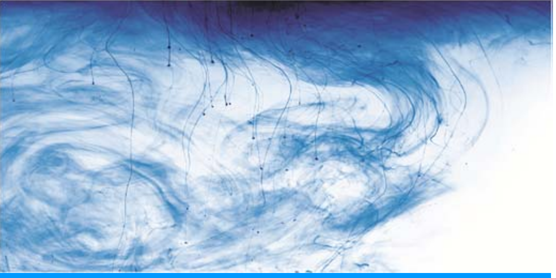

CHEMSYSTEMS
PERP PROGRAM

Biosuccinic Acid

PERP 2011S10

Report Abstract
May 2012

Nexant

Biosuccinic Acid

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INTRODUCTION

Renewed interest in succinic acid and in particular in a bio-based route can be ascribed to the fact that it can substitute maleic anhydride in the production of commodity chemicals such as 1,4-butanediol (BDO). BDO had an annual consumption of about one and half million tons in 2011; it is used as a solvent, in the production of other solvents (such as γ-butyrolactone and tetrahydrofuran), and in the production of plastics. Other uses for succinic acid include as an intermediate in the production of resins and plastics (such as polybutylene succinate), and specialty chemicals (pharmaceuticals, surfactants etc.)

Embryonic bio-based succinic acid technologies as commercially viable routes are attracting investment and partnership from the biggest players in the plastics industry; with several industrial scale projects being announced worldwide.

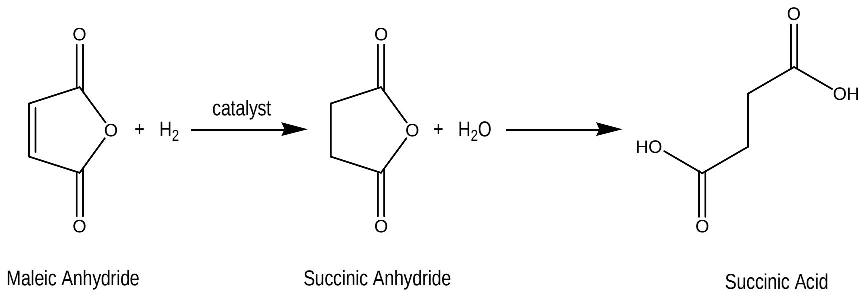
These emerging "green" technologies to produce succinic acid now claim to have a lower operating cost than the butane-based succinic acid route. This development has a very real potential to dramatically alter the maleic anhydride industry landscape.

The report also includes the following:

- An overview of the licensing technology and major producers status
- Strategic considerations for a new entrant to the biosuccinic acid business
- Comprehensive literature review with respect to fermentation pathways and microorganism engineering
- The process technologies being offered by the leading companies developing emerging (bio-based) routes are discussed; and an overview of the conventional (current) fossil fuel based route to succinic acid is given
- Process economics for the biosuccinic acid technologies offered by BASF/Purac, BioAmber, Myriant, Reverdia (DSM / Roquette) have been developed and compared to the process economics for the fossil fuel route (all on the same regional basis)
- An overview on what are the next developments for succinic acid including emerging competitive direct route to butanediol and alternative ethylene oxide to succinic acid route
- Process economics for plants being built in the next five years on a region specific basis (i.e., on the same region basis as where the plant is expected to be built)
- Commercial end-use applications, global and regional market (supply/demand) analysis

PETROCHEMICAL BASED ROUTE

The conventional route to succinic acid is via the hydration of succinic anhydride which is made on purpose from hydrogenation of maleic anhydride in the liquid phase (maleic anhydride itself is obtained from benzene or butane). The reaction takes place in presence of a heterogeneous catalyst (such as nickel or palladium complexes deposited on an inert carrier such as carbon). This route is still practiced in Japan by Showa Denko and Nippon Shokubai.



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A variation on this route to succinic acid is through hydration of maleic anhydride followed by hydrogenation of the resulting maleic acid.

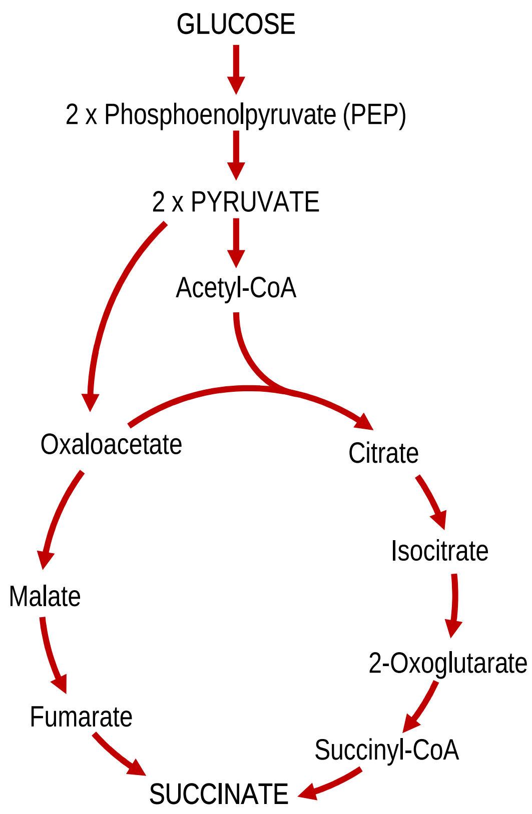
EMERGING BIOTECHNOLOGY PROCESSES

Bio-based succinic acid (biosuccinic acid) is made from fermentation of a carbon source such as a carbohydrate (e.g., glucose) followed by a recovery and purification step. In principle fermentation is a mature process, established for some time now in the production of ethanol, lactic acid, citric acid etc. Biosuccinic acid is more precisely described as being obtained via "mixed acid" fermentation of hexoses (C_6 sugar compounds) and/or pentose (C_5 sugar compounds) by engineered microorganisms acting as a biocatalyst.

As with any bio-route the success of biosuccinic acid lays in developing a process that will not only be more competitive than petroleum-based routes to succinic acid, but also to the derivatives thereof. As biosuccinic acid is produced along with a variety of undesired byproducts, a commercially viable process resides in engineering fermentative pathways to optimize succinic acid yield on substrate, titer and microorganism productivity (i.e., minimize such byproducts).

The key elements of a biosuccinic acid process are:

- An engineered microorganism capable of fermenting a carbon source (such as glucose) to succinate (succinate in this report refers to both acid and base conjugate forms of succinic acid in equilibrium)



- A reasonable feedstock cost and availability to compete with petroleum derived succinic acid and particularly its derivatives
- A recovery and purification section to obtain pure succinic acid crystals (pure meaning it meets downstream specification requirements for derivatives production)

Regardless of the precise microbe, the key steps are similar. Initial conditions are set and lead to the microbe consuming the carbon source it is fed for the purpose of reproduction. A well growth cell mass density is thus obtained. This cell culture is then usually transferred into a larger fermenter, where conditions are set and lead to the microbe fermenting the carbon source it is fed into the desired product. Further to the fermentation, the succinic acid is separated and recovered from the fermentation broth where it is present as a dissolved salt (succinate), along with the microorganism biomass, non-converted sugars, small quantity of byproducts, and other remains of the medium. Depending on the technology, recovery techniques will include various combinations of precipitation, distillation, liquid extraction, counter current extraction, esterification, crystallization, electrodialysis, ion-exchange resins, chromatography etc.

Specific process technologies being commercialized and discussed in the report include:

- **BASF/Purac** technology for its semi-commercial plant is expected to use an engineered bacterial *B. succiniciproducens* strain for succinic acid production from crude glycerol.

  BASF is a renowned and leading chemical producer. Purac is a starch derivatives manufacturer, a subsidiary of Dutch company CSM. BASF and Purac announced in 2009 their partnership in developing a route to biosuccinic acid. Recently the BASF/Purac association (joint venture under negotiation) has announced firm plans for a 25 000 tons per year plant to come on stream in Spain at Purac's site in 2013 (with intentions for a world scale 50 000 tons per year plant at a future unspecified date). Purac is already a leader in producing lactic acid and its derivatives from renewable feedstock having licensed Myriant's lactic acid technology and has partnered with several companies to develop other bioroutes.

BASF/Purac catalyst engineering, process technology and key distinguishing features are discussed.

- **BioAmber** technology for its semi-commercial plant will be using a yeast biocatalyst developed by Cargill (as opposed to an *E.coli* bacteria used previously in its 2 000 tons per year demonstration plant trials).

  BioAmber is the name of the joint venture (JV) between the U.S. company DNP Green Technology and French company Agro-Industries Recherches et Developpements (ARD) in 2008. In 2010, DNP Green Technology bought ARD's share in the venture to acquire 100 percent of the BioAmber JV.

  BioAmber have successfully demonstrated a biosuccinic acid process using a technology based on an *E.coli* species in 2010 at their 2 000 tons per year plant in Pomacle, France. An industrial scale 350 m^3 fermenter was employed. BioAmber is now building a semi-commercial scale plant of 17 000 tons per year using a yeast species. The plant is expected to come on-stream in 2013.

  BioAmber biocatalyst (*E.coli*) engineering, process technology and key distinguishing features are discussed

- **Mitsubishi/ Ajinomoto** technology under development is believed to be using an engineered *B. flavum* or *C. corynebacterium* bacterial strain for succinic acid production from glucose.

  Ajinomoto is a leader in the food industry with its food seasoning products. It is also a leader in the amino-acid business, where its products are used in the agro, cosmetic and pharmaceutical industry. Mitsubishi Chemical is a major petrochemical producer which produces, notably 1,4-butanediol (BDO) from conventional petrochemical-derived feedstock.

  Ajinomoto has been developing biosuccinic acid jointly with Mitsubishi and producing succinic acid from renewable materials since 2006 with a process based on existing fermentation routes used in the amino-acid business.

  Mitsubishi/Ajinomoto biocatalyst engineering, process technology and key distinguishing features are discussed

- **Myriant** technology for its semi-commercial plant will be using an engineered *E. coli* bacterial strain for succinic acid production from glucose.

Myriant Technologies (Myriant) is a private company which focuses on biotechnology development. They have successfully developed and commercialized D-Lactic acid technology from renewable feedstock; a plant has been operating since June 2008. The route to succinic acid is based on the lactic acid process. Myriant was granted a $50 million grant and more recently obtained a $25 million loan guarantee from the USDA (U.S. Department of Agriculture) to help the funding of their forthcoming 13 600 tons per year semi-commercial plant in Lake Providence, LA. (USA). This plant is under construction and expected to be fully operational in the first quarter of 2013.

Myriant biocatalyst engineering, process technology and key distinguishing features are discussed

- **Reverdia** technology for its semi-commercial plant will be using a proprietary yeast-based fermentation process.

  Further to their successful cooperation in developing their own fermentation route to succinic acid, Dutch chemical company DSM and French Starch giant Roquette Freres have agreed to form the joint venture Reverdia to commercialize succinic acid and derivatives. DSM has businesses ranging from vitamins to performance polymers while Roquette is the world largest producer of polyols and operates world-scale biorefineries in Europe, North America, and in Asia. In Lestrem, France, Roquette operates one of the largest biorefineries, which processes over 3 000 tons per day of corn and nearly 4 000 tons per day of wheat as well as starch rich potatoes and varieties of peas from which specialty proteins are derived.

  Reverdia has successfully piloted its technology at Roquette's 300 tons per year plant in Lestrem, operating since 2010. Reverdia has branded its succinic acid "Biosuccinium™" and is in the process of building a semi-commercial 10 000 tons per year plant in Italy, that is expected to come on-stream in late 2012.

  Reverdia's biocatalyst engineering, process technology and key distinguishing features are discussed

ALTERNATIVE AND COMPETING PROCESS ROUTES IN DEVELOPMENT

The fermentation route to succinic acid discussed in the previous sections is considered by Nexant as an emerging technology having been proven at demonstration scale and within a year several semi-commercial scale plants are expected to come on stream. In this section, Nexant briefly discusses an alternative developing process being developed by Novomer. In addition, Nexant briefly discusses the direct fermentation route to 1,4-butanediol (BDO) as this is considered a competing developing technology to the fermentation based routes to succinic acid, since BDO is the largest downstream market for succinic acid.

PROCESS ECONOMICS

In this section, Nexant has developed key mass input/output considerations and costs of production estimates for different semi-commercial bioprocesses expected to come on-stream in the next one year:

- Fermentation of crude glycerol with *B. succiniciproducens* as characterized by BASF/Purac process
- Fermentation of D-glucose (dextrose syrup) with *E.coli* as characterized by BioAmber's process
- Fermentation of D-glucose (dextrose syrup) with yeast as characterized by BioAmber's process
- Fermentation of D-glucose (dextrose syrup) with *E. coli* as characterized by Myriant's process
- Fermentation of D-glucose (dextrose syrup) with *S. cerevisiae* as characterized by Reverdia' process

These are compared to the cost of production developed for the petrochemical route to succinic acid:

- Hydrogenation of maleic anhydride followed by hydration as characterized by the conventional process

The above cost estimates highlight the different process performances on a same location basis (U.S. Midwest), having the same raw materials, utility and labor pricing basis.

To reflect on the forthcoming installed commercial scale competitiveness, Nexant has also developed and compared the economics of production for the main global capacity additions planned in the next five years. The forecast costs of production estimates evaluated are outlined below:

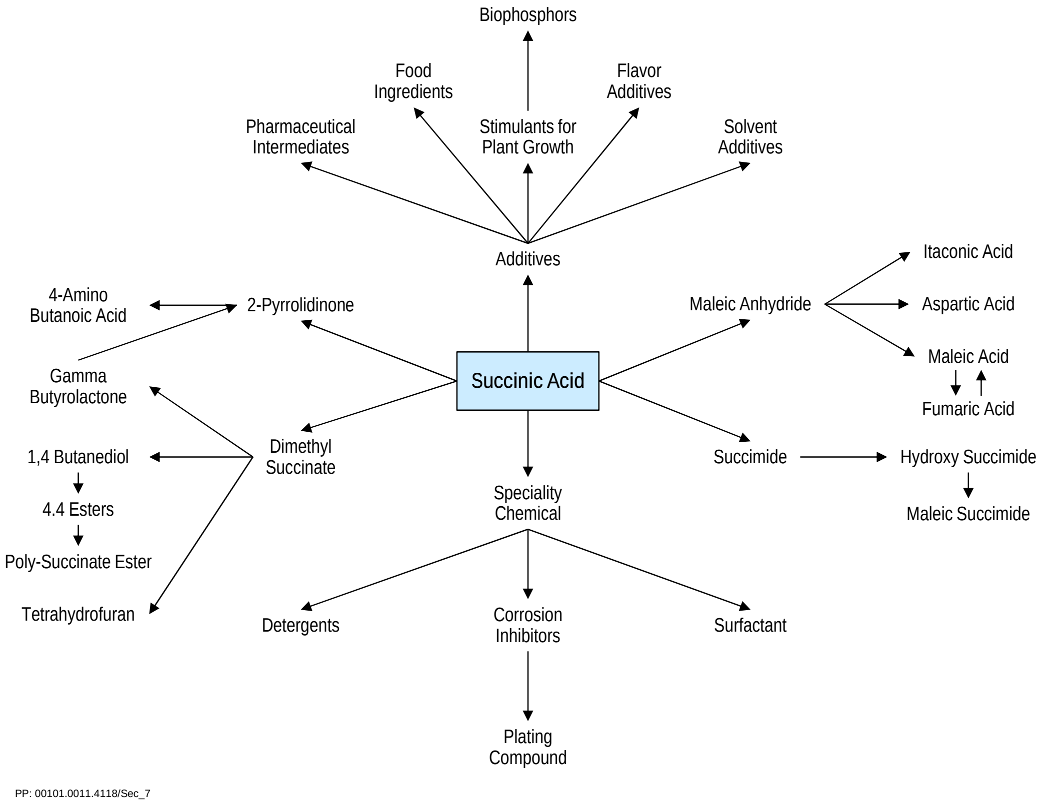
- BioAmber (yeast) 34 000 tons per year process in Canada
- Myriant (*E.coli*) 77 000 tons per year process in U.S. Midwest
- Reverdia (yeast) 30 000 tons per year process in Italy
- BASF-Purac (*B. succiniciproducens*) 50 000 tons per year process in Spain
- BioAmber (yeast) 65 000 tons per year process in Thailand

All cost tables given in this report include a breakdown of the cost of production in terms of raw materials, utilities, and direct and allocated fixed costs. These categories are presented annually by unit consumption and per metric ton. The contribution of depreciation is also included to arrive at a cost estimate.

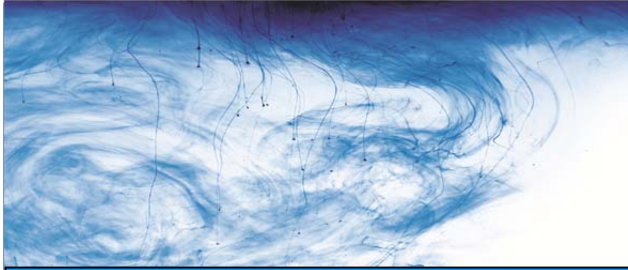
COMMERCIAL MARKET REVIEW

"Traditional" succinic acid applications include coatings & pigments, the metal industry, pharmaceuticals (as an additive in formulation, in the production of medicines), the food industry (as a sweetener/flavoring agent), the photographic industry and the agriculture.

However, biosuccinic acid is the precursor to a wide range of biomass derived biopolymers. In addition to BDO-based polyesters and urethanes, novel polyamides form part of the polymer product family – many more new possibilities exists.



- Commercial applications and emerging end-uses are outlined in the report
- Global demand, supply, and net trade data are provided and discussed including a listing of specific plant capacities in North America, Western Europe and Asia Pacific



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