxylase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase + alpha-acetolactate decarboxylase + acetolactate synthase; lactate dehydrogenase + pyruvate formate lyase activating enzyme + pyruvate formate lyase + alpha-acetolactate decarboxylase
30 + acetolactate synthase.

29. The bacterial cell according to any of embodiments 1-11 or 28, wherein the bacterial cell produces D(-) - lactic acid at a temperature between about 30°C and about 65°C; between about 37°C and about 65°C; between about 37°C and about 55°C; between about 45°C and about 60°C; between about 45°C and about 50°C; or at a temperature of about 30°C; about 37°C; or about 55°C.

30. The method according to any of embodiments 12-28, wherein the method comprises culturing the bacterial cell at a temperature between about 30°C and about 65°C; between about 37°C and about 65°C; between about 37°C and about 55°C; between about 45°C and about 60°C; between about 45°C and about 50°C; or at a temperature of about 30°C; about 37°C; or about 55°C.

Microorganisms were deposited with the Agricultural Research Service Culture Collection, 1815 N. University Street, Peoria, Illinois, 61604 U.S.A (Table 5). These cultures have been deposited under conditions that assure that access to the cultures will be available during the pendency of this patent application to one determined by the Commissioner of Patents and Trademarks to be entitled thereto under 37 CFR 1.14 and 35 USC 122. The deposits are available as required by foreign patent laws in countries wherein counterparts of the subject application, or its progeny, are filed. However, it should be understood that the availability of the deposits does not constitute a license to practice the subject invention in derogation of patent rights granted by governmental action.

Further, the subject culture deposits will be stored and made available to the public in accord with the provisions of the Budapest Treaty for the Deposit of Microorganisms, i.e., they will be stored with all the care necessary to keep them viable and uncontaminated for a period of at least five years after the most recent request for the furnishing of a sample of the deposits, and in any case, for a period of at least 30 (thirty) years after the date of deposit or for the enforceable life of any patent which may issue disclosing the cultures. The depositor acknowledges the duty to replace the deposits should the depository be unable to furnish a sample when requested, due to the condition of the deposits. All restrictions on the availability to the public of the subject culture deposits will be irrevocably removed upon the granting of a patent disclosing them.

The following examples are provided as way of illustrating the present invention. These inventions in no way limit the scope of this invention. A person experienced in the

field of industrial microbiology would be able to practice the present invention in several different embodiments without violating the spirit of the present invention.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

Following are examples which illustrate procedures for practicing the invention. These examples should not be construed as limiting. All percentages are by weight and all solvent mixture proportions are by volume unless otherwise noted.

EXAMPLE 1—Construction of a D(-)-lactic acid producing thermotolerant *Bacillus coagulans*

Materials and Methods

Bacterial strains and plasmids

B. coagulans wild type strain P4-102B was described previously (27). *Escherichia coli* strain Top10 (Invitrogen) and *Bacillus subtilis* strain HB1000 (11) were used as hosts during construction of various plasmids used in this study. Plasmid pGK12 carries chloramphenicol and erythromycin resistance genes and replicates in several Gram-positive bacteria and *E. coli* (17, 21). Although this plasmid has a broad host-range, its replication is naturally restricted to temperatures $\leq 42^{\circ}\text{C}$. This temperature sensitive nature of plasmid pGK12 replication at 50°C provides an opportunity to select for chromosomal DNA integrants of *B. coagulans* that can grow at $50\text{--}55^{\circ}\text{C}$. Plasmid pGK12 and its derivatives were maintained in *B. subtilis* strain HB1000 at 37°C . When transformed into *B. coagulans*, the transformants were selected and maintained at 37°C . *B. coagulans* mutant strains and plasmids used in the construction of mutants are listed in Table 1.

Medium and growth condition

L-broth (LB) (19) was used as the rich medium for culture of bacteria at pH 5.0 or 7.0, as needed. Glucose was sterilized separately and added to the medium at the indicated concentration, before inoculation. Chloramphenicol, erythromycin and ampicillin were added to LB medium at 7.5 mg/L, 5 mg/L and 100 mg/L, respectively, when needed. Calcium carbonate medium was prepared by overlaying glucose-supplemented (2%, w/v) LB-agar medium with 2.5 ml of CaCO_3 agar (solid CaCO_3 suspended in water (1% w/v) with 1.5% agar) as described previously (30).

Aerobic cultures were grown in a shaker at 200 RPM. Fermentations were carried out either in small custom fermenters (2) or 2.5L fermenters (New Brunswick Scientific Bioflo 110). Culture pH was maintained at the set value by automatic addition of 2N or 6N KOH. Solid CaCO₃ (Fisher Scientific, Pittsburgh, PA) was added at the beginning of fermentation, as needed, at a concentration of 2.0% (w/v) unless specified otherwise. Inoculum for these cultures was grown in the same medium aerobically at 50°C overnight and fermentations were started with 1% (v/v) inoculum. Samples were removed periodically for determination of fermentation products and residual sugar concentration.

Construction of deletion mutants of *B. coagulans*

Isolation of deletion mutants of *B. coagulans* was based on previously described methods in which a plasmid DNA containing the two ends of the target gene was integrated into the chromosome at the target site with appropriate DNA sequence homology using a single recombination event. Such recombinants with appropriate antibiotic resistance can be easily identified using replication-conditional plasmids at the restrictive temperature that eliminates the intact plasmid from the cytoplasm (13). The plasmid DNA and associated antibiotic resistance gene are subsequently removed from the chromosome by a single homologous recombination of different parts of the introduced plasmid DNA and appropriate chromosomal DNA leaving a deletion of the target gene. In the construction of an *ldh* gene deletion of *B. coagulans*, plasmid vectors that can not replicate in *B. coagulans* were initially employed. However, using such plasmids, chromosomal insertions of the introduced plasmid DNA was not detected. This could be a consequence of plasmid transformation efficiency of *B. coagulans* strain P4-102B being lower (29) than the potential recombination frequency of the incoming plasmid to the chromosome. To overcome these low frequency events, plasmid pGK12 was used as the primary vehicle for transfer of DNA to *B. coagulans* for deletion construction. Plasmid pGK12 is stable in *B. coagulans* at 37°C and not 50°C. Presence of plasmid in each cell in a population (10⁹CFU/ml) at 37°C helps to overcome the low transformation efficiency of plasmid DNA into this bacterium. The large population of cells with the plasmid DNA allows selection of rare recombination events between the homologous regions of the plasmid DNA and chromosome. These rare recombinants in the population of cells that have the plasmid DNA (along with the antibiotic resistance gene) integrated into the chromosome can be readily identified when the plasmid DNA is eliminated from the cells after growth at 50-55 °C.

Isolation of Δldh mutant strain

For construction of *ldh* deletion derivative, two sets of primers were used [primers 9 (BsaAI), 10 (EcoRI) and 11 (EcoRI), 12 (StuI)] (Table 2) to amplify the 5' and 3'-ends of the *ldh* gene separately using the genomic DNA from *B. coagulans* strain P4-102B as template. These primers have unique endonuclease recognition sequences at the 5'-end. The two amplified fragments were digested with EcoRI and ligated together. The ligation product was used as template (primers 9 and 12) to produce a promoterless *ldh* gene fragment that is lacking a 100 bp region in the middle of the *ldh* starting at 431 bp from the "A" in the "ATG" of the *ldh* gene. This fragment was digested with BsaAI and StuI and then ligated to similarly digested plasmid pGK12 (plasmid pQZ44). Insert in this plasmid was confirmed by sequencing. Plasmid pQZ44 was transformed into strain P4-102B and erythromycin resistant colonies were selected at 37°C. One of the transformants was cultured at 50°C and an erythromycin-resistant derivative that was also L-LDH-minus (about 1%) was selected (strain QZ3). Presence of the plasmid DNA in the *ldh* gene in the chromosome of strain QZ3 was confirmed by PCR amplification of the genomic DNA with appropriate primers and sequencing the amplified product. During sub-cultures in medium without erythromycin, the *ldh*-minus property of strain QZ3 was found to be unstable and *ldh*⁺ revertants were readily isolated. Strain QZ3 was serially transferred into fresh medium (1% v/v inoculum) everyday at 55°C without erythromycin for 10 days. The final culture was diluted and plated on LB-agar medium. After overnight growth at 50°C, the colonies were transferred by replica plating to LB-agar, LB-agar + erythromycin and calcium carbonate medium (LB-agar supplemented with glucose and CaCO₃ (30)). The colonies that grew on LB-agar, but not on LB-agar + erythromycin and also did not produce lactate based on the extent of clearing in calcium carbonate medium were picked and tested further in liquid cultures for lactate production. The second recombination is expected to yield erythromycin sensitive derivatives lacking L-LDH activity because of the 100 bp deletion in the *ldh* gene. In these experiments the frequency of Δldh was 1 of 5000 erythromycin-sensitive colonies. One of these Δldh mutants, strain QZ4 was selected for further study.

Using similar methods, a Δldh mutant could not be isolated using chloramphenicol resistance as a selective marker. Irrespective of the plasmid backbone, presence of chloramphenicol resistance gene was found to target plasmid DNA insertion to a unique location in the chromosome that is unrelated to the *B. coagulans* chromosomal DNA in the

plasmid (Su and Rhee, unpublished data). These results indicate that chloramphenicol resistance gene is unsuitable for mutant construction in this *B. coagulans* strain.

Construction of a Δals mutant

5 A mutant derivative of strain QZ4 lacking acetolactate synthase activity is not expected to produce acetoin and 2,3-butanediol, fermentation products produced by *ldh* mutant of *B. coagulans* (30). As a first step towards the construction of this double mutant ($\Delta ldh \Delta als$), the *alsD* (alpha-acetolactate decarboxylase) and *alsS* (acetolactate synthase) sequences were amplified by PCR from the genomic DNA of strain P4-102B using primers
10 17 and 21. This PCR fragment was treated with T4 polynucleotide kinase and ligated to HincII digested plasmid vector pUC19 to form plasmid pQZ45. This *alsSD* DNA insert in plasmid pQZ45 was verified by sequencing with appropriate primers. Primers 18 and 22 were used to amplify by PCR a 2,380 bp DNA from plasmid pQZ45 containing only the *alsSD* coding regions (without the promoter). The amplified DNA was cloned into the HincII site of
15 plasmid pUC19 generating plasmid pQZ45-1. A 596 bp region of the *alsS* was removed from plasmid pQZ45-1 after digestion by AfeI and HincII and an erythromycin-resistance gene cassette was inserted at that location. This new plasmid, pQZ54 served as template (primers 18 and 22) to amplify a fragment with the *alsSD* genes with a 596 bp deletion in *alsS* and the gene encoding erythromycin resistance. The PCR product was phosphorylated with
20 polynucleotide kinase and ligated to plasmid pGK12 digested with BsaAI and AfeI. The resulting plasmid, pQZ64 was transformed into *B. coagulans* strain QZ4 (Δldh) by electroporation and erythromycin-resistant colonies were selected at 37°C. Using the procedures described above for construction of Δldh , a $\Delta alsS$ mutation was introduced into strain QZ4. This method yielded several *alsS* mutants differing in their growth rates under
25 both aerobic and anaerobic condition. One of the mutants with the highest growth rate (strain QZ5) was selected for further study.

Transformation of *E. coli*, *B. subtilis* and *B. coagulans*

30 *E. coli* transformation was based on standard technique as described previously. *Bacillus subtilis* strain HB1000 was transformed according to the procedure described by Boylan et al. (4) with some changes. Cells from an overnight culture in stationary phase of growth in LB medium was inoculated (10% v/v) into 10 ml of freshly prepared modified competence medium (29), which contained 100mM phosphate buffer (pH 7.0), 3mM

trisodium citrate, 3mM magnesium sulfate, 2% glucose, 22 µg/ml ferric ammonium citrate, 0.1% casein hydrolysate and 0.2% potassium glutamate, in a 125 ml Erlenmeyer flask and incubated at 37°C with shaking for 3 h. When the OD_{600nm} reached around 0.6, 0.6 ml of the culture was removed to a 13 × 100 mm test tube and DNA was added to the cells. This culture with DNA was incubated in a rotator at 37°C for 2.5 hours. Cells were collected by centrifugation at room temperature and resuspended in 0.1 ml of LB and plated on LB-agar with appropriate antibiotics. Plates were incubated at 37°C and transformants were selected next day.

For transformation of wild type *B. coagulans* P4-102B, Cells growing in 10 ml of LB in a 125 ml flask at 50°C (OD_{420nm} 0.3) was inoculated (10% v/v) into 100ml LB medium in a 1 liter flask. Cells were incubated at 50°C with shaking (200 RPM) for about 3–4 h until the OD at 420nm reached about 0.3–0.5. Cells were collected by centrifugation (4°C; 4,300 x g; 10 min) and washed three times with 30, 25 and 15 ml of ice-cold SG medium (sucrose, 0.5 M, glycerol, 10%). These electro-competent cells were used immediately. Seventy five µl of cell suspension was mixed with 0.1 µg of plasmid DNA and transferred to chilled electroporation cuvette (1 mm gap). The electroporation conditions (Bio-Rad electroporator) were set as square wave for 5ms at 1.75 KV. After electroporation, cells were transferred to 2 ml of pre-warmed (37°C or 50°C) RG medium (LB medium with 0.5M sucrose, 55.6mM glucose and 20mM MgCl₂). These cells were transferred to a 13 × 100 mm screw cap tube and incubated in a tube rotator for 3 h at 50°C before plating on selective antibiotic medium. For transformation of temperature sensitive plasmids, the regeneration temperature was 37°C and the cultures were incubated overnight. For transformation of the mutant QZ4, the DNA concentration was increased to 1 µg plasmid DNA, and the electroporation condition was altered to a time constant of 10 ms at 1.5 KV, 25µF and 600 ohms.

Growth-based selection for spontaneous mutants with desired phenotype

Since every microbial culture will have a certain number of spontaneous random mutations, a mutant with desired phenotype can be readily isolated from that population by providing a growth condition that would preferentially support growth of the specific mutant. Since $\Delta ldh \Delta alsS$ mutant, strain QZ5, is anaerobic growth defective at a culture pH of 5.0, mutation(s) that would increase anaerobic growth by initiating a new fermentation pathway (for example, D-lactic acid production) is expected to have a growth advantage over the rest of the parent population. Achieving a higher anaerobic growth rate may require more than

one mutation (to initiate the fermentation pathway, to enhance metabolic flux to that pathway by increasing enzyme concentration, etc.). Accumulation of beneficial mutations, each providing incremental increase in growth rate and/or product production, can be achieved by serial transfer of a culture until the desired number of mutations accumulates in a single cell and manifests as an identifiable phenotype. Since strain QZ5 is anaerobic growth defective, cultures were started in small pH controlled fermenters (250 ml in a 500 ml vessel) with air as the gas phase. As the culture starts to grow, severe O₂-limitation would limit growth and cell yield. Further increase in cell density would depend on the ability of the cell to ferment sugars present in the medium. To isolate a mutant derivative of strain QZ5 that can grow anaerobically, the fermenter culture was sequentially subcultured under indicated conditions using small pH controlled fermenters. The transfer conditions were adjusted to different time and inoculum amount. On an average, transfers were after every 2 or 3 days of growth with 2% inoculum during adaptation to increasing sugar concentration.

Determination of mRNA levels

For determination of mRNA levels in *B. coagulans*, cells grown under different conditions were collected by centrifugation (16,000 x g; 30 sec, room temperature). RNA was isolated using the acid phenol extraction method as described before (30). Total RNA concentration was determined from the absorbance at 260 nm (NanoVue, GE). The cDNA copy was prepared with Superscript III reverse transcriptase (Invitrogen) using primers specific for the gene of choice. The cDNA (mRNA) concentration was determined by PCR using gene specific primers and SYBR-green containing PCR reaction mix (Bio-Rad Laboratories, Hercules, CA). The threshold cycle for each of the PCR reaction with different concentrations of cDNA was determined and compared against a standard DNA template that was also run at the same time (16). From these results, a ratio of the concentration of gene-specific mRNA present in the sample was calculated. Reported results are the average of at least three experiments. The primers used for RT-PCR are listed in the Table 2; *ldh* primers – primer 23 and 24, *pfl* primers - primer 25 and 26, *pdhA* (E1 α) primers - primer 27 and 28, *dldh* primers - primer 29 and 30, *als* primers – primer 31 and 32, *polA* primers used as internal control - primer 33 and 34.

Enzyme analysis

To determine the level of PDH and LDH activity, cells were cultured in LB until the culture reached the mid- to late- exponential phase of growth. Cells were harvested by centrifugation ($10,000 \times g$, 10 min; room temperature), washed once with 10 ml of phosphate buffer (50 mM, pH 7.0) and resuspended in 5.0 ml of same phosphate buffer. Cells were broken by passage through a French pressure cell (20,000 PSI). All operations after this step were at 4°C. The cell extract was centrifuged at $12,000 \times g$ for 30 min to remove the cell debris and the supernatant was centrifuged again at $100,000 \times g$ (Beckman) for 1 h to remove large particulates and membrane vesicles. Supernatant was used for enzyme assay. PDH activity assay was based on pyruvate-dependent reduction of NAD^+ at 340 nm ($\epsilon = 6,220 \text{ M}^{-1} \text{ cm}^{-1}$) as described previously (33). Each 1 ml reaction mixture contained potassium phosphate buffer (50 mM; pH 7.5), thiamine pyrophosphate (0.4 mM), CoA (0.13 mM), $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ (2 mM), dithiothreitol (2.6 mM), NAD^+ (0.75 mM) and crude extract. The reaction was started by the addition of pyruvate (5 mM). LDH activity was assayed as described previously (35) as the oxidation of NADH in the presence of pyruvate. Each 1 ml reaction mixture contained potassium phosphate buffer (50 mM; pH 7.5), NADH (0.1 mM) and crude extract. The reaction was started by the addition of pyruvate (25 mM). Protein concentration was determined by Bradford method with bovine serum albumin as standard (5).

Analytical methods.

Glucose and fermentation products were determined by HPLC with the Aminex HPX-87H ion exclusion column (300mm x 7.8mm) as described previously (32). Optical isomers of D-(-)- and L-(+)- lactic acids were determined by HPLC with a Chirex 3126(D)-penicillamine column (150 x 4.6 mm, 5 micron) (Phenomenex) with 2 mM CuSO_4 as eluent. The D-(-)-lactate was also analyzed by enzyme-based method with D-lactate dehydrogenase (Sigma Chemical Co., St. Louis, MO).

Materials

Biochemicals were from Sigma Chemical Co. (St. Louis, MO) and organic and inorganic chemicals were from Fisher Scientific (Pittsburgh, PA). Molecular biology reagents and supplies were from New England Biolabs (Ipswich, MA), Invitrogen or Bio-Rad Laboratories.

Results and Discussion

Sporogenic lactic acid bacteria such as *B. coagulans* produce L(+)-lactic acid as the primary fermentation product irrespective of the carbon source (glucose, xylose, cellobiose, etc.) (10, 27, 28). In support of this, the mRNA encoding *ldh* gene was present at the highest level among the genes encoding proteins at the pyruvate node, irrespective of the growth pH or growth stage (Table 3) (30). A gene encoding D(-)-lactate dehydrogenase (*ldhA*) has been identified in *B. coagulans*, cloned and expressed in *Escherichia coli* in an active form. However, the level of D(-)-lactate in the fermentation broth of *B. coagulans* never exceeded 5% of the total lactic acid produced and most of the fermentation broths indeed lack detectable D(-)-lactic acid (27). The level of *ldhA* mRNA level in the cell was less than 0.5% of the *ldh* mRNA level (Table 3).

Small amounts of acetate, ethanol and formate are also produced by *B. coagulans* during sugar fermentation, especially during fermentation of pentoses, such as xylose indicating the presence of an active pyruvate formate-lyase (27). Although the genes encoding the enzymes in the 2,3-butanediol pathway are present in the sequenced genome of *B. coagulans*, 2,3-butanediol was not detected in the fermentation broth of wild type *B. coagulans* irrespective of the growth pH. This is apparently a consequence of poor expression of the *alsSD* operon in the wild type (Table 3) or the flux to lactate is high enough to deplete the pyruvate pool. In order to construct a derivative of *B. coagulans* that produces D(-)-lactic acid as the major fermentation product, the primary fermentation pathway to L(+)-lactic acid catalyzed by L-LDH (*ldh*) needs to be deleted and the level of expression of *ldhA* encoding D-LDH needs to be enhanced.

Construction of a Δldh mutant

A *B. coagulans* mutant lacking L-LDH activity described previously (30) produced acetate, ethanol, formate and 2,3-butanediol as fermentation products but not D(-)-lactate. This *ldh* mutant, Suy27-13, carried a single base change in the *ldh* gene and was subject to reversion during anaerobic growth, especially during growth at pH 5.0. In order to overcome the high reversion rate of the *ldh* mutation in strain Suy27-13, the *ldh* gene was deleted.

Several methods for constructing gene deletions in bacteria are available and many of these utilize appropriate linear DNA with a positive selection gene such as an antibiotic resistance gene flanked by short DNA sequence corresponding to the target gene (7, 20, 24).

However, attempts to construct Δldh mutants using linear DNA were unsuccessful in *B. coagulans*. This could be a result of low transformation efficiency of *B. coagulans* combined with the need for the incoming DNA to recombine to yield selectable transformants. In order to overcome this limitation, an alternate method that has proven useful in gene deletions was used (13). A temperature sensitive plasmid with appropriate target *ldh* gene sequence and erythromycin resistance gene was constructed (plasmid pQZ44). After transformation of *B. coagulans* strain P4-102B by electroporation, plasmid pQZ44-containing transformants were selected at 37°C that supported stable maintenance of the plasmid. Continued culturing of this plasmid-containing derivative is expected to mobilize the plasmid to the chromosome in a fraction of the population by a single recombination at the *ldh* gene. During growth at 50°C, due to the inability of the plasmid to replicate at this temperature, plasmids will be cured off the cells and erythromycin-resistant colonies that appear at 50°C are expected to have the plasmid DNA at the chromosomal *ldh* gene. Further cultivation of these derivatives will lead to DNA rearrangements leading to deletion of the target gene *ldh*. One such *ldh* mutant, strain QZ4, was identified by the loss of erythromycin resistance and absence of lactate as a fermentation product (Table 3 & 4). In agreement with the previous report on *ldh* mutant (30), anaerobic growth of strain QZ4 was very minimal even in rich medium with glucose at pH 5.0.

Properties of the Δldh strain QZ4

The *ldh* mutant strain QZ4 produced ethanol as the main fermentation product when cultured at pH 7.0 and 2,3-butanediol as the primary product during growth and fermentation at pH 5.0 (Table 4; Fig. 1). Both PFL and PDH contributed acetyl-CoA to ethanol production at pH 7.0 and the contribution of PDH to ethanol was calculated to be about 80% based on the amount of formate in the broth. In support of the PDH-based ethanol production, the PDH activity was about 2-fold higher in the mutant grown in pH 7.0 fermentations during the exponential phase of growth (Table 2). However, the PDH activity declined as the culture entered stationary phase in contrast to an increase in activity in the parent strain at the same growth stage. At pH 5.0, anaerobic growth of the mutant was undetectable and pH controlled fermentation started with air in the gas phase (O_2 -limiting condition) did allow growth of the mutant. However, as the O_2 became very limiting due to increase in cell density, growth stopped and the final cell yield of the pH 5.0 fermentation culture was only about ½ of the parent culture. In such an oxygen-limited fermentation, the *ldh* mutant produced very low

level of ethanol compared to the pH 7.0 fermentations. Most of the product of the pH 5.0 culture was 2,3-butanediol (Table 4; Fig. 1).

The comparatively low level of expression of *pflB* gene in pH 5.0 cultures and low level of formate in the O₂-limited fermentation (Tables 3, 4; Fig. 1) suggest that at pH 5.0, the *ldh* mutant is phenotypically LDH- and PFL- minus. It has been reported previously that an *ldh*, *pfl* double mutant of *E. coli* is anaerobic minus (15) and the same characteristics is also carried through to *B. coagulans*. Although the *ldh* mutant produced 2,3-butanediol as the major fermentation product at pH 5.0, it failed to grow anaerobically using this fermentation pathway. This is apparently due to redox imbalance since introduction of small amount of O₂ into the pH 5.0 fermentation did support production of higher level of 2,3-butanediol and associated growth. Since butanediol is a significant fermentation product of the *ldh* mutant even during growth at pH 7.0, a double mutant, strain QZ5, lacking both L-LDH and ALS was constructed.

***B. coagulans* Δldh $\Delta alsS$ double mutant**

The *ldh alsS* double mutant, strain QZ5, grew aerobically at both pH 5.0 and 7.0. Anaerobic growth of the double mutant in pH-controlled fermentations that started aerobically was detectable only at pH 7.0, a property, the double mutant shared with the parent, strain QZ4 (Fig. 2). The primary products of the pH 7.0 fermentation were ethanol, formate, pyruvate and acetate. Significant amount of pyruvate in the fermentation broth of pH 7.0 cultures of the double mutant indicates that the PDH and PFL combined could not match the rate of glucose conversion to pyruvate by glycolysis. Neither the single or the double mutant produced L(+)-lactic acid at detectable level.

Since the double mutant produced significant amount of formate and other products of PFL activity, a triple mutant lacking the PFL activity was constructed. However, this triple mutant lacking L-LDH, ALS and PFL activities failed to grow anaerobically under all conditions tested and was not used further.

Growth-based selection for D(-)-lactic acid production

The small amount of lactic acid produced by the double mutant was D(-)-lactic acid (Table 4). Increasing the level of D(-)-lactic acid production is expected to support anaerobic growth of the double mutant as the case with the wild type strain that can grow anaerobically with L(+)-lactic acid as the primary fermentation product. The *ldh* mutant strain did produce

higher level of *ldhA* mRNA compared to the wild type irrespective of the culture pH (Table 3). Very low level of PFL activity (based on formate production) (Table 4) and low level of expression of *pflB* (Table 3) during growth of the mutant strains at pH 5.0 suggest that culture pH plays a role in the control of PFL. To increase the anaerobic growth rate and cell yield in pH 5.0 fermentations due to an increase in expression of *ldhA* and/or activity of D-LDH over that of PFL, a growth-based selection was implemented. In contrast, a similar growth-based selection of the *ldh*, *alsS* double mutant at pH 7.0 that has higher level of PFL activity could lead to derivatives with elevated level of PFL and not D-LDH.

Anaerobic growth-dependent selection of strain QZ5 at pH 5.0 in LB + glucose fermentations yielded a derivative after about 120 days (Fig. 3). This strain, QZ13, produced higher cell yield than the starting strain QZ5 in pH 5.0 fermentations. Although the cell yield and glucose consumption of strain QZ13 and its starting parent, QZ5 were about the same in pH 7.0 fermentations, the D-lactic acid yield of strain QZ13 in pH 7.0 fermentations was about 10-fold higher than the lactic acid yield of strain QZ5 at the same fermentation pH (Table 4). The PDH/PFL contribution to the fermentation products also decreased to about 0.4 of the glucose consumed from 0.85 for strain QZ5.

The need to increase D-lactic acid yield with a concomitant reduction in PFL/PDH derived products in pH 7.0 fermentations of strain QZ13 led to further selection for higher growth and cell yield at pH 7.0 in LB + glucose fermentations. Strain QZ14 was derived after about 40 days of continual selection and enrichment at pH 7.0 (Fig. 4). Lactate yield of strain QZ14 was about 0.8 of the glucose fermented and the PFL/PDH contribution decreased to about 7% of the glucose derived products (Table 4). Strain QZ14 fermentation broth still contained detectable level of pyruvate, suggesting that the D-LDH level in the cell is not matching glucose flux through glycolysis. Next set of selections focused on increasing lactate titer to isolate a mutant derivative that effectively couples LDH activity to glycolytic flux of glucose. Strain QZ15 was isolated after an additional 60 days of sequential transfer and selection with increasing glucose concentration (Fig. 5). The D(-)-lactic acid titer of strain QZ15 in pH 7.0 fermentations of glucose was over 80 g/L. Continued evolution of strain QZ15 led to further increase in glucose flux to lactic acid reaching about 90 g/L in less than 48 hours of pH 7.0 fermentations (Strain QZ19; Table 4; Fig. 6). Formate was not detected in these derivatives with high lactic acid titer. The small amount of ethanol and acetate produced by these cultures is probably derived from PDH-produced acetyl-CoA (15).

These results show that by deletion of the *ldh* and *alsS* genes combined with anaerobic growth-based selection for appropriate mutations based on an understanding of the physiology of the organism at the pyruvate node can lead to alteration of the primary fermentation product of *B. coagulans* to D(-)-lactic acid from that of L(+)-lactic acid. Although the *pflAB* genes are still intact in the final derivative, increasing metabolic flux to D-lactate through D-LDH, essentially neutralized any pyruvate flux to acetyl-CoA through PFL. Further studies to identify the mutation(s) that led to elevated D-LDH activity in QZ19 have been conducted (the results of which have been published in an article entitled “Evolution of D-lactate dehydrogenase activity from glycerol dehydrogenase and its utility for D-lactate production from lignocellulose”, Wang *et al.*, *Proc. Natl. Acad. Sci., USA*, 2011, published online November 7, 2011; doi 10.1073/pnas.1111085108 and which is hereby incorporated by reference in its entirety).

Conclusion

Using a method developed for deleting a specific gene in the genetically recalcitrant *B. coagulans*, the *ldh* gene encoding L-LDH was deleted. The Δldh mutant failed to grow anaerobically at pH 5.0 while growth at pH 7.0 was not significantly affected. PFL, PDH and 2,3-butanediol pathway supported fermentative growth at pH 7.0. Deleting *ldh*, *alsS* and *pflB* eliminated anaerobic growth of the mutant although a gene encoding D-LDH (*ldhA*) is present in the chromosome. Based on an understanding of the physiological properties of *Bacillus coagulans* at various growth pH and the flow of carbon at the pyruvate node during anaerobic growth in this bacterium, a growth-based selection starting with an *ldh*, *alsS* double mutant yielded a mutant with enhanced ability to produce D-lactic acid to levels that are comparable to the L-lactic acid yield and titer of the wild type. Further increase in the rate of lactic acid production is expected to eliminate the small amount of co-products ethanol and acetic acid present in the fermentation broth. This is the first report of a thermophilic lactic acid bacterium in which the primary fermentation product has been changed from L(+)-lactic acid to D(-)-lactic acid using only the native genes of the bacterium (without foreign gene). This is based on selective mutations and evaluation of the physiology of the bacterium that led to appropriate additional strategies. Availability of thermotolerant *B. coagulans* strains that produce optically pure D(-)- or L(+)- lactic acid at 50-55 °C is expected to help reduce the cost of lactic acid as a feedstock for production of bio-based polylactide plastics of

varying thermochemical properties by minimizing potential contaminants that can lower the optical purity of lactic acid.

Table 1. Bacterial strains, plasmids and primers used in this study		
Strain	Relevant genotype	Source or Reference
P4-102B	Wild type	(26)
<i>E. coli</i> Top10		Invitrogen
<i>B. subtilis</i> HB1000		(11)
QZ3	P4-102B <i>ldh</i> ::pQZ44, Em ^R	This work
QZ4	QZ3 Δ <i>ldh</i>	This work
QZ5	QZ4 Δ <i>alsS</i>	This work
QZ13	QZ5 evolved at pH 5.0 for higher cell yield	This work
QZ14	QZ13 evolved at pH 7.0 for higher lactic acid titer	This work
QZ15	QZ14 evolved for higher sugar use	This work
QZ16	QZ15 selected for higher rate of glucose use and lactate production from CaCO ₃ medium	This work
QZ19	QZ16 further evolved for higher rate of lactate production.	This work
plasmid		
pGK12	Broad host-range, Cm ^R , Em ^R	(16)
pUC19	Plasmid vector Ap ^R	Lab stock
pQZ44	pGK12 with promoterless <i>ldh</i> (P4-102B) with 100 bp deletion	This work
pQZ 45	pUC19 with P4-102B <i>alsSD</i>	This work
pQZ45-1	pUC19 with 2,380 bp promoterless P4-102B <i>alsSD</i>	This work
pQZ54	pQZ45-1 with 596 bp <i>alsS</i> deletion with Em ^R gene insertion	This work
pQZ64	pGK12 with 506 bp <i>alsS</i> deletion with Em ^R gene insertion	This work

Table 2. Primers used	
Primer name	Sequence(5'-3')
Primer9	ccctacgtaTTGGAACGGGTGCAGTTGGT (SEQ ID NO: 4)
Primer10	cccgaattcCCGGGTGCTGGCAACAAGA (SEQ ID NO: 5)
Primer11	cccgaattcTTTGAGCGCCCAATTGGAA (SEQ ID NO: 6)
Primer12	cccaggectCCGGAACGCCAACGTACACA (SEQ ID NO: 7)
Primer17	ACGAGCCGCTGACACTGGAT (SEQ ID NO: 8)
Primer18	GCCGTCTTCGCCTTCGTTCA (SEQ ID NO: 9)
Primer19	TGAACCGAACCGCCTGCTGT (SEQ ID NO: 10)
Primer20	TCGCGCCAGACGATATGCAC (SEQ ID NO: 11)
Primer21	TGTCATAAGTCGCCGAACCG (SEQ ID NO: 12)
Primer22	TGATTGTATGCCGCCACGAA (SEQ ID NO: 13)
Primer23	GGTGTTCAGAAAGAGCTTGT (SEQ ID NO: 14)
Primer24	GTGCCGCAATCGGAATAATC (SEQ ID NO: 15)
Primer25	CATCAACGCCGCCGTTAATC (SEQ ID NO: 16)
Primer26	TCGTTCCGCTTCCTGAACAC (SEQ ID NO: 17)
Primer27	CCCGCCGCAAATCATTATCG (SEQ ID NO: 18)
Primer28	TAAAAGCACCCGCAAAGTT (SEQ ID NO: 19)
Primer29	AGATCTTAAGCCGTGTGGAG (SEQ ID NO: 20)
Primer 30	CGCAACAATACTGCCGATTC (SEQ ID NO: 21)
Primer 31	TCGCTTCGCTCGTCGTCTT (SEQ ID NO: 22)
Primer32	TCCCGCAAATCCCTTACCTG (SEQ ID NO: 23)
Primer33	TTGGAGGCGAACAAGAACA (SEQ ID NO: 24)
Primer 34	CGGCAATGGAAAAAGAAATG (SEQ ID NO: 25)

Capital letters represent *B. coagulans* sequence. Lower case letters indicate the restriction enzyme recognition sequence and 5'extensions for optimum cleavage of the amplified product by the respective enzyme.

Table 3. mRNA level of genes encoding enzymes at the pyruvate node in *B. coagulans* wild type and Δldh mutant, strain QZ4

Strain	Culture pH	OD 420 nm*	mRNA Level (ng/ml)**				Enzyme Activity†	
			<i>pdhA</i>	<i>ldh</i> ‡	<i>pflB</i>	<i>alsS</i>	<i>ldhA</i> ‡	PDH LDH
P4-102B (wild type)	5.0	1.0	2.73	61.92	0.02	0.08	0.12	0.4 14.0
	5.0	3.4	25.59	61.55	0.87	0.27	0.19	8.0 23.5
	7.0	1.0	2.59	55.11	0.09	0.14	0.22	3.8 29.9
	7.0	4.3	11.53	12.75	3.20	0.11	0.15	20.6 28.1
Mutant QZ4 (Δldh)	5.0	1.0	3.39	0.02	0.37	5.30	1.08	1.9 1.6
	5.0	2.0	2.76	0.001	0.57	1.32	1.95	6.3 2.2
	7.0	1.0	2.51	0.004	1.22	3.07	1.65	6.6 1.6
	7.0	7.0	33.41	0.21	2.67	5.62	0.88	3.1 2.5

* Represents the OD420 nm at the time of harvest. Cells were harvested from pH controlled fermentations (LB+glucose) during early to mid-exponential phase of growth (OD value of 1.0) and late-exponential phase of growth (the second OD value).

** Concentration of specific mRNA in the total isolated RNA.

† Enzyme activity was determined in crude extracts and expressed as $\mu\text{moles min}^{-1} \text{mg protein}^{-1}$.

‡ *ldh* and *ldhA* represent the genes encoding the L(+)- and D(-)- lactate dehydrogenases, respectively.

Table 4. Fermentation profiles of *B. coagulans* derivatives on the path to D(-)-lactic acid production at 50°C

Strain	Genotype	Culture pH	Growth (OD420 nm)	Glucose Consumed (mM)	Product (mM)						Yield		
					Lactate*		Pyruvate	Acetate	Succ	Formate	Ethanol	Lac	Total
					L(+)-	D(-)							
P4-102B	wild type	5.0	3.0	144.3	255.6	UD	UD	5.7	0.6	UD	10.5	0.90	1.00
		7.0	7.1	188.6	336.4	UD	UD	15.9	0.4	UD	4.6	0.89	0.96
QZ4**	Δ <i>ldh</i>	5.0	1.8	53.8	UD	1.0	UD	UD	1.0	6.5	20.3	0.01	0.21
		7.0	8.1	226.0	UD	9.7	UD	42.3	6.7	90.6	224.5	0.02	0.63
QZ5	Δ <i>ldh</i> Δ <i>alsD</i>	5.0	2.5	32.8	UD	9.8	4.5	4.6	0.1	25.3	25.6	0.15	0.72
		7.0	5.8	152.5	UD	12.8	10.1	95.4	2.1	154.6	164.5	0.04	0.94
QZ13	Continued selection	5.0	3.7	34.5	UD	20.9	20.9	2.5	0.4	15.9	18.8	0.30	0.92
		7.0	5.1	148.7	UD	139.9	15.8	45.2	3.2	90.0	80.7	0.50	1.00
QZ14	Continued selection	5.0											
		7.0	5.8	199.0	UD	335.3	11.4	5.7	0.5	44.0	39.0	0.80	0.99
		7.0†		265.7	UD	468.4	1.6	UD	1.3	21.5	28.4	0.88	0.93
QZ15	Continued selection	7.0† (68h)		562.6	UD	928.2	UD	22.6	8.1	UD	97.5	0.83	0.94
QZ19		7.0† (48h)		590.0	UD	993.0	UD	45.3	5.7	UD	84.2	0.84	0.96

All fermentations were in LB medium with glucose and the reported values were after 72 h, unless indicated otherwise.

* Values in parenthesis indicate that both isomers were present.

** Strain QZ4 also produced acetoin and 2,3-butanediol; pH 5.0 culture, 44.5 mM 2,3-butanediol; pH 7.0 culture, 31.6 mM acetoin and 93.1 mM 2,3-butanediol. These two products were not detected in the broths from other cultures.

† Due to the presence of CaCO₃ in the medium, the cell density of these cultures was not determined.

UD – undetectable
Succ, succinate; Lac, lactate

Table 5.		
Culture	Strain Designations	Deposit Date
QZ4	NRRL B-50438	November 4, 2010
QZ5	NRRL B-50439	November 4, 2010
QZ13	NRRL B-50440	November 4, 2010
QZ14	NRRL B-50441	November 4, 2010
QZ15	NRRL B-50442	November 4, 2010
QZ19	NRRL B-50443	November 4, 2010

REFERENCES

1. Abdel-Banat BMA, Hoshida H, Ano A, Nonklang S, Akada R (2010) High-temperature fermentation: how can processs for ethanol production at high temperatures become superior to the traditional process using mesophilic yeast? Appl Microbiol Biotechnol 85:861-867.
2. Beall DS, Ohta K, Ingram LO (1991) Parametric studies of ethanol production from xylose and other sugars by recombinant *Escherichia coli*. Biotechnol Bioeng 38:296-303.
3. Benninga H 1990. A history of lactic acid making. Kluyver Academic Publishers, Dordrecht, the Netherlands.
4. Boylan RJ, Mendelson NH, Brooks D, Young FE (1972) Regulation of the bacterial cell wall: analysis of a mutant of *Bacillus subtilis* defective in biosynthesis of teichoic acid. J Bacteriol 110:281-290.
5. Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal Biochem 72:248-254.
6. Carr FJ, Chill D, Maida N (2002) The lactic acid bacteria: A literature survey. Crit Rev Microbiol 28:281-370.
7. Datsenko KA, Wanner BL (2000) One-step inactivation of chromosomal genes in *Escherichia coli* K-12 using PCR products. Proc Natl Acad Sci U S A 97:6640-6645.
8. Datta R, Henry M (2006) Lactic acid: recent advances in products, processes and technologies - a review. J Chem Technol Biotechnol 81:1119-1129.
9. Davis RW, Botstein D, Roth JR 1980. Advanced Bacterial Genetics. Cold Spring Harbor Laboratory, Cold Spring Harbor, New York.
10. De Clerck E, Rodriguez-Diaz M, Forsyth G, Lebbe L, Logan NA, DeVos P (2004) Polyphasic characterization of *Bacillus coagulans* strains, illustrating heterogeneity within this species, and emended description of the species. System Appl Microbiol 27:50-60.
11. Fredrick K, Helmann JD (1996) FlgM is a primary regulator of sigmaD activity, and its absence restores motility to a *sinR* mutant. J Bacteriol 178:7010-7013.
12. Grabar TB, Zhou S, Shanmugam KT, Yomano LP, Ingram LO (2006) Methylglyoxal bypass identified as source of chiral contamination in L(+) and D(-)-lactate fermentations by recombinant *Escherichia coli*. Biotechnol Lett 28:1527-1535.
13. Hamilton CM, Aldea M, Washburn BK, Babitzke P, Kushner SR (1989) New method for generating deletions and gene replacements in *Escherichia coli*. J Bacteriol 171:4617-4622.
14. Hofvendahl K, Hans-Hagerdal B (2000) Factors affecting the fermentative lactic acid production from renewable resources. Enz Microb Technol 26:87-107.
15. Kim Y, Ingram LO, Shanmugam KT (2007) Construction of an *Escherichia coli* K-12 mutant for homoethanologenic fermentation of glucose or xylose without foreign genes. Appl Environ Microbiol 73:1766-1771.
16. Kim Y, Ingram LO, Shanmugam KT (2008) Dihydrolipoamide dehydrogenase mutation alters the NADH sensitivity of pyruvate dehydrogenase complex of *Escherichia coli* K-12. J Bacteriol 190:3851-3858.
17. Kok J, van der Vossen JM, Venema G (1984) Construction of plasmid cloning vectors for lactic streptococci which also replicate in *Bacillus subtilis* and *Escherichia coli*. Appl Environ Microbiol 48:726-731.

18. Kulkarni RK, Moore EG, Hegyeli AF, Leonard F (1971) Biodegradable poly(lactic acid) polymers. *J Biomed Mater Res* 5:169-181.
19. Lee JH, Patel P, Sankar P, Shanmugam KT (1985) Isolation and characterization of mutant strains of *Escherichia coli* altered in H₂ metabolism. *J Bacteriol* 162:344-352.
- 5 20. Lin Y, Hansen JN (1995) Characterization of a chimeric proU operon in a subtilin-producing mutant of *Bacillus subtilis* 168. *J Bacteriol* 177:6874-6880.
21. Luchansky JB, Muriana PM, Klaenhammer TR (1988) Application of electroporation for transfer of plasmid DNA to *Lactobacillus*, *Lactococcus*, *Leuconostoc*, *Listeria*, *Pediococcus*, *Bacillus*, *Staphylococcus*, *Enterococcus* and *Propionibacterium*. *Mol Microbiol* 2:637-646.
- 10 22. Matsumoto K, Taguchi S Enzymatic and whole-cell synthesis of lactate-containing polyesters: toward the complete biological production of polylactate. *Appl Microbiol Biotechnol* 85:921-932.
23. Mecking S (2004) Nature or petrochemistry?-biologically degradable materials. *Angew Chem Int Ed* 43:1078-1085.
- 15 24. Morimoto T, Kadoya R, Endo K, Tohata M, Sawada K, Liu S, Ozawa T, Kodama T, Kakeshita H, Kageyama Y, Manabe K, Kanaya S, Ara K, Ozaki K, Ogasawara N (2008) Enhanced recombinant protein productivity by genome reduction in *Bacillus subtilis*. *DNA Research* 15:73-81.
- 20 25. Okano K, Yoshida S, Yamada R, Tanaka T, Ogino C, Fukuda H, Kondo A (2009) Improved production of homo-D-lactic acid via xylose fermentation by introduction of xylose assimilation genes and redirection of the phosphoketolase pathway to the pentose phosphate pathway in L-Lactate dehydrogenase gene-deficient *Lactobacillus plantarum*. *Appl Environ Microbiol* 75:7858-7861.
- 25 26. Ou MS, Ingram LO, Shanmugam KT (2011) L: (+)-Lactic acid production from non-food carbohydrates by thermotolerant *Bacillus coagulans*. *J Ind Microbiol Biotechnol*. 38: 599-605..
27. Patel MA, Ou MS, Harbrucker R, Aldrich HC, Buszko ML, Ingram LO, Shanmugam KT (2006) Isolation and characterization of acid-tolerant, thermophilic bacteria for effective fermentation of biomass-derived sugars to lactic acid. *Appl Environ Microbiol* 72:3228-3235.
- 30 28. Payot T, Chemaly Z, Fick M (1999) Lactic acid production by *Bacillus coagulans* - Kinetic studies and optimization of culture medium for batch and continuous fermentations. *Enz Microb Technol* 24:191-199.
- 35 29. Rhee MS, Kim JW, Qian Y, Ingram LO, Shanmugam KT (2007) Development of plasmid vector and electroporation condition for gene transfer in sporogenic lactic acid bacterium, *Bacillus coagulans*. *Plasmid* 58:13-22.
30. Su Y, Rhee MS, Ingram LO, Shanmugam KT (2011) Physiological and fermentation properties of *Bacillus coagulans* and a mutant lacking fermentative lactate dehydrogenase activity. *J Ind Microbiol Biotechnol*.38:441-450..
- 40 31. Tanaka K, Komiyama A, Sonomoto K, Ishizaki A, Hall SJ, Stanbury PE (2002) Two different pathways for D-xylose metabolism and the effect of xylose concentration on the yield coefficient of L-lactate in mixed-acid fermentation by the lactic acid bacterium *Lactococcus lactis* IO-1. *Appl Microbiol Biotechnol* 60:160-167.
- 45 32. Underwood SA, Zhou S, Causey TB, Yomano LP, Shanmugam KT, Ingram LO (2002) Genetic changes to optimize carbon partitioning between ethanol and biosynthesis in ethanologenic *Escherichia coli*. *Appl Environ Microbiol* 68:6263-6272.

33. Visser J, Kester H, Jeyaseelan K, Topp R (1982) Pyruvate dehydrogenase complex from *Bacillus*. Methods Enzymol 89 Pt D:399-407.
34. Yanez R, Moldes AB, Alonso JL, Parajo JC (2003) Production of D(-)-lactic acid from cellulose by simultaneous saccharification and fermentation using *Lactobacillus coryniformis* subsp. *torquens*. Biotechnol Lett 25:1161-1164.
35. Yoshida A, Freese E (1975) Lactate dehydrogenase from *Bacillus subtilis*. Meth Enzymol 41:304-309.
36. Zhou S, Shanmugam KT, Ingram LO (2003) Functional replacement of the *Escherichia coli* D(-)-lactate dehydrogenase gene (*ldhA*) with the L-(+)-lactate dehydrogenase gene (*ldhL*) from *Pediococcus acidilactici*. Appl Environ Microbiol 69:2237-2244.

CLAIMS

We claim:

1. An isolated genetically modified bacterial cell comprising:
 - (i) inactivation or deletion of the L(+)-lactate dehydrogenase gene; and
 - (ii) inactivation or deletion of the acetolactate synthase gene.
2. The bacterial cell as in claim 1, further comprising inactivation or deletion in one more genes selected from a group consisting of the: pyruvate formate lyase gene, gene coding for pyruvate formate lyase activating enzyme, alpha-acetolactate decarboxylase gene, pyruvate dehydrogenase gene and alcohol dehydrogenase gene.
3. The bacterial cell according to claim 1, further comprising genetic modifications introducing exogenous genes into said bacterial cell.
4. The bacterial cell according to claim 1, wherein said genetic modification comprises the mutation of a gene encoding lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*) or the deletion of all or a portion of a gene encoding lactate dehydrogenase (*ldh*), pyruvate formate lyase (*pflB*), pyruvate formate lyase activating enzyme (*pflA*), alpha-acetolactate decarboxylase (*alsD*) and/or acetolactate synthase (*alsS*).
5. The bacterial cell according to claim 4, the mutation of said genes comprises the introduction of one or more point mutation(s) or the introduction of one or more stop codon in the open reading frame of the gene.
6. The bacterial cell according to claim 3, wherein said genetic modification comprises a point mutation or a deletion in the coding sequence of lactate dehydrogenase, pyruvate formate lyase and/or acetolactate synthase or insertion of an exogenous sequence into the coding region of lactate dehydrogenase, pyruvate formate lyase and/or acetolactate synthase.

7. The bacterial cell according to claim 1, wherein said bacterial cell does not contain exogenous genes or portions thereof.

8. The bacterial cell according to claim 1, wherein said bacterial cell enzymatic activity of lactate dehydrogenase, pyruvate formate lyase and/or acetolactate synthase is inactivated by homologous recombination, optionally using a plasmid sensitive to temperature.

9. The bacterial cell according to claim 8, wherein said genetic modification comprises complete or partial deletion of the gene encoding acetolactate synthase.

10. The bacterial cell according to claim 1, wherein said bacterium is a *Bacillus spp* or is a bacterium selected from the group consisting of *Bacillus coagulans*, *Bacillus licheniformis*, *Bacillus subtilis*, *Bacillus amyloliquifaciens*, *Bacillus pumilus*, *Bacillus circulans* or *Bacillus thiaminolyticus*.

11. A genetically modified bacterial cell according to claim 1, wherein said genetically modified bacterial cell is QZ4, QZ5, QZ13, QZ14, QZ15 or QZ19.

12. A method of producing D(-)- lactic acid comprising culturing a genetically modified bacterial cell according to in a medium comprising a carbon source under conditions that allow for the production of D(-)- lactic acid, wherein said genetically modified bacterial cell is selected from:

a) a genetically modified bacterial cell comprising (i) inactivation or deletion of L(+)-lactate dehydrogenase gene; and (ii) inactivation or deletion of acetolactate synthase gene; or

b) QZ4, QZ5, QZ13, QZ14, QZ15 or QZ19.

13. The method according to claim 12, further comprising isolating or purifying the D(-)- lactic acid.

14. The method according to claim 13, wherein said bacterial strain is cultured under anaerobic conditions.

15. The method according to claim 12, wherein said medium comprises between 2% and 20% (w/v) carbon source.

16. The method according to claim 12, wherein the carbon source is glucose, fructose, xylose, arbinose, galactose, mannose, rhamnose, sucrose, cellobiose, hemicelluloses, cellulose, glycerol or combination thereof.

17. The method according to claim 12, wherein said fermentation is conducted under anaerobic conditions at a pH of:

- a) about 5.0 to about 7.5; or
- b) about 7.0; or
- c) about 5.0.

18. The method according to claim 12, wherein said genetically modified bacterial cell produces at least 60g of lactic acid per liter of fermentation medium within 48 hours of the start of fermentation.

19. The method according to claim 12, wherein the pH of medium used to culture said genetically modified bacterial cell is maintained by the automatic addition of acid or base.

20. The method according to claim 12, wherein the method comprises culturing the bacterial cell at a temperature between about 30°C and about 65°C; between about 37°C and about 65°C; between about 37°C and about 55°C; between about 45°C and about 60°C; between about 45°C and about 50°C; or at a temperature of about 30°C; about 37°C; or about 55°C.