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A systems perspective on chemical production from mixed food waste: The case of bio-succinate in Sweden

Emma Rex[a,*], Erica Rosander[b], Frida Røyne[a], Andres Veide[b], Johanna Ulmanen[a]

[a] RISE Research Institutes of Sweden, Division of Energy and Circular Economy, Eklandagatan 86, SE-412 61 Gothenburg, Sweden
[b] KTH Royal Institute of Technology, School of Biotechnology, Division of Industrial Biotechnology, AlbaNova University Center, SE-106 91 Stockholm, Sweden

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ABSTRACT

The option of producing the chemical succinic acid from bio-based resources is well in line with current political and industrial ambitions for a bio-based economy. A little explored but intriguing biomass feedstock opportunity is food waste. Mixed food waste is especially appealing as it represents less resource competition than more homogenous food waste fractions. The feasibility of producing succinic acid from mixed food waste depends on both technical and societal system structures. Therefore, to assess the production prospect, it is important to investigate all relevant system components. This study explores from such multiple perspectives the feasibility of chemical production as a viable added pathway for mixed food waste, using microbial production of succinic acid from municipal solid waste in Sweden as an example. The perspectives explored are: 1) feedstock feasibility, 2) societal drivers and barriers for technology progress, and 3) resource availability. Findings show that even though, from a technical feasibility and resource availability perspective, production seems possible, it lacks institutional support and actor commitment and alignment for development in Sweden. Findings also show that a holistic and interdisciplinary systems perspective contributes valuable insight when assessing prospects for bio-based chemicals.

1. Introduction

The European Commission (2016a) has identified food waste as a resource opportunity for the bio-economy; that is for the substitution of fossil with biomass resources for the sustainable production of a range of products (BECOTEPS, 2011). As the use of food crops for non-food applications has been questioned, for example, due to negative effects on food security (Pimentel and Burgess, 2014; To and Grafton, 2015), food waste represents a promising alternative. In line with bio-economy ambitions, food waste is gaining increasing interest among researchers in chemistry and biotechnology as a feedstock for various kinds of fuels, chemicals, and materials (Lin et al., 2013; Sanchez-Vazquez et al., 2013; Begum et al., 2016). Even though the demand for biofuel is increasing, stand-alone biofuel production is often an economic challenge, as fuel is a low-value product in economic terms (Bozell and Petersen, 2010). Co-production with chemicals can generate a necessary added economic value (International Energy Agency, 2013). The biotechnical feasibility of producing high-value chemicals from food waste has been demonstrated by several researchers (Sakai et al., 2004; Huang et al., 2015; Liu et al., 2016) and even on the pilot plant stage (Wageningen UR, 2016).

An example of a platform chemical that can be made from food waste is succinic acid (SA) (Leung et al., 2012; Zhang et al., 2013; Sun et al., 2014). SA is a water-soluble crystal, traditionally made from fossil resources, that is used as a chemical intermediate in a high number of chemicals and products: medicine, the manufacture of lacquers, perfume, and as a sequestrant, buffer, and neutralizing agent in food (Lewis, 2007). It can also be used as an intermediate for producing bio-degradable polymers (NOVA Institute, 2015b). This convertibility makes SA a high-value platform chemical, and, as a result, the US Department of Energy has selected bio-based SA (i.e. SA produced from biomass) as one of the top bio-based chemicals from a market perspective (US Department of Energy, 2004). Bio-based SA is already produced commercially by several companies (Choi et al., 2015), often through the biotechnological fermentation of refined sugars or starch from cultivated crops (e.g. corn).

The production of chemicals from food waste has, so far, primarily involved specified industrial waste streams from well-defined sources. Examples of applications include the production of ethanol from leftover bread (Leung et al., 2012), SA from waste coffee grounds (ACS, 2012), and the conversion of citrus residues into feed, essential oils, and biofuels (Lin et al., 2013). Compared to such “pure” industrial waste

* Corresponding author.
E-mail address: emma.rex@ri.se (E. Rex).

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streams that often have the benefit of being relatively homogenous and uncontaminated, mixed food waste is much less explored. Sanchez-Vazquez et al. (2013) have concluded that it is the waste from agriculture, postharvest, processing, and distribution that is sufficiently uncontaminated that can be used in secondary processes, such as polymer production, while consumer waste generally can be assumed to be too contaminated for secondary processes other than anaerobic digestion. Yet there are many advantages if more complex waste streams are used. Biomass does not exist in absolute abundance (Scarlat et al., 2015), and, in a growing bio-economy, there are many potential applications for different biomass sources. Food waste is generated in all parts of the food value chain; from primary production through food industry, to retail and distribution, restaurants, catering, and households. The nearer the consumer, the more heterogeneous, variable, contaminated, impure, and degraded waste streams often are, however, these waste streams compete less with other purposes. Therefore, from a resource point of view, it is appealing to explore the opportunities of utilizing the heterogeneous food waste fractions close to the consumer: mixed food waste (MFW). If the MFW that today largely goes to composting or biogas were used for bio-based chemicals and material production, this would mean advancement to a higher level in the bio-economy's value pyramid (Betaprocess, 2012; BioBased Economy, n.d.).

Several different production routes for bio-based SA exist, mainly based on cultivation through the use of microbial strains (see e.g. Song and Lee, 2006). The conversion of food waste to chemicals through microbial cultivation has the benefit of exploiting the inherent chemical complexity of the waste, which is lost in the conversion to biogas or if the waste is composted (Lin et al., 2013). Extensive research has been performed on developing a microbial production of bio-based SA (Ahn et al., 2016), and great technical progress on suitable micro-organisms, culture conditions, and integrated production has been made in recent decades (Cheng et al., 2012). Although mainly focused on defined nutrient media, a few examples also exist where the technical feasibility of MFW SA production has been explored and deemed to have intriguing potential (Sun et al., 2014).

In parallel to feedstock availability and feasibility, the importance of wider system challenges related to political ambitions, actors, and markets is often highlighted in relation to the realization of bio-economy and green chemistry and materials (see e.g. European Commission, 2014; Swedish Energy Agency, 2014; SAT-BBE, 2016). For bio-based SA, extensive attention has been paid to finding economically viable production routes (Cao et al., 2013; Ahn et al., 2016). However, from a sustainability transition studies perspective, actors' willingness and capacity to act and collaborate as well as policies, norms, and values in society are also critical for the success or failure of the development and market diffusion of a novel and potentially sustainable technology (Bergek et al., 2008; Grin et al., 2010; Markard et al., 2012). Yet, in waste reduction and resource management, an end-of-pipe approach focusing on treatment processes of an already existing waste still dominates, which often fails to recognize many of the challenges throughout the production and consumption system (Singh, 2016).

This article reports on multiple perspectives involved in the exploration of chemical production as a viable added pathway for MFW, including both the feasibility and availability of the feedstock, and societal drivers and barriers. This was done by means of a case study of the microbial production of SA using an organic fraction of municipal solid waste in Sweden as the feedstock. Insights from the study serve as a starting point for the discussion of methods and aspects to consider when analyzing the prospects of using MFW for the production of chemicals and related materials more broadly.

2. Methodology

This section introduces the case study, the systems perspectives with which the case is analyzed, and the main data sources used.

2.1. Case study of succinic acid from mixed food waste in Sweden

The case study involved microbial growth on MFW derived from municipal solid waste to produce bio-based SA in Sweden. This is a tentative production route in which the organic fraction of municipal solid waste is used as a nutrient source for the cultivation of bacterial strains of the species *Escherichia coli* to produce SA for further polymerization to various products. Municipal solid waste was received from the waste management company Ragn-Sells AB, a full-scale facility that collects waste from the municipality of Stockholm, Sweden. The company collects non-source sorted household waste together with leftover food from grocery stores. Thus, the MFW referred to in this study is of a more complex character than the MFW mostly used in the literature (more defined waste from cafeterias, restaurants, and source-sorted households).

A production system, using an engineered *E. coli* strain as the host was chosen as the model process. *E. coli* has the advantage over other production strains as the bacterium is able to grow on a minimal salt medium only supplemented with a single nitrogen source. Also, *E. coli* has a high maximum theoretical yield, determined with metabolic flux analysis, of SA (1.67 mol/mol of glucose) compared to other organisms (Hong et al., 2003).

The case study was selected by participating academic and industry partners in a multidisciplinary research project exploring how MFW, combined with advanced knowledge on biotechnology, can be turned into bio-based chemical and related products with higher value than biogas and potentially complement the current biogas production process (FORMAS 211-2012-70). Bio-based SA production using modified *E. coli* strains was chosen for the case study, from among many potentially high-value chemical processes, due to its maturity.

A specific country was selected for the study: Sweden. Sweden represents an intriguing potential for chemical production from MFW; the country has had a landfill ban on organic waste since 2005 (European Environmental Agency, 2013), and a well-developed infrastructure for the biological valorization of food waste. Today, most of this waste goes to anaerobic digestion to produce biogas (Avfall Sverige, 2016a). Sweden also has a chemical industry with a variety of actors along the value chain (Mossberg, 2013). Furthermore, Sweden has a high share of renewable energy consumption compared to other European member states (European Commission, 2009). This is also true for the Swedish transport sector, whose share of renewables is dominated by biofuels (Swedish Energy Agency, 2015; Eurostat, 2016). Nevertheless, Swedish substitution of fossil resources with biomass in the chemicals and materials industry remains in its infancy.

Bio-based SA is expected to substitute fossil succinate and other fossil building blocks in existing chemical conversion routes and product applications. This implies that the main changes in the value chain of SA will be in the beginning of the process. Consequently, this case study focuses on the possibility of using MFW as feedstock for SA production. It centers on feedstock availability and feasibility along with premises for market implementation. The study does not assess specific production technologies, nor does it assess economic feasibility or the possibility of co-production with other products.

2.2. Assessment approach

The multidisciplinary FORMAS research project referred to above involves a number of perspectives which together constitute the systems approach of this study: 1) feedstock feasibility, 2) societal drivers and barriers for technology progress, and 3) resource availability.

Feedstock feasibility was evaluated based on growth requirements for a generic *E. coli* cell, laboratory tests, and input from the waste industry. Focus was on using MFW as a feedstock for bio-based SA production, not the biotechnical conversion from nutrient media to SA. Feedstock feasibility was explored using literature studies and laboratory tests as shown in Table 1. The laboratory tests included analyses of