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Minireview

Q4 Biorefineries for the production of top building block chemicals and their derivatives

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ABSTRACT

Due to the growing concerns on the climate change and sustainability on petrochemical resources, U.S. DOE selected and announced the bio-based top 12 building blocks and discussed the needs for developing biorefinery technologies to replace the current petroleum based industry in 2004. Over the last 10 years after its announcement, many studies have been performed for the development of efficient technologies for the bio-based production of these chemicals and derivatives. Now, ten chemicals among these top 12 chemicals, excluding the aspartic acid and 3-hydroxybutyrolactone, have already been commercialized or are close to commercialization. In this paper, we review the current status of biorefinery development for the production of these platform chemicals and their derivatives. In addition, current technological advances on industrial strain development for the production of platform chemicals using micro-organisms will be covered in detail with case studies on succinic acid and 3-hydroxypropionic acid as examples.

1. Introduction

The development of technologies for establishing successful biorefineries has been actively pursued in order to substitute the current petrochemical technologies based on fossil resources. In 2004, the U.S. department of energy (U.S. DOE) selected top 12 platform chemicals that can be produced from biomass (Werpy et al., 2004) (Fig. 1). These chemicals can be produced *via* microbial fermentation or simple chemical process starting from sugars and can be further converted to other valuable or commodity products. After 6 years since its publication in the U.S. DOE report, an update was made, that selected a few novel bio-based platform chemicals based on the new criteria (Bozell and Petersen, 2010). The major difference in the updated 2010 report was that certain chemicals with lesser growth market were removed and new chemicals with high potential in industries were additionally selected (Bozell and Petersen, 2010). Since the first U.S. DOE report was published, a number of biorefinery processes have been commercialized or are getting close to commercialization.

The most important factor in commercialization of biorefinery process based on microbial fermentation is that the production process should be economically competitive with petroleum refinery process. Thus, it is important to maximize the performance of micro-organism with respect to the titer, productivity and yield of the desired product. In this paper, we review the current technological achievements and progress on the commercialization for the production of top value added building blocks and their derivatives. Also, the metabolic engineering strategies for developing high performance strains toward the commercialization of biorefinery process are reviewed using the case studies on microbial production of succinic and 3-hydroxypropionic acids.

2. Current systems for the production of top building block chemicals and their derivatives

2.1. Production of building blocks via biological route and their conversion to derivatives

2.1.1. Succinic acid

Succinic acid was selected as one of the top bio-based chemicals both in 2004 and 2010 reports. It is a four carbon (C4)

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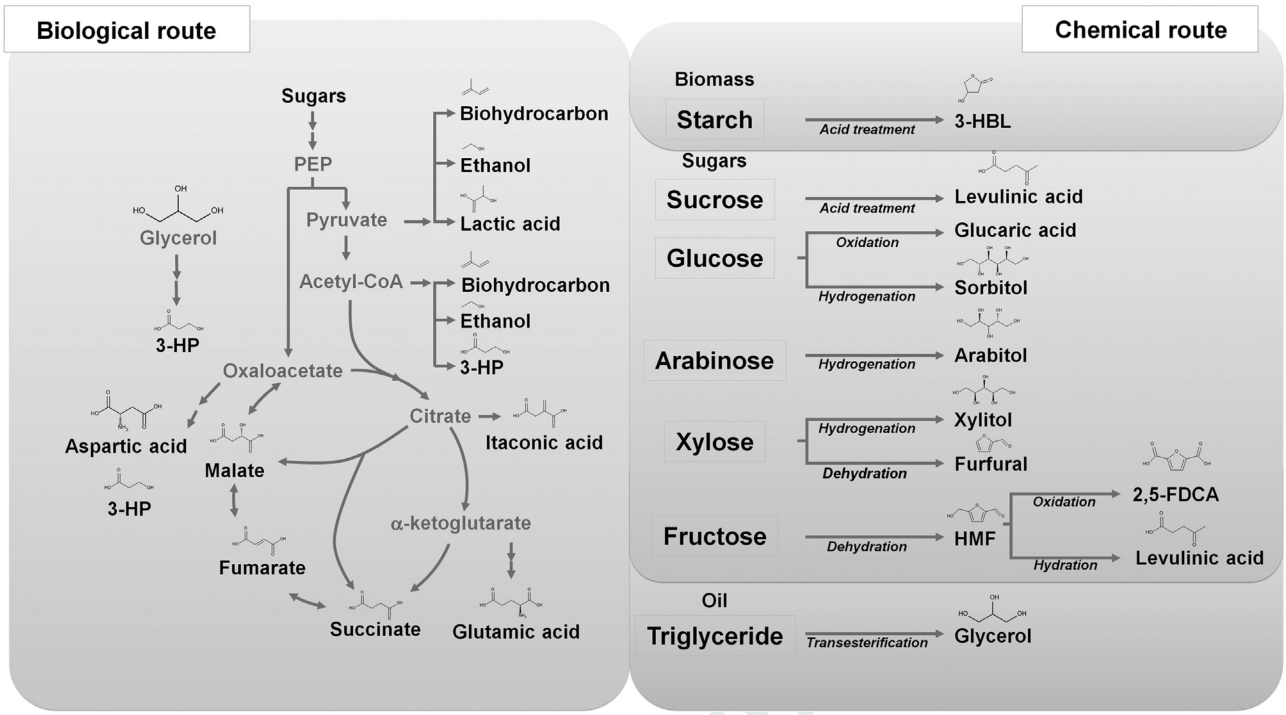

Fig. 1. Biological and chemical routes for the production of the 2004 US DOE's top 12 chemicals and the revised 2010 top 10 chemicals from biomass.

dicarboxylic acid and can be easily produced through microbial fermentation. As a platform chemical, it can be chemically converted to many other valuable chemicals such as 1,4-butanediol (1,4-BDO), gamma-butyrolactone (GBL), tetrahydrofuran (THF) and N-methylpyrrolidone (NMP) by simple chemical processes (Zeikus et al., 1999). The current market size for succinic acid itself is rather small at about 30,000–50,000 t per year (Jansen and van Gulik, 2014), mainly because many of the valuable succinic acid derivatives have been produced directly from petroleum-based chemicals without passing through the succinic acid route. However, as the technology for the bio-based production of succinic acid has improved, the use of succinic acid as a starting chemical is expected to increase to reach the market size of more than 700,000 t per year in 2020 (web citation number 1). Currently, four companies including Reverdia (joint venture of DSM and Roquette), Succinity (joint venture of BASF and Corbion Purac), Bioamber (joint venture of DNP Green Technology and ARD) and Myriant already have commercialized processes for the bio-based production of succinic acid. Also, works on the conversion of succinic acid to various derivatives have been performed by many companies (Table 1).

The processes for the production of succinic acid derivatives are shown in Fig. 2. Chemicals such as 1,4-BDO, GBL, THF, and pyrrolidones can be produced from succinic acid by direct hydrogenation (Cukalovic and Stevens, 2008; Werpy et al., 2004). Bioamber–Dupont and Myriant–Johnson Matthey Davy Technologies have been working on the direct chemical conversion of succinic acid to 1,4-BDO (Table 1). Although 1,4-BDO itself is a highly demanded commodity chemical for spandex and other applications, it can also be used as a good starting chemical for manufacturing derivative chemicals including THF and GBL (Cukalovic and Stevens, 2008). In this context, Genomatica has developed 1,4-BDO overproducing *Escherichia coli* strain through systems metabolic engineering strategies (Yim et al., 2011). In another example, Metabolix has developed a process for the production of the bio-based GBL *via* direct heating of fermentation broth containing cells that accumulated a large amount of poly(4-hydroxybutyrate) (Table 2).

Succinic acid also has a great potential to be used as a monomer for the production of several bio-based polymers. It can be used to produce polybutylene succinate (PBS) which has similar physical properties as polyethylene terephthalate (PET) (web citation number 1). Although current market size of PBS is rather low due to the high price and limited manufacturing, it will become competitive with PET in the future (web citation number 1). Several companies such as BioAmber–PTTMCC, BioAmber–Sinovec Biopolymers, Reverdia and Myriant–Showa Denko K.K. have been preparing the commercialization of the bio-based PBS production (Table 1). Additionally, succinic acid has been proposed as a replacement monomer for adipic acid in polyurethane and plasticizer production due to its similar structures and characteristics (web citation number 1).

Succinic acid can be converted to succinonitrile, which is a precursor for the production of 1,4-diaminobutane (putrescine), by reaction with ammonia (Fig. 2). Putrescine can be used as a monomer of polyamide including polyamide 4,6 and polyamide 4,10 (Fig. 2). DSM has commercialized the production of EcoPaXX, which is polyamide 4,10, using bio-based sebacic acid and petroleum-based putrescine (web citation number 2). A few years ago, microbial production of putrescine using metabolically engineered *E. coli* strain has been demonstrated (Qian et al., 2009), which suggests that polyamide 4,10 can be manufactured using 100% bio-based monomers.

2.1.2. *Ethanol*

Ethanol was not selected as one of the top 12 chemicals in 2004, due to its limited application in the fuel sector. However, it was recognized and selected as a promising platform chemical in the revisited platform chemical list in 2010. The current market size of ethanol is about 86 million tons per year, and most of it has been used as a fuel additive. Only 18% of bioethanol has been used for non-fuel applications (Harmsen et al., 2014). Ethanol can be converted to various derivatives *via* different chemical reactions (Fig. 2). First, dehydration of ethanol is used to make ethylene (Morschbacker, 2009). Ethylene has the largest market size over 100 million tons per year (Harmsen et al., 2014), and can be used