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Review

Challenges of scaling-up PHA production from waste streams. A review

Santiago Rodriguez-Perez [a], Antonio Serrano [b], Alba A. Pantión [c], Bernabé Alonso-Fariñas [c, *]

[a] Molecular Biology and Biochemical Engineering Department, Universidad Pablo de Olavide, Ed. 22 Ctra. deUtrera, km. 1, Seville, Spain
[b] Instituto de Grasa, Spanish National Research Council (CSIC), Campus Universitario Pablo de Olavide, Ed. 46, Ctra. deUtrera, km. 1, Seville, Spain
[c] The University of Seville, Higher Technical School of Engineering, Department of Chemical and Environmental Engineering, Camino de losDescubrimientos, s/n, Seville, Spain

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ABSTRACT

The search for new materials that replace fossil fuel-based plastics has been focused on biopolymers with similar physicochemical properties to fossil fuel-based plastics, such as Polyhydroxyalkanoates (PHA). The present paper reviews the challenges of scaling-up PHA production from waste streams during the period from 2014 to 2016, focusing on the feasibility of the alternatives and the most promising alternatives to its scaling-up. The reviewed research studies mainly focus on reducing costs or obtaining more valuable polymers. In the future, the integration of PHA production into processes such as wastewater treatment plants, hydrogen production or biodiesel factories could enhance its implementation at industrial scale.

Contents

1. Introduction

Plastic materials are increasingly used in many domestic and industrial fields. Their use is usually associated with the development of a comfortable life. The global production of plastic materials reached 299 million tons in 2013, where 98% of the total

* Corresponding author. Tel.: +34 954 48 72 79; fax: +34 954 48 60 82.
E-mail address: bernabeaf@us.es (B. Alonso-Fariñas).

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production corresponded to fossil fuel-based plastics obtained from petroleum (Mozejko-Ciesielska and Kiewisz, 2016). Moreover, global plastic production presents a growing trend, with an increase of 4% in the production of plastic materials in 2016 (Muhammadi et al., 2015). In fact, the growing trend in plastic production is expected to continue at least until 2020 (Anjum et al., 2016).

Fossil fuel-based plastics from petroleum are supported by a highly limited natural resource. The exploitation of petroleum for the current demand of plastic materials poses serious environmental concerns, such as global warming, human health risks or ecosystem toxicity (Harding et al., 2007). Furthermore, fossil fuel-based plastic materials are resistant to microbial degradation, and are accumulated in the environment with a highly polluting potential (Mozejko-Ciesielska and Kiewisz, 2016). In fact, 17 million tons of plastic waste were generated in the European Union in 2012 (Eurostat, 2017a). Plastic packing material accounted for around 88% of the plastic waste generated in the European Union in 2012, i.e., 15 million tons (Eurostat, 2017b). Therefore, the production and disposal of fossil fuel-based plastics are not sustainable and they can be considered as contrary to the European policies in relation to waste management, emission reduction, and sustainable development (Directive 2008/98/EC on waste).

Even with the recycling and awareness policies, the situation shows a favorable scenario for the search of alternative technologies regardless of the petroleum that can satisfy the potential demand for plastic materials (Anjum et al., 2016). The search for new materials to replace fossil fuel-based plastics has focused on biopolymers with similar physicochemical properties to fossil fuel-based plastics. Biopolymers, or organic plastics, are plastic materials that can be produced from renewable sources or waste streams, and to reduce fuel consumption (Pittmann and Steinmetz, 2016). Moreover, biopolymers can reduce the environmental impact derived from plastic waste disposal due to the fact that the biodegradation time for biopolymers in the land surface under standard conditions is approximately two months (Hassan et al., 2013).

Indeed among the different biopolymers, polyhydroxyalkanoates (PHA) are polyesters produced by prokaryotic microbes as intracellular storage materials, which can be extracted and then formulated and processed for plastic production (Kushwah et al., 2016). Depending on the chain length, PHAs could be thermoplastic polyester, elastomers or even sticky resins composed of several R-hydroxyalkanoic acids that can be produced by numerous microorganisms (Koller and Braunegg, 2015; Anjum et al., 2016). Nowadays, over 90 microbial species that generate PHA and about 150 different monomers of PHA have been identified (Zinn et al., 2001). PHAs have a great potential because of their interesting properties, high biodegradability, and their recyclable nature (Anjum et al., 2016; Kushwah et al., 2016). In fact, Essel and Carus (2012) showed that PHA production can save on average 2 kg CO_2 emitted and around 30 MJ of fossil resources for 1 kg PHA produced compared to fossil-fuel plastic production. Alternatively, accumulated PHA in the biomass could be used to enhance the production of volatile fatty acids, hydrogen, and/or methane in anaerobic digestion processes (Wang et al., 2015a, 2015b).

Currently, commercial PHA production uses expensive raw materials and chemicals as sources of organic matter, which entails high costs at industrial scale. These costs must be offset to be an economically attractive alternative to fossil-fuel plastic production (Madkour et al., 2013). To enhance the profitability of the system and to facilitate its implementation in the plastic market, many operating alternatives have been proposed at lab-scale. One of the most promising alternatives is the use of industrial by-products and/or waste streams, i.e. agriculture feedstock, waste plant oils or wastewater, as sources of carbon for PHA production (Narodoslawsky et al., 2015). PHA production using waste streams can be considered an environmentally friendly management method (Anjum et al., 2016). However, pilot and industrial scale implementation require new technological advances to facilitate the employment of waste streams as raw material.

The present paper reviews the challenges of scaling-up PHA production that used waste streams as a carbon source in recent years, focusing on the feasibility of the alternatives and the most promising alternatives to its scaling-up. The review is focused on the 2014–2016 period, where a significant increase in scientific publications about PHA production can be found.

2. Scientific impact of PHA production

Fig. 1 shows studies on PHA production from waste materials in the last 24 years. A huge increase in the studies has been produced over the 2014–2016 period. This increase is related to the need to introduce bioplastics in the market at competitive prices in comparison to fossil fuel-based plastics. Table 1 shows reviews and studies based on relevant steps of the PHA production process.

The timeline of these reviews shows the evolution in the development of PHA production research. During the 2012–2014 period, authors were mostly focused on strain improvement by selection, DNA extraction, and super productive strains (Mohammadi et al., 2012; Wang et al., 2014). In 2015, studies were mostly dedicated to reducing costs through the reuse of waste generated from PHA production or an increase in the generation of high added-value products (Wei et al., 2015). In addition, the identification of the weakest points in the process for implementation at industrial scale revealed the next research lines (Muhammadi et al., 2015; Chen et al., 2015a; Kaur and Roy, 2015; Liu et al., 2015). In 2016, authors had maintained attention on the improvement of genotypes and operational conditions of fermentation (Kawaguchi et al., 2016; Tai et al., 2016; Inoue et al., 2016). The integration of the PHA production into other industrial processes, use of mixed cultures and use of waste streams as a source of organic matter have been considered as main research lines (Anjum et al., 2016; Valentino et al., 2017; Koller et al., 2017; Jiang et al., 2016; Mohan et al., 2016).

Table 1 shows that most authors have focused on reducing the cost of the PHA production process. Different strategies have been used to reduce costs such as genetic studies (Wang et al., 2014; Liu et al., 2015; Tai et al., 2016; Inoue et al., 2016); and optimization of the PHA purification/extraction step (Mohammadi et al., 2012; Liu et al., 2015; Kawaguchi et al., 2016); to obtain PHA compounds with higher economic value and/or promising new applications (Muhammadi et al., 2015; Anjum et al., 2016; Wang et al., 2014; Chen et al., 2015a; Kaur and Roy, 2015; Zia et al., 2016; Koller and Braunegg, 2015); implementation of continuous processes (Anjum et al., 2016; Kaur and Roy, 2015; Valentino et al., 2017; Koller et al., 2017; Mohan et al., 2016; Koller and Muhr, 2014); to diversify the feed streams (Liu et al., 2015; Kawaguchi et al., 2016; Inoue et al., 2016; Valentino et al., 2017; Koller et al., 2017; Koller and Braunegg, 2015; Mohan et al., 2016; Obruca et al., 2015); to re-use the bacterial biomass generated from PHA production (Wei et al., 2015); to reduce the energy consumption of the PHA production process (Mohammadi et al., 2012; Liu et al., 2015), integration into bio-refinery systems (Jiang et al., 2016), and to improve the yield of PHA production (Liu et al., 2015; Kawaguchi et al., 2016).

Previously described reviews and the increment in the scientific production research demonstrate the huge interest in PHA production from waste streams. However, a holistic and critical overview of the alternatives proposed in the literature is required in