Polyhydroxyalkanoates: Their Importance and Future

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This editorial considers biosynthesis of polyhydroxyalkanoates (PHA), polymer processing of PHA, and the use of PHA in production of bioplastics or biocomposites. The views come from a workshop aimed to join students and experts working with PHA or those interested in the application of biopolymers. The goals are 1) to synchronize their opinions with up-to-date knowledge published in the literature within the last 10 years, and 2) to formulate perspectives and conclusions.

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Introduction

Polyhydroxyalkanoates (PHA) are polyesters that are naturally or artificially accumulated as water-insoluble granules within a variety of microorganisms, subject to specific conditions. PHAs are regarded as a renewable resources-based alternative to petrochemical polymers. The advantageous character of PHAs lies in its environmental biodegradability and biocompatibility (Muhammadi *et al.* 2015). PHAs cover a large scale of biological polyesters having properties in the range from thermoplastic to elastomers (Koller 2018). The first identified and still the most investigated PHA is poly(3-hydroxybutyrate) (PHB). The chemical structure of formed PHA is primarily influenced by the microbial strains, carbon source, and eventually by the addition of precursors (Braunegg *et al.* 2002). A crucial role is played by PHA synthase enzymes (Smolke 2009). Biochemists, microbiologists, and bioengineers have focused their interest in forced bioproduction of PHAs using different substrates and employing various microorganisms with the aim to produce industrially acceptable concentrations of PHAs in bioreactors and to isolate biopolyesters and copolyesters with different chemical compositions and physical properties (Koller *et al.* 2017; Kumar and Kim 2018). However, the production costs of PHAs compared to conventional non-biodegradable plastics are still much higher than can compete in most significant industrial sectors (*e.g.*, packaging). Besides, other disadvantages such as limited thermo-mechanical stability, environmental instability, insufficient worldwide production facilities, and strict requirements for sterile fermentation conditions, hinder the larger industrial application of PHAs (Kovalcik *et al.* 2017). Therefore, intensive research for the production of PHA under non-sterile conditions, for example by using mixed microbial consortia or mutant strains of microorganisms, have been applied and tested as means to simplify operational requirements (Anjum *et al.* 2016; Kourmentza *et al.* 2017).

At the beginning of the workshop, a brief introduction into the topic was provided in short lectures by Fritz, Obruca, and Kovalcik. After that, six questions, as discussed below, were discussed. This work is an attempt to synthesize information found in the literature with the acute problems that have arisen in the praxis.

1. Which production concept for PHA is the most promising?

Polyhydroxyalkanoates are produced by biotechnological means, which brings many inherent limitations at the production scale, including all upstream and downstream procedures. All production steps contribute to the costs. Key questions include: Which kind of PHA will be produced and which final chemical and physical properties are expected? What will be the source of carbon for PHA biosynthesis? How to reach the highest PHA accumulation? Which producing microorganisms have the highest potential? Is it industrially realizable to switch from batch production systems to continuous processes? How to decrease requirements regarding an aseptic environment? Which agricultural waste and surplus waste materials could be used as carbon sources and which pretreatments or derivatization of these substrates are required? How will the PHA be isolated? Based on the questions mentioned above and knowledge from the literature and laboratory experience, it can be noted that PHB is preferably produced. Only a few microorganisms are known to accumulate other PHA types without the addition of precursors that intervene in the metabolism of microbial strains. Application of extremophiles could decrease the requirements for process sterility and thereby improve the economic feasibility of the process. Under the condition that specific quality control will be incorporated, the derivation of carbon or nitrogen sources from waste substrates (such as food production residues) should help to decrease the final costs and avoid the ethical conflict of using agricultural resources for plastic production. Another way to minimize costs and to extend the production capacity could be the implementation of carbon dioxide as the carbon source, for example in the case of cyanobacterial PHA production. The application of continuous fermentation processes could enhance productivity. The participants of the workshop did not identify any incompatibilities between various PHA production scenarios and, oppositely, suggested that most of PHA production approaches are complementary. The extracting solvents should be reused to minimize environmental impacts and to improve economic prospects.

2. What is the most critical parameter influencing the final price of PHA (*e.g.*, substrate, productivity, cultivation mode, downstream process)?

All mentioned parameters influence the costs of PHA, and it is hard to tell which parameter is the most important. However, only a small number of industrial plants are currently producing and selling PHA, so current prices may not be a reliable measure of potential future prices. The isolation processes of PHA from biomass as well as any pre-cleaning steps and post-cleaning steps of PHA may markedly affect the final price.

3. How can the use of genetically modified organisms (GMOs) affect consumer preferences and thus the future of the PHA production segment?

Generally, ordinary customers remain aware and often reject anything connected with production using genetically modified organisms, even though PHA produced by genetically modified bacteria does not contain any genetic information. Moreover, from a legislative point of view, such produced PHAs are not considered as being GMO products. However, ordinary customers consider the use of genetic manipulation in PHA production as a harmful factor, which erases the ecological “green” status of these materials. This negative opinion may come from the area of gene-modified food. One way how to change this opinion could be by paying attention to more considerable publicity with clear information.

4. Where is the most prominent application potential of PHA?

Industrial production follows current market needs. Legislation and penalties also influence the market tendency. In this context, two main production lines for PHA can be anticipated: 1) High-end products with distinct properties and definite purpose of utilization, for which biodegradation and biocompatibility are required as advantageous properties. Examples include drug delivery materials, tissue engineering (pharmacy, medicine), and nanobiotechnology (medicine). There is high potential for PHA polymers to replace conventional plastics used as additives and filler in cosmetics. In such cases a higher price of PHA compared to conventional petroleum-based plastics may be acceptable. 2) Low-end products for which the circular economy is the main advantage and minor benefits may come from biodegradability, optical activity, piezoelectricity, and barrier properties. The applications cover mainly organic waste collection bags, single-use packaging, mulching foils and geotextiles, toys, souvenirs, decoration and materials used for various sport entertainment products, *e.g*., airsoft balls, badminton shuttlecocks. In such cases the production capability of PHA is in an early phase, such that the price is much higher than that of conventional plastics. There are other ways to decrease the price of PHA, but first is the development of a fermentation process allowing higher production yields than 10 to 20 g PHA per liter of media. Secondly, the origin and the price of the ingredients, *e.g.* carbon source should be substituted with the waste materials from non-food chains (*e.g*., lignocellulosic biomass). Thirdly, the thermal processing stability of PHA polymers has to be improved.

5. What are the biggest weaknesses of PHA in competition with other polymers? How can these weaknesses be balanced?

In addition to high price, the first problem, concerning poly(3-hydroxybutyrate), which is the most offered PHA in the market, is its very narrow thermal processing window. The low hydrothermal stability of PHB causes difficulties during processing with conventional polymer processing equipment (*e.g*., extruders, injection molding machines, and 3-D printing equipment). Thermal degradation of PHB leads to quick and substantial decreases of molecular weight, color changes (from white/yellow to brown), and the loss of final rheological and mechanical properties. Secondly, there is a high similarity of PHA in physical properties with the conventional plastics (*e.g*., density); this can adversely affect recyclability of the conventional plastics in the case of confusion of plastic wastes. In some applications there may be a problem with excessively fast biodegradation of PHA. A straight-line solution to the mentioned problems does not exist; however, the price is mainly a question of the fermentation methodology, down-stream and upscaling. The thermal stability of PHA during polymer processing can be improved by chemical modification directly during fermentation (copolymers) or after fermentation with post-polymerization, click-chemistry, or blending techniques.

6. Do advantages of PHA overcome the disadvantages in some sectors?

PHA polymers face many research gaps and questions. Advantages of PHA include bio-origin (processing by microorganisms), biocompatibility, biodegradability, transformations of toxic materials by microorganisms during fermentation (halogenated derivatives, CO_2), additional unique properties such as piezoelectricity, and excellent barrier properties. Moreover, the production of PHA polymers is independent of fossil resources. In the case of those produced by cyanobacteria, CO_2 is absorbed and bound in the polymer. Besides, independence from agricultural areas is possible (cyanobacteria on the tops of buildings, at industrial sites, or in the ocean). Application areas in which PHA polymers offer unique values include medicine, cosmetics, pharmacy, and eco-agriculture.

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