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Potential for polyhydroxyalkanoate production on German or European municipal waste water treatment plants

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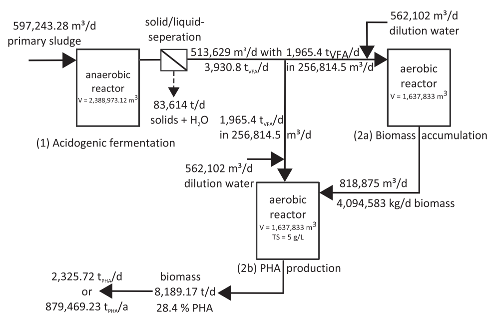
HIGHLIGHTS

- Potential analysis for PHA production on wastewater treatment plants was calculated.
- Results show that high amounts on PHA could be produced on treatment plants.
- 20% of current biopolymer production could be produced on German treatment plants.
- 115% of current biopolymer production could be produced on EU treatment plants.
- Organic matter in waste water could be recycled.

GRAPHICAL ABSTRACT



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ABSTRACT

Biopolymers, which are made of renewable raw materials and/or biodegradable residual materials present a possible alternative to common plastic. A potential analysis, based on experimental results in laboratory scale and detailed data from German waste water treatment plants, showed that the theoretically possible production of biopolymers in Germany amounts to more than 20% of the 2015 worldwide biopolymer production. In addition a profound estimation regarding all European Union member states showed that theoretically about 115% of the actual worldwide biopolymer production could be produced on European waste water treatment plants. With an upgraded biopolymer production and a theoretically reachable biopolymer proportion of around 60% of the cell dry weight a total of $1,794,656 \frac{t_{PHA}}{a}$ or approximately 236% of today's biopolymer production could be produced on waste water treatment plants in the European Union, using primary sludge as raw material only.

1. Introduction

Common plastic is derived from petrochemicals based on the limited natural resource petroleum. This causes serious environmental problems. Beside the exploitation of natural resources the use of petrochemical plastic is responsible for major waste problems. However, biopolymers present a possible alternative to common plastics.

Beside other polymers polyhydroxyalkanoates (PHA), which are biodegradable polyesters accumulated by bacteria under nutrient limited conditions (Nikodinovic-Runic et al., 2013), are a source for bioplastic production. More than 150 component parts of PHA have been identified so far (Cavalheiro et al., 2009). The possibility for chemical modification of PHA provide a wide range of material

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properties and an even wider range of use (Zinn and Witholt, 2005; Akaraonye et al., 2010). However, the main raw material for the biopolymer production are starchy plants like maize, constituting the disadvantages of high land consumption, diminishing food resources as well as problems like leaching of nutrients, input of pesticide and soil erosion. Additionally, bioplastic production is rather expensive, with a majority of the costs accounting for the raw material.

In many of the research projects on PHA production, synthetic waste water was used to gain knowledge about single steps of the PHA production or the required operating conditions (Albuquerque et al., 2007, 2010, 2011; Bengtsson, 2009; Bengtsson et al., 2010; Choi and Lee, 1997; Dionisi et al., 2005). In contrast recent research in the field of PHA production have shown the possibility to produce biopolymers out of waste water sludge (Reddy et al., 2008; Pittmann and Steinmetz, 2013, 2014; Jia et al., 2014; Morgan-Sagastume et al., 2015).

The biological process of PHA production takes place in two steps, which composes the production of volatile fatty acids (VFA) in an anaerobic process and finally the PHA production in an aerobic process (see also Fig. 1). In contrast to Bengtsson et al. (2008) and Morgan-Sagastume et al. (2015) the PHA production process described by Pittmann and Steinmetz (2013, 2014) is designed as a side stream process of a municipal waste water treatment plant (WWTP) and does not include the treatment of waste water. Therefore the whole process must consider the polymer production only.

On the basis of the results from theses investigations concerning biopolymer production (Pittmann and Steinmetz, 2013, 2014) and detailed data about the amounts of sewage sludge on WWTPs the possible PHA production on German and European municipal WWTPs was calculated within this work.

The PHA potential on German WWTPs was calculated based on detailed data from operators of WWTPs (DWA, 2011, 2012) and own PHA production experiments (Pittmann and Steinmetz, 2013, 2014). Afterwards a profound estimation of the biopolymer potential of all WWTPs in the 28 member states of the European Union (EU) was made based on data provided by the EU (Eurostat, 2015) and the mentioned PHA production experiments.

2. Definition and calculations

The term "biopolymer" or "bioplastic" is not yet uniformly defined. To compare the results of this potential analysis with the annual amount of biopolymer production it is necessary to provide a clear definition first.

Common definitions of the term "biopolymer" also include biodegradable plastics from fossil fuels and non-biodegradable plastics from renewable resources as seen in Fig. 2. To eliminate the problems accompanied by polymer production from crude oil a more stringent definition is introduced by the authors:

Biopolymers are made from renewable resources and/or biodegradable waste materials (e.g. waste water, sewage sludge, organic waste) and are fully biodegradable by naturally occurring microorganisms.

This definition ensures that polymers from fossil resources and non-biodegradable polymers, which cause at least one of the mentioned problems, are excluded and that the term biopolymer is just used for polymers, which allow the preservation of limited resources and also suit the idea of sustainability. This type of biopolymers are shown in the upper right of Fig. 2.

Based on the results of PHA production experiments described in Pittmann and Steinmetz (2013, 2014) a potential analysis was created. The aim of this analysis was to determine the potential of biopolymer production on German and European WWTPs by using sewage sludge as a substrate. All used input data for the analysis' calculation steps can be found in Table 1.

The most important input values have been cross-checked in order to prove their plausibility. Thus it could be checked whether input data like the amount of primary sludge (PS) per population equivalent (PE) is plausible.

As there are very detailed data about waste water and sewage sludge production in Germany, the first step of the potential analysis was calculated using these data together with results of PHA production experiments described in Pittmann and Steinmetz (2013, 2014). Thereafter data provided by the European Union were used to estimate the biopolymer potential considering all 28 member states of the EU.

3. Results and discussion

3.1. Calculation on the basis of data for German waste water treatment plants

The calculation results for possible biopolymer production on German WWTPs are shown in Fig. 4. All material streams and reactor volumes in this figure are theoretical values showing the size of the flows, if primary sludge – as the best substrate for acidification (Pittmann and Steinmetz, 2013) – of all German WWTPs with preliminary sedimentation potential (PSP = more than 10.000 PE) would be used for PHA production.

First of all the amount of primary sludge in Germany is calculated regarding the PEs (Table 1) connected to all German WWTPs and the daily primary sludge production per PE (Table 1) (Eqs. (1) and (2))

$$109,000,000\ \text{PE} \cdot 1.1 \frac{\text{L}_{\text{PS}}}{(\text{PE} \cdot \text{d})} = 119,900,000 \frac{\text{L}_{\text{PS}}}{\text{d}} = 119,900 \frac{\text{m}^3_{\text{PS}}}{\text{d}} \tag{1}$$

Around 92% of PEs are coming from WWTPs with PSP, on which a primary clarifier is installed or the construction of a primary clarifier would make sense (Table 1). Thus the actual amount of primary sludge is calculated as follows:

$$119,900 \frac{\text{m}^3_{\text{PS}}}{\text{d}} \cdot 92\% = 110,308 \frac{\text{m}^3_{\text{PS}}}{\text{d}} \tag{2}$$

Using these data and the results of experiments conducted by Pittmann and Steinmetz (2013, 2014) one can calculate the possible PHA production through various steps.

With the best reactor operation method using a RT = 4 d and a WD = 25% (Table 1) 110,308 $\frac{\text{m}^3}{\text{d}}$ acidified material could be used for PHA production every day (Eq. (3)).

$$110,308 \frac{\text{m}^3_{\text{PS}}}{\text{d}} \cdot 4\ \text{d} \cdot 25 \frac{\%}{\text{d}} = 110,308 \frac{\text{m}^3}{\text{d}} \tag{3}$$

The total solid (TS) concentration of the acidified material of 35 $\frac{\text{kg}}{\text{m}^3}$ (Table 1) and the assumed residual moisture after dewatering of 75% leads to a daily acidified liquid production of 94,865 $\frac{\text{m}^3}{\text{d}}$ (Eqs. (4)–(6))

$$110,308 \frac{\text{m}^3}{\text{d}} \cdot 35 \frac{\text{kg}_{\text{TS}}}{\text{m}^3} = 3,860,780 \frac{\text{kg}_{\text{TS}}}{\text{d}} = 3,860.8 \frac{\text{t}_{\text{TS}}}{\text{d}} \tag{4}$$

The assumed residual moisture of 75% means that the calculated 3,861 t biomass is 25% of the total mass separated by the centrifuge. Accordingly, 75% of the separated total mass is water. Assuming that the solid phase is completely separated it follows: