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Research review paper

Strategies for enhancing fermentative production of acetoin: A review

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ABSTRACT

Acetoin is a volatile compound widely used in foods, cigarettes, cosmetics, detergents, chemical synthesis, plant growth promoters and biological pest controls. It works largely as flavour and fragrance. Since some bacteria were found to be capable of vigorous acetoin biosynthesis from versatile renewable biomass, acetoin, like its reduced form 2,3-butanediol, was also classified as a promising bio-based platform chemical. In spite of several reviews on the biological production of 2,3-butanediol, little has concentrated on acetoin. The two analogous compounds are present in the same acetoin (or 2,3-butanediol) pathway, but their production processes including optimal strains, substrates, derivatives, process controls and product recovery methods are quite different. In this review, the usages of acetoin are reviewed firstly to demonstrate its importance. The biosynthesis pathway and molecular regulation mechanisms are then outlined to depict the principal network of functioning in typical species. A phylogenetic tree is constructed and the relationship between taxonomy and acetoin producing ability is revealed for the first time, which will serve as a useful guide for the screening of competitive acetoin producers. Genetic engineering, medium optimization, and process control are effective strategies to improve productivity as well. Currently, downstream processing is one of the main barriers in efficient and economical industrial acetoin fermentation. The future prospects of microbial acetoin production are discussed in light of the current progress, challenges, and trends in this field.

Contents

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1. Introduction

Acetoin (3-hydroxy-2-butanone or acetyl methyl carbinol) is a pale to yellowish liquid with a pleasant yogurt odour and a fatty creamy butter taste. It exists widely in nature and commercial acetoin is mainly used in foods as additives to enhance the flavour of the products. Acetoin can also be used in cosmetic products, soaps, detergents, lotions, and so on, to form a desirable fragrance profile with other flavouring compositions. As the simplest acyloin, acetoin has some unique characteristics and is widely used in chemical synthesis. Acetoin is a bioactive molecule and this makes it useful in agriculture as well.

Acetoin and 2,3-butanediol are neighbouring metabolites in the acetoin metabolic pathway in bacteria. Biological 2,3-butanediol production has been reviewed extensively (Celińska and Grajek, 2009; Garg and Jain, 1995; Ji et al., 2010a, 2011a; Magee and Kosaric, 1987; Syu, 2001). But rather surprisingly, few reviews have concentrated on acetoin although it is also a versatile compound and there are fast extending interests on its biological production. We have previously discussed the acetoin metabolism in bacteria (Xiao and Xu, 2007) focusing on its bacterial physiology and catabolism. To extend our knowledge on the topic, we hereby provide a comprehensive outline of biological acetoin production, with emphasis on how to improve bacterial acetoin fermentation.

1.1. Applications of acetoin

Categorized as flavour and fragrance agents, acetoin is a substance generally recognized as safe (GRAS) by JECFA (1998) and US FDA. With FEMA No. 2008, acetoin is used in foods as a common additive (Burdock, 2004; Morris, 2002). It is a flavour ingredient in formulations for strawberry, raspberry, vanilla, walnut, rum, butter, butterscotch, caramel, coconut, coffee and fruit flavours. Acetoin is usually added to baked goods, confection, frosting, candy, fats, oils, puddings, dairy, sweet sauce, beverages, etc. Acetoin has a moderate boiling point (148 °C at 1 atm) and this makes it advantageous among cigarette additives. As a neutral and non-ionic compound, acetoin also has good solubility and biocompatibility, which expands its uses into cosmetic products, soaps, detergents, lotions, etc.

In chemical synthesis, acetoin can be used as a precursor in composing a variety of useful products. As shown in Table 1, acetoin is particularly useful in the synthesis of heterocyclic compounds, in which 2,3,5,6-tetramethylpyrazine (TTMP) is a good representative of them. TTMP, a biologically active ingredient originally isolated from *Ligusticum wallichii*, a famous herb in Chinese herbology, is routinely medicated in China (Xiao et al., 2006). Actually pyrazines were found in a wide range of foodstuffs. All these alkyl pyrazines including TTMP are important in contributing special flavours with nutty, roasty, and toasty tonalities. In addition to pyrazines, acetoin can be used to produce other kinds of flavour and fragrance agents. Diacetyl, an acetoin analogue with a stronger buttery aroma, can be easily and efficiently produced by the oxidation of acetoin (Chen et al., 2007). Acetoin esters and glycosidically bound acetoin (Chyaua et al., 2003) were detected in different kinds of fruits and some of these compounds like acetate acetoin (3-oxobutan-2-yl acetate) are also commercially used.

Acetoin have stabilization effects on alkoxides and can act as a chelating agent. Acetoin itself and the imine derivatives of acetol and acetoin were found to show extraordinarily strong stabilizing effect for the alkoxide in the titanium alkoxide-based sol–gel process (Takahashi et al., 2000). Effects of hydroxyketones as chelate ligand on dip-coating of zirconia thin films were later investigated. The hydroxyketones, especially acetoin, were found to have stabilization effects on the alkoxides of Ti-IV, Nb-V, Ta-V, and Zr-IV (Ohya et al., 2002). The first example of an aluminium Cram-type chelate complex was derived from the reaction of Et3Al with acetoin (Lewiński et al., 1999). In the preparation of SBT (strontium bismuth tantalate) thin films (Frattini et al., 2006; Machado et al., 2008), acetoin showed

Table 1
The applications of acetoin.

Applications	Functions	References
Foods	Flavour enhancer	Burdock (2004)
Foods, cosmetic products, soaps, detergents, lotions	Flavour enhancer	Morris (2002)
Cigarettes	Flavour enhancer	Carmines, 2002; Coggins et al., 2011
Hair treatment composition	Dyeing keratinous fibres	Thiesen et al. (2012)
Laundry detergent	Flavour enhancer	Sivik (2002)
A particle useful in detergents, fabric softeners, and textile treatments	Flavour enhancer	Gonzalez et al. (2008)
Compositions effective in altering the perception of malodour	Flavour enhancer	Pinney (2007)
Research in yeast strain differentiation	Biomarker	Romano et al. (2003)
Research in the biological aging of sherry wines	Indicator	Cortes et al. (1999)
Research in the growth and metabolic disruption against Listeria monocytogenes	Indicator	Romick and Fleming (1998)
Anaerobic batch fermentation of xylose in recombinant *Saccharomyces cerevisiae*	External electron acceptor	Wahlbom and Hahn-Hägerdal (2002)
Synthesis of pyrazines	Precursor	Rizzi (1988)
Synthesis of 2,4,5-trisubstituted-1H-imidazoles	Precursor	Yu et al. (2007)
Fabrication of SBT thin films	Chelating agent	Frattini et al., 2006; Machado et al., 2008
Preparation of SBT precursor solutions	Chemical modifier	Stachiotti et al. (2005)
Fabrication of PZT powders and films	Chelating agent	Tahar et al. (2007)
Preparation of dibasic tridentate semi- and thiosemicarbazones	Precursor	Singh et al. (1993)
The kinetic study of the oxidation of monosaccharides with bromamide-T	Reactant	Kiviniemi et al. (1994)
Preparation of an aluminium Cram-type chelate complex	Reactant	Lewiński et al. (1999)
Synthesis of novel optically active α-hydroxyketone derivatives and liquid crystal composites	Precursor	Saito et al. (1992)
Preparation of amino nitriles	Precursor	Ohfune et al. (1996)
Synthesis of 4,5-dimethylimidazole	Precursor	D'Sa and Cohen (1991)
Preparation of diacetyl	Precursor	Chen et al. (2007)
Preparation of acetylbutanediol	Precursor	Xiao et al. (2009)
Enzymatic formation of 1-deoxy-d-*altro*-heptulose phosphate	Precursor	Yokota and Sasajima (1983)
Use in titanium alkoxide-based sol–gel process	Stabilizing effect	Takahashi et al. (2000)
Dip-coating of zirconia thin films	Chelate ligand	Ohya et al. (2002)
Fabrication of sol–gel ZnO thin films	Chemical modifier	Ohya et al. (2005)
Synthesis of NSO heterocyclic compounds	Precursor	Xi et al. (1999)
Attract-and-trap of fly	Insect attractant	Negishi et al. (2001)
Attract-and-kill of white-spotted flower chafer	Insect attractant	Chen and Li (2011)
Triggering induced systemic resistance and protect plants against certain pathogen infection	Plant growth promoter	Rudrappa et al., 2010; Ping and Boland, 2004
Contribution in controlling postharvest decay in citrus	Antifungal activity	Arrebola et al. (2010)