Bio-plastic (poly-hydroxy-alkanoate) production from municipal sewage sludge in the Netherlands: a technology push or a demand driven process?

E. D. Bluemink, A. F. van Nieuwenhuijzen, E. Wypkema and C. A. Uijterlinde

ABSTRACT

Valorisation of components from municipal 'waste' water and sewage sludge gets more and more attention in order to come to a circular economy by developing an efficient 'waste' to value concept. On behalf of the transition team 'Grondstoffenfabriek' ('Resource factory') a preliminary research was performed for all the Dutch water boards to assess the technical and economical feasibility of poly-hydroxy-alkanoate (PHA)-production from sewage sludge, a valuable product to produce bio-plastics. This study reveals that the production of bio-plastics from sewage sludge is feasible based on technical aspects, but not yet economically interesting, even though the selling price is relatively close to the actual PHA market price. (Selling price is in this particular case the indicative cost effective selling price. The cost effective selling price covers only the total production costs of the product.) Future process optimization (maximizing the volatile fatty acids production, PHA storage capacity, etc.) and market developments are needed and will result in cost reductions of the various sub-processes. PHA-production from sewage sludge at this stage is just a technology; every further research is needed to incorporate the backward integration approach, taking into account the market demand including associated product quality aspects.

Key words | bio-plastic, business case, municipal sewage sludge, poly-hydroxy-alkanoate, PHA, waste to value

E. D. Bluemink (corresponding author)
A. F. van Nieuwenhuijzen
Witteveen + Bos Consulting Engineers,
7400AE Deventer,
The Netherlands
E-mail: *erwin.bluemink@witteveenbos.com*

E. Wypkema
Waterboard Brabantse Delta,
4836AA Breda,
The Netherlands

C. A. Uijterlinde
STOWA,
3800CD Amersfoort,
The Netherlands

INTRODUCTION

Approximately 300 million tons of plastic are globally produced each year (PlasticEurope 2015). Biodegradable plastic is regarded as an interesting substitute for non-degradable plastics, especially for products with short life-times. The entire bio-plastic market is stimulated by the growing demand for sustainable solutions and the constant development of new materials. The European bio-plastic market is growing by approximately 20% each year (European Bio-plastics Association n.d.). Growth is stimulated by the reduction in production costs, and the drive to a sustainable world and innovation. This significant increase in global bio-plastics production is also expected for poly-hydroxy-alkanoate (PHA)-based bio-plastics.

PHA is a group of biodegradable polymers (linear polyesters) that can be used to produce bio-plastics. It is produced by microorganisms, using a carbon source as substrate. During PHA-production, at proper conditions and by means of various intermediate steps a part of the carbon will be interlinked to form a biopolymer. These PHAs are then stored in intracellular granules. The type of the carbon source, fed to the PHA-fermentation process, influences the finally produced type of biopolymer (Lee 1996).

The conventional way of PHA-production using microorganisms is based on fermentation under sterile conditions using monocultures. The microorganisms are fed with food-related carbon sources like glucose, starch or vegetable oil (Bolck *et al.* 2012). About 40% of the production costs of conventionally produced PHA are related to the crude materials. These crude materials include carbon sources and nutrients. Approximately 70% of the costs of crude materials are attributed to the carbon source (Choi & Lee 1999).

The current PHA market price is approximately EUR 4–5 per kilogram produced biopolymer. Despite the attractive

doi: 10.2166/wst.2016.191

product features, PHA is not yet applied frequently due to this relatively high production cost and resulting high market price. The future application of PHA mainly depends on production price and product quality. Market analysts indicate that the application of PHA becomes financially attractive at bulk prices of approximately EUR 3.0 per kilogram produced biopolymer, referred to in this paper as 'desired market price'.

For reducing the PHA-production costs, specific waste activated sludge can be used as a source of PHA-producing microorganisms. These microorganisms can be used to produce and store PHA by addition of a carbon source, without the need of sterile conditions. The costs can be further reduced by using 'waste' material, e.g. waste water or sewage sludge, as a carbon source (Salehizadeh & Van Loosdrecht 2004; Mudliar *et al.* 2008).

The approach to use 'waste' material as a carbon source has been discussed since 2003 (Chua *et al.* 2003). Fermented waste activated sludge, pre-treated via high pressure thermal hydrolysis, was proven to be a feasible route (Morgan-Sagastume *et al.* 2010). Also the use of alkaline fermentation liquid from waste activated sludge can be used directly for PHA-production (Jiang *et al.* 2009). Also, in the Netherlands, different pilot studies are being performed (Veghel, Leeuwarden and Bath), using 'waste' streams as carbon source, by several parties including technology providers and suppliers like Paques (en.paques.nl) and AnoxKaldnes (www.veoliawatertechnologies.com). However, these studies do not contain detailed economical evaluations.

On behalf of the expert team Bio-plastics of the 'Grondstoffenfabriek' ('Resource factory', see www.efgf.nl/english) a preliminary research was performed to assess the technical and economical feasibility of PHA-production from waste water and sewage sludge to produce commercially applicable bio-plastics. This includes activated sludge as a source of microorganisms and primary sludge as a carbon source to reduce the overall production costs (STOWA 2014). The main driver for this study is the valorisation of 'waste' water and sewage sludge: the so-called 'waste to value' principle. The Dutch water boards give more and more attention to valorisation in order to come to a circular economy by developing an efficient 'Waste to Value' concept. A circular economy prefers to create products with the highest possible value according to the value pyramid (Langeveld et al. 2010). The Dutch roadmap 'Routekaart Afvalwaterketen tot 2030' (Roadmap Wastewater Cycle up to 2030) describes 'waste' water as a source of nutrients, energy and clean fresh water (Römgens & Kruizinga 2012).

Furthermore this article reviews the current needs for 'technology push' (producing as much PHA for an acceptable price) and 'demand driven' (producing PHA of the right quality and with the right properties as requested by the market) approaches.

METHODS

This paper focuses on a preliminary assessment to determine the technical and economical feasibility of two selected PHA-production routes based on current (2015) knowledge. Sustainability analysis is beyond the scope of this study; however, we will provide more insight into the sustainability of PHA-production compared to the reference situation (conventional digestion).

Two alternative PHA-production routes from sewage sludge were investigated:

1. The 'rich culture' route: a continuously selected bacterial culture in which all organisms are able to store PHA. However, the biomass consists of several bacteria species.
2. The 'mixed culture' route: a bacterial culture in which part of the microorganisms are able to store PHA. Secondary sewage sludge from a municipal waste water treatment plant (WWTP) is an example of a mixed culture.

Rich culture PHA route

The rich culture PHA-production route (see Figure 1) is based on a bacterial culture in which all organisms are able to store PHA, with several bacteria species (different from the conventional PHA-production process). The rich culture PHA-production route includes the following:

- Acidification of primary sludge from a WWTP to create volatile fatty acids (VFAs), which are used for:
  - growth and continuous selection of the rich culture route (inoculated once with secondary sludge); the continuous selection pressure excludes the need for sterile processing;
  - PHA-fermentation using part of the biomass obtained from the cultivated rich culture.
- Downstream processing of the PHA-enriched biomass to deliver the final product.
- Biogas production from the residuals of primary sludge, secondary sludge and if applicable the residuals from the downstream processing.

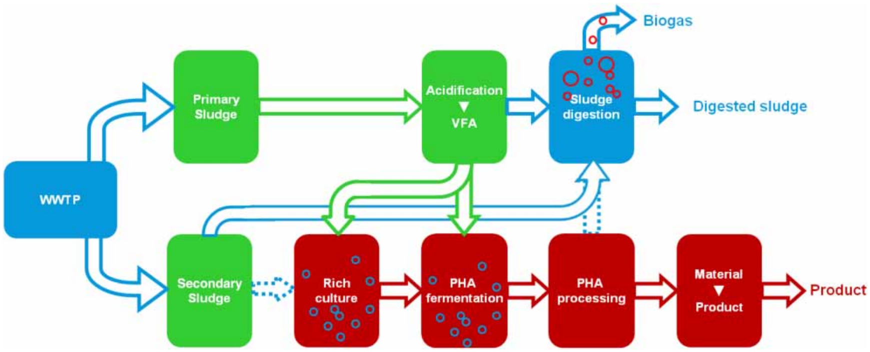

Figure 1 | Schematic overview of the PHA-production route using a rich culture.

Mixed culture PHA

The mixed culture PHA-production route (Figure 2) is based on a bacterial culture in which some of the microorganisms are able to store PHA (different from the rich culture route). Secondary sewage sludge from a municipal WWTP is an example of such a mixed culture. The rich culture PHA-production route includes the following:

- Acidification of primary sludge from a WWTP to create volatile fatty acids, which are used for PHA-fermentation. Secondary sludge is used as source of microorganisms which are able to store PHA.
- Downstream processing of the PHA-enriched biomass for final product delivery.
- Biogas production from the residuals of primary sludge, and if applicable the residuals from the downstream processing.

Methodological approach

The following three processes are considered in this paper:

- PHA-production by the rich culture route (including PHA-processing).
- PHA-production by the mixed culture route (including PHA-processing).
- Reference process: biogas production by sludge digestion.

For all three processes, technological designs and process flow diagrams were prepared in which equipment as per Table 1 was included.

For this investigation, the process design of the two selected PHA-production routes is based on a methodological case study design of 28 fictitious 'PHA-from-sludge' production facilities with a total capacity of 10 million population equivalent (p.e.). PHA-processing is considered in this study as a large-scale centralized PHA-processing facility. For all three processes mass balances were prepared, using main starting points as per Table 2.

Based on the mass balances, the size of equipment listed in Table 1 was determined. Based on the equipment size, the construction costs were determined using key indicators (±30%). Pumps were selected based on the mass balance and costs were calculated accordingly (±50%). Instrumentation and automation costs are estimated to be 20% of the total construction costs. Furthermore an incompleteness factor of 1.3 was applied. The investment costs were calculated using a factor of 1.7 over the total construction costs to include value

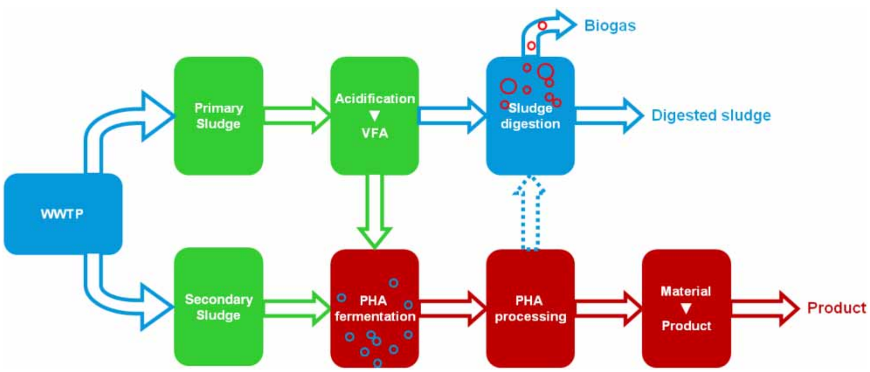

Figure 2 | Schematic overview of the PHA-production route using a mixed culture.

Table 1 | Equipment list of the rich and mixed culture route and the reference process

Rich culture	Mixed culture	Reference process
VFA-production	VFA-production	Digestion
Sludge thickener	Sludge thickener	Sludge thickener
5 VFA reactors	5 VFA reactors	–
Decanter	Decanter	–
PHA-production	PHA-production	–
2 rich culture reactors	–	–
–	Secondary sludge buffer	–
PHA-fermentation reactor	PHA-fermentation reactor	–
Biomass settler	Biomass settler	–
Decanter	Decanter	–
Biomass silo	Biomass silo	–
Digestion	Digestion	–
Belt thickener	Belt thickener	Belt thickener
Digester	Digester	Digester
Sludge buffer	Sludge buffer	Sludge buffer
Decanter	Decanter	Decanter
Sludge silo	Sludge silo	Sludge silo
Gas storage	Gas storage	Gas storage
Combined heat & power	Combined heat & power	Combined heat & power
Biogas boiler	Biogas boiler	Biogas boiler
Biogas flare	Biogas flare	Biogas flare
PHA-processing	PHA-processing	–
Biomass buffer	Biomass buffer	–
NaCl reactor	NaCl reactor	–
NaOH reactor	NaOH reactor	–
Decanter	Decanter	–
Wash reactor	Wash reactor	–
Decanter	Decanter	–
Ethanol reactor	Ethanol reactor	–
Decanter	Decanter	–
Dryer	Dryer	–

added tax, engineering costs, insurance, ground work etc. Capital costs were calculated based on annuity (5% interest and a depreciation time of 15 years). Operational costs include labour, sludge handling, maintenance, energy consumption, utilities and chemicals use.

The costs for the centralized PHA-processing are included in the calculations of the selling price of PHA as a feedstock for bio-plastics. The costs for the centralized

Table 2 | Starting points for mass balance calculations

Parameter	Unit	Value
Sludge production		
Primary sludge	kgDS/(p.e. year)	7.9
Secondary sludge	kgDS/(p.e. year)	8.4
VFA-production		
VFA-production	gVFA/gVSS	0.25
Batch time	days	4
PHA-production		
Growth rate rich culture	/day	2
PHA-production	gPHA/gVSS	0.43
PHA-storage rich culture	%DS	60
PHA-storage mixed culture	%DS	40
Digestion		
Primary sludge	Nm^3/kgVSS	0.55
Secondary sludge	Nm^3/kgVSS	0.25
PHA-processing		
NaCl	g/l	8
NaOH	g/l	4
Ethanol	%(w/w)	20

DS: dry solids; VSS: volatile suspended solids

PHA-processing are left out in the calculation of selling price of PHA-rich biomass leaving the WWTP as raw product. The selling product price is calculated in relation to the reference process (conventional digestion).

The following situations were chosen as a starting point for the cost estimate:

- The 'green field' alternative: this assumes complete construction of the PHA-production facility and the associated sludge digestion line, which turns the residual organic material into biogas and dewatered sludge. Biogas production by digestion is used as the reference process. The difference in annual costs between the PHA-production process and the reference process is divided by the annually produced kilos of PHA, which provides the selling price of PHA in EUR/kg PHA.
- The alternative with an existing sludge digestion line: this assumes full construction of the PHA-production facility; the existing sludge digestion remains intact. Since, in the case of PHA-production, less sludge is fed into the digester, the existing digester will have spare capacity in the new situation. The annual costs of the PHA-production process are divided by the annually produced amount (in kilos) of PHA, which provides the selling price of PHA in EUR/kg PHA.

For the design and business case, one large-scale centralised PHA-processing facility was assumed to treat PHA-enriched cells into pure PHA. Only primary sludge is used as a carbon source for the two selected PHA-production routes. The outcome of this study is therefore very specific to this case study (more details can be found in the next section).

RESULTS AND DISCUSSION

Both PHA-production routes proved to be technically feasible, according to the review of several pilot studies. As explained the current market price of PHA is approximately EUR 4-5 per kg PHA. The desired market price for the implementation of PHA in a broader range of products is about EUR 3.0 per kg PHA.

The results of the business case (28 WWTPs; equal to 10,000,000 p.e. produce PHA-enriched sludge which is processed in one centralised downstream processing plant) according to the selling prices are listed in Table 3.

The mass balance shows an annual PHA-production of 2,940 tons using the rich culture route and 5,240 tons using the mixed culture route.

The mixed culture route is economically more feasible compared to the rich culture route (with the chosen assumptions, based on current knowledge) according to this study. However, it is not ruled out that the rich culture route has the preference in other circumstances and with a different reference situation. Despite the mixed culture route for this case being most favourable, PHA-production in this way is currently not economically feasible. It should be noted that the local situation will affect the viability of PHA-production. Available equipment or buildings, or the possibility to buy cheaper VFAs are examples of factors which positively influence the feasibility for a specific location. This statement is confirmed by the additional case for WWTP Bath (The Netherlands); purchasing fatty acids and the benefits of scale result in an indicative selling product price of EUR 2.5/kg PHA-rich biomass (without PHA-processing, crude product) (STOWA 2014).

It should be noted that some assumptions in this study are based on current theoretical knowledge. Most of them have not yet been tested in practice. Furthermore the choice of the PHA-processing procedure will influence the outcome of the study (this specific PHA-processing route covers 16 and 37% of the total costs (PHA production and processing) for rich and mixed culture, respectively). The PHA-processing procedure for this study is based on a method with pre-treatment using NaCl, a treatment with NaOH and a post-treatment with 20% ethanol. It is not exactly known if this technique is applicable for this specific product (PHA-rich cell material derived from a municipal WWTP) and the type of biopolymer. It is also unknown whether the performance from the literature corresponds with practical performance.

The effects on the municipal WWTP are relatively small when PHA-processing is performed at a centralized location. The biogas production is reduced (by approximately 25–30%) since VFAs are produced from primary sludge and since the mixed culture route uses secondary sludge for PHA-storage (approximately 15%). Furthermore a relatively small waste water stream will be produced (<1% of influent). A relatively large waste stream is produced at the centralized PHA-processing facility. It mainly consists of dissolved chemical oxygen demand, NaCl and NaOH. The centralized PHA-processing as used in this study results in a waste stream equal to 45,000 p.e. for the rich route and 262,000 p.e. for the mixed culture route. It should be noted that this waste stream is specifically related to the selected PHA-processing method and accounts for the business case of 10,000,000 p.e. Additional costs for the treatment of the additional stream are incorporated in this study.

Table 3 | Selling prices per situation

	Rich (EUR/kg)	Mixed (EUR/kg)
Selling price without PHA-processing (crude):		
Green field	6.0	2.5
Existing sludge digestion	9.1	5.3
Selling price with PHA-processing (pure):		
Green field	7.9	5.7
Existing sludge digestion	11.0	8.5

CONCLUSIONS

This study shows that production of bio-plastics from sludge is technically feasible but not economically interesting yet, even though the production price determined in this study is relatively close to the actual PHA market price. Future PHA processing optimization (maximizing the VFA-production, PHA-storage capacity, PHA extraction, etc.) and market development is needed for cost reduction of the various sub-processes to increase market opportunities.

The set-up of this study is mainly technology-driven, which means that the economic viability is calculated with potential techniques as starting point. The selling product price is compared to the desired market price. The relationship between quality, functionality and the fair market price is disregarded in this exploratory study. This specific aspect requires further research outside the scope of this survey.

Knowing this, it must be noted that the requirements of the user (client/consumer) must be kept in mind. Only in this way will it be possible to produce a product with the applicable quality and associated product price (sales price for PHA). Thus 'technology push' and 'demand driven' are not explicitly contradictable. However, a technology producing a product which is not demand driven is not viable and this aspect should be taken into account from the very beginning of each research and development route.

For a successful implementation of the bio-plastic production route from waste water, the final bio-plastic industry has to step up and determine the exact needs on volume and quality and has to evaluate if the 'Waste to Value' PHA processing chain is complying to its requirements.

REFERENCES

Bolck, C., Ravenstijn, J., Molenveld, K. & Harmsen, P. 2012 *Biobased Plastics 2012*, Wageningen UR. Food & Biobased Research, Wageningen, The Netherlands.

Choi, J. & Lee, S. Y. 1999 Factors affecting the economics of polyhydroxyalkanoate production by bacterial fermentation. *Applied Microbiology and Biotechnology* **51** (1), 13–21.

Chua, A. S. M., Takabatake, H., Satoh, H. & Mino, T. 2003 Production of polyhydroxyalkanoate (PHA) by activated sludge treating municipal wastewater: effect of pH, sludge retention time (SRT), and acetate concentration in influent. *Water Research* **37** (15), 3602–3611.

European Bio-plastics Association n.d. *Market Drivers and Development*. http://en.european-bio-plastics.org/market/market-drivers/ (accessed 2013).

Jiang, Y., Chen, Y. & Zheng, X. 2009 Efficient PHA production from a waste-activated sludge alkaline fermentation liquid by activated sludge submitted to the aerobic feeding and discharge process. *Environmental Science & Technology* **43**, 7734–7741.

Langeveld, H., Sanders, J. & Meeusen, M. 2010 *The Biobased Economy*. Earthscan, London, pp. 111–113.

Lee, S. 1996 Plastic bacteria? Progress and prospects for polyhydroxyalkanoate production in bacteria. *Trends in Biotechnology* **14**, 431–438.

Morgan-Sagastume, F., Karlsson, A., Johansson, P., Pratt, S., Boon, N., Lant, P. & Werker, A. 2010 Production of PHA in open, mixed cultures from a waste sludge stream containing high level of soluble organics, nitrogen and phosphorus. *Water Research* **44**, 5196–5211.

Mudliar, S. N., Vaidya, A. N., Suresh Kumar, M., Dahikar, S. & Shakrabarti, T. 2008 Techno-economic evaluation of PHB production from activated sludge. *Clean Technologies and Environmental Policy* **10**, 255–262.

PlasticEurope 2015 Plastics – the Facts 2014/2015. An analysis of European plastics production. http://www.plasticseurope.org/documents/document/20150227150049-final_plastics_the_facts_2014_2015_260215.pdf (accessed in 2015).

Römgens, B. & Kruizinga, E. 2012 *Routekaart Afvalwaterketen tot 2030 (Roadmap Wastewater Cycle up to 2030)*. Vereniging van Nederlandse gemeenten, The Hague, The Netherlands.

Salehizadeh, L. & Van Loosdrecht, M. 2004 Production of polyhydroxyalkanoates by mixed culture: recent trends and biotechnological importance. *Biotechnology Advances* **22**, 216–279.

STOWA 2014 *Bioplastic uit Slib, Verkenning naar PHA-Productie uit Zuiveringsslib (Bio-Plastic from Sludge; Investigations into PHA Production from Municipal Sewage Sludge)*. STOWA report 2014-10, STOWA, Amersfoort, The Netherlands.

First received 21 October 2015; accepted in revised form 6 April 2016. Available online 27 April 2016