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Techno-economic feasibility of waste biorefinery: Using slaughtering waste streams as starting material for biopolyester production

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ABSTRACT

The utilization of industrial waste streams as input materials for bio-mediated production processes constitutes a current R&D objective not only to reduce process costs at the input side but in parallel, to minimize hazardous environmental emissions. In this context, the EU-funded project ANIMPOL elaborated a process for the production of polyhydroxyalkanoate (PHA) biopolymers starting from diverse waste streams of the animal processing industry. This article provides a detailed economic analysis of PHA production from this waste biorefinery concept, encompassing the utilization of low-quality biodiesel, offal material and meat and bone meal (MBM). Techno-economic analysis reveals that PHA production cost varies from 1.41 €/kg to 1.64 €/kg when considering offal on the one hand as waste, or, on the other hand, accounting its market price, while calculating with fixed costs for the co-products biodiesel (0.97 €/L) and MBM (350 €/t), respectively. The effect of fluctuating market prices for offal materials, biodiesel, and MBM on the final PHA production cost as well as the investment payback time have been evaluated. Depending on the current market situation, the calculated investment payback time varies from 3.25 to 4.5 years.

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1. Introduction

Materials with plastic-like properties facilitate our daily life and are, among various other beneficial applications, indispensable for secure storage and distribution of food and various other goods. Because of our increasing need for such plastics, an annual quantity already exceeding 300 Mt of synthetic polymers is produced globally (Koller et al., 2010a,b; Koller et al., 2012). From the

chemical point of view, these anthropogenically designed polymers are, in most cases, characterized by their full carbon backbones; hence, they display structures that are not found in nature. Consequently, they are highly recalcitrant towards natural degradation, making them stable and long-lasting. This calls for end-of-life-strategies like recycling, pyrolysis, incineration, or disposal in landfills. In addition, the lions share of these polymers is based on the chemical conversion of limited fossil resources. Provoked by environmental concerns caused by convenient established strategies like disposal or incineration of spent plastics, and due to the predictable depletion of fossil resources, we nowadays witness tremendously emerging activities to develop biopolymers as sustainable, biodegradable alternatives based on renewable resources (Koller et al., 2013a; Tan et al., 2014).

Polyhydroxyalkanoates (PHAs) are one of the classes of biopolymers currently attracting the interest of both academia and industrial sectors involved in polymer production and processing. As microbial reserve materials, PHAs are accumulated as intracellular

Abbreviations: BOD, Biological Oxygen Demand; BSE, Bovine Spongiform Encephalopathy; CA, Casamino acid; CGP, Crude glycerol phase; DM, Dry matter; FM, Fermentation media; HQ, High quality; LQ, Low quality; MBM, Meat and bone meal; mf, Microfiltration; oDM, Organic dry matter; P.E., Population Equivalent; PHA, Polyhydroxyalkanoate; PHB, Poly(3-hydroxybutyrate); SFAE, Saturated fatty acid esters; SJ, Silage juice; SPI, Sustainable process index; TME, Tallow methyl ester; TSE, Transmissible spongiform encephalopathy; uf, Ultrafiltration; WWTP, Wastewater treatment plant.

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carbon and energy storage compounds by a variety of prokaryotic species under similar nutritional stress conditions which provoke accumulation of other reserve compounds such as, e.g., glycogen, volutin, and others. Organized as so-called “carbonosomes”, PHAs do not only constitute simple inert inclusion bodies, but can be considered as complex, smart granules consisting of a polyester core body surrounded by a highly functional enzymatic neighborhood (Jendrossek and Pfeiffer, 2014; Mravec et al., 2016; Vadlja et al., 2016). In analogy to the scientific fields of genomics, proteomics and metabolomics, the complex area of PHA-biosynthesis, structure, and degradation was recently addressed to as the field of “PHAomics” by leading scholars in this field (Chen and Hajnal, 2015).

After recovery from microbial biomass, PHAs fascinate due to their manifold plastic-like properties, which make them easy to process. These materials resemble, depending on their compositions on the monomeric level, thermoplasts, elastomers, or latex-like resins. In contrast to classical petrol-based “full carbon backbone” plastics, PHAs are “biobased”, “biosynthesized”, “compostable”, “biodegradable”, and “biocompatible”, hence, they can in fairness be classified as “green plastics”. Their composition and, as a consequence, exact material properties are pre-defined *in statu nascendi* during biosynthesis under controlled environmental conditions in discontinuously, semi-continuously or, to an increasing extend, continuously operated bioreactors (reviewed by Chen, 2010; Koller et al., 2013b; Koller and Muhr, 2014; Kaur and Roy, 2015).

PHAs and PHA-based composites and blends display new basic materials to manufacture, e.g., compostable packaging for food and other goods (Koller, 2014), devices for medical and surgical purposes (Francis et al., 2016; Luef et al., 2015; Zinn et al., 2001), tissue- and cell repair (Ching et al., 2016; Rai et al., 2016), drug delivery matrices (Luef et al., 2015; Nigmatullin et al., 2015; Zinn et al., 2001), nano-scale carriers (Khosravi-Darani and Bucci, 2015), or electronic components (Koller et al., 2013b). According to the customers' demands, parameters like density, crystallinity, elasticity, or biodegradability can be fine-tuned *in statu nascendi* by developing optimized biotechnological production protocols, identifying adequate compatible blending materials and (nano)-fillers, and post-synthetic modification and functionalization (Gao et al., 2011; Khosravi-Darani and Bucci, 2015).

Scientists involved in PHA-related R&D endeavors are profoundly challenged not only by the fact that PHAs must meet the benchmark of established plastics in terms of material performance, but, as the major economic issue, also production costs have to be taken into account. As comprehensively described in the related literature of the last decades, the predominant part of the entire PHA production costs is allotted to the carbon-rich raw materials needed to generate a desired concentration of active microbial biomass and, after switching to nutritionally stressed conditions, to boost the biosynthesis of PHA as secondary product of the microbial metabolism. Up to now, PHA production resorts to costly raw materials like carbohydrates of dietary significance (sucrose, glucose, fructose, or starch) or edible vegetable oils, hence, to such materials better to be used for securing human nutrition (reviews by Koller et al., 2010a; Koller et al., 2017; Obruca et al., 2015; Tan et al., 2014).

PHA produced from such nutritionally relevant carbon substrates can, in analogy to biofuels based on sucrose or rapeseed oil, be classified as “1st generation PHA”. Replacing such feedstocks by carbon-rich surplus streams from industrial branches related to agriculture, pulp- and paper industry, etc. (“2nd generation PHA”), firstly alleviates disposal problems, secondly preserves food resources, and, in parallel, reduces costs for PHA production (Koller et al., 2017). The availability of such feedstocks defines

the location of a new PHA production facility; PHA production facilities (bioreactors and equipment for recovery of PHA from biomass) should be integrated into existing industrial production lines, where carbon-rich waste is produced at ample quantity (Nonato et al., 2001; Koller et al., 2017). Research endeavors distributed all over the planet resulted in the publication of a myriad of articles dealing with inexpensive carbon sources upgraded to feedstocks for PHA production. *Inter alia*, the conversion of whey lactose (Koller et al., 2007; Obruca et al., 2011), molasses (Zafar et al., 2012), lignocelluloses (Haas et al., 2015; Obruca et al., 2015), or glycerol (Hermann-Krauss et al., 2013; Naranjo et al., 2013) to generate “2nd generation PHA” is reported.

In addition, the utilization of liquid C1-compounds such as methanol is described (Khosravi-Darani et al., 2013). In the case of photo- or mixotrophic PHA biosynthesis by cyanobacteria, the use of CO₂ from industrial effluent gases generates “3rd generation PHA” (Wagner et al., 2016). Applying recombinant cyanobacteria for autotrophic PHA production and parallel CO₂ sequestration can be regarded as a strategy for production of “4th generation PHA” (Bhati and Mallick, 2016; Drosig et al., 2015; Koller and Maršálek, 2015).

As an unprecedented approach, the EU-funded project ANIMPOL, enabled by the 7th Framework Programme of the European Commission, resorted to waste streams derived from the animal-processing industry. In this context, lipid-rich surplus streams from slaughterhouses and rendering industry, which accrue at vast quantities in diverse global regions, were upgraded to feedstocks for PHA production. After extractive degreasing of the animal-based waste materials, these lipids undergo chemical transformation to crude glycerol phase (CGP) and fatty acid esters (biodiesel) by simple and well-established techniques. Only in Europe, such lipid-rich streams of bovine, porcine, avian, etc. origin accrue at estimated annual quantities of 500,000 t. The saturated share of biodiesel (also termed as “saturated fatty acid esters”, SFAE) counteracts its applicability as biofuel, but can be converted by different microbial species to a theoretical quantity of 35,000 annual tons of PHAs (Koller et al., 2013a). Kinetic data for PHA production based on animal-waste derived SFAE, together with data reflecting the material characteristics of the generated PHA, were recently reported for different microbial production strains. In dependence on the applied production strain, structurally diversified PHA biopolyesters can be produced. Whereas *Pseudomonas citronellolis* (Muhr et al., 2013a) and *Pseudomas chlororaphis* (Muhr et al., 2013b) convert SFAE into elastomeric medium chain length PHA copolyesters of rather low molecular mass and low degree of crystallinity, the application of *Curpiavidus necator* results in the formation of the thermoplastic poly(3-hydroxybutyrate) (PHB), a member of the short chain length PHA family (Špoljarić et al., 2013).

In addition, considering the entire amount of biodiesel that is currently produced in the EU-28 (about 20–30 Mt annually), more than 2 Mt of crude glycerol phase (CGP) are available as the major by-product of the conversion of lipids to biodiesel (Koller and Braunegg, 2015; Titz et al., 2012). This is in considerable excess over the quantities of glycerol needed for its various classical applications. If applied for production of microbial PHA accumulating biomass, one can expect more than 0.4 g biomass or PHA per g of glycerol. Regarding the entire quantity of glycerol from animal lipid transesterification, one can estimate that annually more than 20,000 t of PHA-rich biomass can be produced thereof (Koller and Braunegg, 2015). To visualize the significance of this novel process for PHA production, one has to face the fact that the contemporary disposal of lipid-rich slaughtering waste amounts to about 1 € per kg of waste material (personal communication with industrial project partner company U. Reistenhofer GesmbH, Austria).

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