Generally, the disclosure~~invention~~ features methods that include using a microorganism and/or an enzyme that is immobilized on a substrate, e.g., fibers or particles, to convert a carbohydrate to a product.

In one embodiment~~aspect~~, the disclosure~~invention~~ features a method that includes using a microorganism that is immobilized on a substrate, e.g., inorganic or plastic particles or fibers, to convert a low molecular weight sugar, e.g., sucrose, glucose, xylose, or a mixture of any of these, to an intermediate or a product. In some cases, the substrate is functionalized with functional groups that the substrate does not have in its natural state.

In one aspect, there is provided a fermentation method comprising: (a) functionalizing inorganic fibers by irradiating the fibers with ionizing radiation and quenching the irradiated fibers; and (b) contacting a low molecular weight sugar with the functionalized inorganic fibers and a fermenting microorganism immobilized on the fibers, within a medium, for a period of time and under suitable fermentation conditions to convert the low molecular weight sugar to a fermentation product, whereby the immobilization occurs as a result of interaction between functional groups on the functionalized fibers and functional groups on the microorganism.

By "immobilized," it is meant that the microorganism or enzyme is bonded, directly or indirectly (e.g., through a chemical linker), to the substrate (e.g., particles or fibers) by covalent, hydrogen, ionic, or equivalent bonding, and/or by mechanical interaction, e.g., between the microorganism and pores of a fiber or particle. Bonding may be created, e.g., by electrically polarizing the substrate material. The interaction can be permanent, semi-permanent, or fleeting. Mechanical interaction may include the microorganism or enzyme nesting in or clinging to pores or other sites of a fiber or particle.

Some implementations include one or more of the following features.

Converting can include allowing the microorganism to convert at least a portion of the low molecular weight sugar to an alcohol, e.g., ethanol or butanol, or to a hydrocarbon or hydrogen. Converting may include fermentation. The microorganism may comprise a yeast, e.g., S. cerevisiae and/or P. stipitis, or a bacterium, e.g., Zymomonas mobilis. The method may further include irradiating the substrate, e.g., inorganic fibers, for example with ionizing radiation, such as a particle beam. The fibers or particles may have a BET surface area of greater than 0.25 m^2/g, and/or a porosity of at least 70%. In some cases the BET surface area may be greater than 10, 100, 250, 500, or even 1000 m^2/g. The method may further include reusing the substrate in a subsequent conversion process.

In another embodiment~~aspect~~, the disclosure~~invention~~ features a mixture that includes a substrate, e.g., a particulate material, having polar functional groups, a microorganism or enzyme having complementary functional groups, and a liquid medium. In some cases, the substrate comprises fibers, e.g., inorganic fibers or plastic fibers.

In a further embodiment~~aspect~~, the disclosure~~invention~~ features a composition comprising a substrate, e.g., fibers or particles, having functional groups, and a microorganism or enzyme having complementary functional groups, the microorganism or enzyme being immobilized on the substrate. When fibers are used the fibers may be, for example, inorganic fibers or plastic fibers.

The disclosure~~invention~~ also features a method that includes converting a low molecular weight sugar, or a material that includes a low molecular weight sugar, in a mixture with a substrate, a microorganism, and a solvent or a solvent system, e.g., water or a mixture of water and an organic solvent, to an intermediate or a product. Examples of solvents or solvent systems include water, hexane, hexadecane, glycerol, chloroform, toluene, ethyl acetate, petroleum ether, liquefied petroleum gas (LPG), ionic liquids and mixtures thereof. The solvent or solvent system can be in the form of a single phase or two or more phases. The substrate can be, e.g., in fibrous form. For example, the substrate may comprise inorganic fibers or synthetic fibers, e.g., plastic fibers.

In some instances, having a substrate (e.g., fibers treated by any method described herein or untreated) present during production of an intermediate or a product, such as ethanol, can enhance the production rate of the product. Without wishing to be bound by any particular theory, it is believed that having a solid present, such as a high surface area and/or high porosity solid, can increase reaction rates by increasing the effective concentration of solutes and providing a substrate on which reactions can occur.

For example, an irradiated or an un-irradiated fibrous material, e.g., inorganic materials such as carbon fibers or glass fibers, or synthetic polymeric materials such as plastic fibers, can be added to a fermentation process, such as a corn-ethanol fermentation or a sugarcane extract fermentation, to increase the rate of production by at least 10, 15, 20, 30, 40, 50, 75, or 100 percent, or more, e.g., at least 150 percent or even up to 1000 percent. The fibrous material can have a high surface area, high porosity, and/or low bulk density. In some embodiments, the fibrous material is present in the mixture at a concentration of from about 0.5 percent to about 50 percent by weight, such as between about 1 percent and about 25 percent by weight, or between about 2 percent and about 12.5 percent by weight. In other embodiments, the fibrous material is present in amounts greater than about 0.5 percent by weight, such as greater than about 1, 2, 3, 4, 5, 6, 7, 8,

some embodiments, irradiating includes applying two or more radiation sources, such as gamma rays and a beam of electrons.

In another embodimentaspect, the substrate is included in a saccharification process, in which the presence of the substrate can enhance the reaction rate and yield of low molecular weight sugar from a cellulose-containing feedstock. In this embodimentaspect, the disclosureinvention features a method comprising utilizing a saccharifying agent that is immobilized on particles to saccharify a cellulosic or lignocellulosic material. The saccharifying agent can be, for example, an enzyme.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. All publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

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

DESCRIPTION OF DRAWINGS

FIG. 1 is a block diagram illustrating treatment of fibers and the use of the treated fibers in a fermentation process. FIG. 1A is a schematic representation of a functionalized fiber interacting with a microorganism.

DETAILED DESCRIPTION

The substrate materials described herein, e.g., functionalized particulate materials, can facilitate conversion of low molecular weight sugar to an intermediate or a product, e.g., during a fermentation process. Functionalized substrate materials having desired types and amounts of functionality, such as carboxylic acid groups, enol groups, aldehyde