PRODUCTION OF POLYHYDROXYALKANOATES (PHA) FROM WASTEWATER IN LAHTI REGION: A TECHNO-ECONOMIC ASSESSMENT

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Examiners: Associate Professor Ville Uusitalo
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ABSTRACT

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This research explores the feasibility of producing renewable PHA plastic from the sludge of wastewater treatment plants (WWTPs) in Finland, with a centralized extraction location in the Lahti region. With a current market price of 3.5-4.5 €/kg PHA, the research calculates the cost of producing wastewater PHA in Finland. It also attempts to estimate the total capacity of Finland's wastewater PHA, and additionally the effect of population dispersity and transportation costs on wastewater PHA's production cost.

Geolocation and annual inflow of Finland's WWTPs were used as the source data in this thesis. A technoeconomic assessment based on similar recent projects was created and operational and capital expenditures were calculated in each WWTP. Values from literature were used for determining operational and capital expenditures of a centralized extraction facility. Several scenarios were built by selecting different plants to make the minimum annual output of 5,000 tons of PHA. Unit cost of PHA for each scenario was then determined.

Results of this research show that the unit cost of producing wastewater PHA in Finland is between 3.40 – 3.76 €/kg of PHA in different scenarios, while PHA can be produced in a scenario consisting mostly of WWTPs of the capital region and the city Lahti for 3.45 €/kg of PHA. Finland's total wastewater PHA capacity is estimated to be between 12,000 and 26,000 tons of PHA per year, and transportation costs are deemed insignificant and not prohibitive in participation of larger yet farther WWTPs. Electricity and heat costs make up 60% of the PHA's total cost.

This assessment is among first of its kind regarding producing wastewater PHA in Finland. Based on real data from Finland's WWTPs, the research provides realistic scenarios for producing wastewater PHA, while it determines the production costs for each scenario. It also provides an overview of wastewater PHA developments.

To my mother, Akram, and in memory of my father, Mohsen,

for providing me with all the opportunities

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Loviisa, April 30, 2022

Jubeen Sharbaf

ABBREVIATIONS

°C	degree centigrade
API	Application Programming Interface
BOD	biochemical oxygen demand
CAPEX	capital expenditure
CH_4	methane
COD	chemical oxygen demand
DMC	dimethyl carbonate
EU	European Union
GWh	gigawatt-hour
LCA	lifecycle assessment
MMC	mixed microbial cultures
MWh	megawatt-hour
OPEX	operating expense
PAP	PHA accumulation potential (gPHA/gVSS)
PBS	polybutylene succinate
PE	polyethylene
PE	population equivalent
PET	polyethylene terephthalate
PHA	polyhydroxyalkanoate
PHB	polyhydroxybutyrate
PHBV	polyhydroxy-butyrate-co-valerate
PHV	polyhydroxyvalerate
PLA	poly(lactic acid)
PP	polypropylene
PS	polystyrene
PVC	polyvinyl chloride
RBCOD	readily biodegradable chemical oxygen demand
VFA	volatile fatty acids
VSS	volatile suspended solids
WWTP	wastewater treatment plant

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1 Introduction

Plastic entered the mainstream in 1950's and since then, it has become an important part of everyday life, with many use cases from food packaging and clothing to pipes and car interior. As energy transition from fossil fuels to renewables is increasingly pursued in global scale, there is a question hanging regarding how to replace fossil gas and oil as the main feedstock in plastic production. In 2019, plastic production has been 58 and 368 million tons in Europe and worldwide, respectively, while Finland's plastic demand has been about 0.7 million tons during the same year (PlasticsEurope, 2020). Replacing this sizeable demand with renewable resources is a challenge of great significance.

In addition to finding sustainable resources for plastics production, the end-of-life phase of these materials is also an issue worth addressing. Like many other substances used by humans, a substantial amount of plastic ends up in aquatic ecosystems and eventually in the oceans every year. Not only this type of waste is dangerous to marine life, as it breaks into microplastics, it can also appear in the food chain, which creates hazard both to animals and humans. Recent research shows plastics pollution is one important factor in pushing humanity towards living outside planetary boundaries (Persson et al., 2022; Steffen et al., 2015).

The New Plastic Economy by Ellen MacArthur Foundation (2016) describes the transition to renewably sourced plastics as "decoupl[ing] the production of plastics from finite resources by sourcing the virgin feedstock either from captured greenhouse gases or biomass". In such a context, attentions are increasingly given to other types of plastics, which are both bio-based and bio-degradable. Polyhydroxyalkanoates, more commonly known as PHAs, have come to the centre of attention in recent years as one of the candidates to replace fossil-based plastics. With high levels of biodegradability while still possessing many attributes of fossil plastics, PHA has been particularly promising. (Tullo, 2019)

PHAs are currently made from monoculture, using feedstocks such as sugar beets, molasses, and corn starch. Production of PHA from mixed microbial culture (MMC) has been investigated in recent years. The essential question in these studies has been whether PHA plastics produced from MMC can compete with PHA from biomass, in terms of quality and cost. Various feedstocks have been evaluated for PHA production, and among them is urban waste and specifically, urban wastewater or sewage. Prospect of producing added value from urban waste has been the focus of attention in recent times, with examples such as biogas production from waste being pursued by many municipalities worldwide. Production of material with much higher value such as bioplastics from waste seems a natural next step in such a transition, in pursuit of ‘urban biorefineries’.

1.1 Research problems

To compete with fossil-based plastics, wastewater PHA needs to be price competitive. Economic viable production of PHA from wastewater requires sizeable amount of wastewater sludge. As there are not many Wastewater Treatment Plants (WWTPs) in Europe which can provide such a high capacity, several WWTPs need to join effort in such a production (Khan et al., 2021). This will in turn increase the capital expenditure costs, which leads to higher cost of PHA. Moreover, the distance between the WWTPs might be considered a prohibitive factor as well. Considering the wide range of Finland’s WWTPs in terms of their capacities and distance from each other, the unit cost of wastewater PHA needs be calculated using real data.

Lahti has been selected as the European Green Capital in 2021, and production of PHA from wastewater falls into this region’s long-term sustainability strategy. Yet, it is imperative that a detailed study explores the economic feasibility of such an endeavour.

1.2 Research questions

This research performs an initial economic analysis to evaluate the feasibility of producing PHA plastics from wastewater in Finland. With that goal in mind, the following research questions are considered:

- What is the approximate market size of wastewater PHA in Finland?
- How much is the unit cost of PHA produced from wastewater, in a central facility in the Lahti region?
- What is the impact of Finland’s wastewater treatment plants’ dispersity on the cost of wastewater PHA?

1.3 Thesis structure

In chapter 2, an overview of plastic market is provided and then PHA plastic and its qualities are introduced. Following that, the previous research on production of PHA from wastewater are reviewed, while a special focus is given to recent pilot projects in Europe, with an example of PHA production process from wastewater introduced.

Chapter 3 explains the methods used in the research, including techno-economic assessment, matter flows and energy demand calculations, criteria for selecting the candidate wastewater treatment plants and building different scenarios, and methods used for computing the unit cost and transportation cost of wastewater PHA production. Chapter 4 shares the research findings, while it also provides sensitivity analysis of the results. A summary of findings and contributions, alongside limitations and suggestions for future research are provided in chapter 5.

2 Literature Review

In this chapter, first an overview of plastic market is presented. In section 2.2, PHA is introduced, and its characteristics and advantages are explained. Section 2.3 presents a review of literature on PHA production from wastewater and section 2.4 summarizes the outcomes of two recent wastewater PHA pilot projects.

2.1 Overview of plastics

Vast majority of plastics in use are currently sourced from either fossil gas or oil. The most well-known plastics include polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS), all of which are non-biodegradable in short term. There are few types of fossil-based plastic that are biodegradable but are not widely used and will be out of favour in future, regardless, due to their source. Meanwhile, with current technologies, some of the common plastics such as PE and PET can be produced using biomass feedstock, such as corn, sugar cane and cellulose (European Bioplastics, n.d.). However, these plastics still impose the non-biodegradability challenges. In fact, some argue that the term ‘bioplastic’ has been used by many companies with the intention of gaining green credentials, as using a bio-based plastic does not necessitate biodegradability. Based on these observations, the real transition needs to happen towards types of plastic, which are both renewably sourced and are biodegradable (figure 1). In 2019, more than 370 million tons of plastic was produced, only about 2 million tons of which were bioplastics (European Bioplastics, 2020),which shows that this transition is in its infancy.

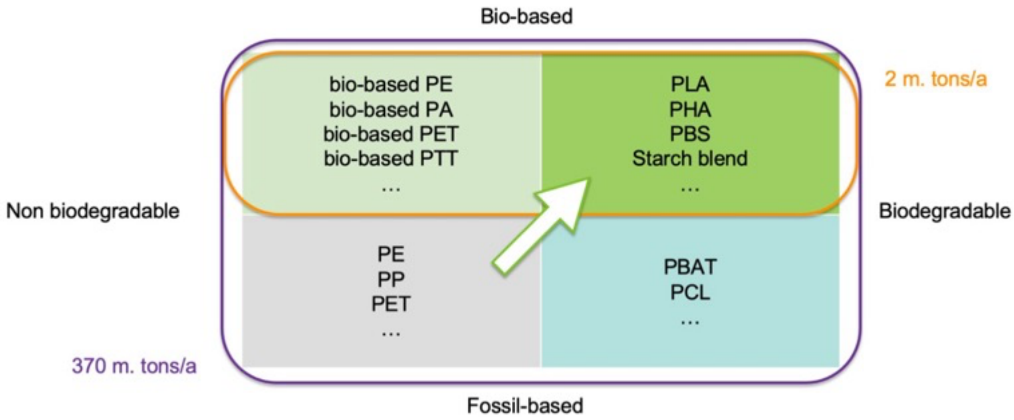

Figure 1. Plastics classification by source and end of life (European Bioplastics, n.d.).

Alongside polylactic acid (PLA) and polybutylene succinate (PBS), polyhydroxyalkanoate or PHA is one of the few plastics with high levels of biodegradability, hence has become the focus of in-depth research during the past couple of decades.

2.2 PHA – an introduction

PHAs are a family of biopolymers, that many plants produce and store as energy sources. About 300 species have been identified as capable of producing PHA as a polymer (Anjum et al., 2016).

More than 150 types of PHA have been already recognized, with new types introduced regularly (Hassan et al., 2013). Polyhydroxy-butyrate (PHB) and polyhydroxyvalerate (PHV) are couple of most common types of PHA.

Based on the number of carbons in a PHA polymer, it can be classified into short-chain PHA (with 3-5 carbon atoms) and medium-chain PHA (with 6-14 carbon atoms) (Aldor & Keasling, 2003). Short chain PHAs tend to be stiff and brittle, while the medium chain PHAs are more elastic and flexible (Anjum et al., 2016). To improve the functionality of PHA, Li et al. (2016) suggest blending the raw PHA with other biodegradable polymers such as starch, lignin, cellulose and PLA.

Being sourced from plants gives PHA the advantage of biocompatibility. PHA can biodegrade in different environments, and so far, is the only type of plastic that is fully biodegradable in water (Wang et al., 2018). It is expected that further development of PHAs would lead them to replace most common fossil plastics such as PE, PET, and PP (Ellen MacArthur Foundation, 2016). PHAs have also come into attention in other fields such as in medicine, where they can be used in tissue engineering, in bio-implant patches, and for drug delivery purposes (Raza et al., 2018).

Production of PHA from monoculture had already been discovered in 1920's, and it has been in industrial production since 1970's from carbon sources such as sugar, corn or starch (Wupperverband, 2019). PHA development has faced fluctuations during the past half a century, as it was fiercely pursued during the oil crisis of 1970's and in 2000's, when sharp increase in oil prices was observed (*Biodegradable Plastic*, n.d.). Those efforts, however, slowed down after the oil prices reached normal levels (*Biodegradable Plastic*, n.d.). As one industry executive put it, patient capital is the key in pursuit of PHA, as development process tends to be lengthy and error prone (Tullo, 2019). Since market conditions tend to alternate, there is a need for supportive regulatory environment to create a sustainable long-term market for PHA and other biodegradable plastics.

Both monoculture and mixed-microbial culture (MMC) have been widely investigated as possible feedstock for PHA production. Anjum et al. (2016) registered at least 70 different substrates as PHA feedstock, including sugar cane molasses and liquor, cheese whey, starch, cellulose, rice bran, corn starch, linseed oil, corn oil, acetic acid, lactic acid, waste vegetable oil, waste rapeseed oil, food processing waste, municipal wastewater, and more.

Both monoculture and MMC paths of PHA production have their own benefits and drawbacks. Production of PHA from MMC can have lower production cost since feedstock cost is low or zero in many cases. Moreover, such production does not involve land use challenges, as there is no need for growing crops as feedstock. Finally, handling the waste that makes up most of the MMC feedstock prompts circularity and industrial symbiosis.

2.3 PHA from mixed-microbial culture and wastewater

Many waste streams have been researched in either laboratory or pilot scale as feedstock for PHA production. Such waste streams include whey, waste oil, lignocellulosic waste, spent coffee grounds, glycerol, and even CO_2 (Khatami et al., 2021). Estévez-Alonso et al. (2021) have listed 19 pilots of microbial community-based PHA productions in the previous decade.

Among different waste streams, wastewater has an important place due to its abundance. Material recovery from wastewater has been investigated considerably in recent years. In a critical review of the literature, Kehrein et al. (2020) identified 11 resources that can be recovered from wastewater, including water, energy, nitrogen, phosphorus, CO_2, extracellular polymeric substances, volatile fatty acids (VFA), single-cell protein and more. WOW! project explored production of PHA, bio-oil, activated bio-char, bio-diesel, and acid acidic from the materials recovered from the wastewater (Wupperverband, 2020).

The variety of material that can be recovered from wastewater has started a new pattern, where waste is no longer seen as 'waste' but as 'residual material' (Best, n.d.) and consequently, municipal (solid and water) waste treatment plants can be regarded as 'urban bio-refineries'.

2.3.1 PHA production process from mixed-microbial culture

Figure 2 shows the process for production of PHA from MMC, including wastewater. An example of this process will be explained in section 2.4.2.1.

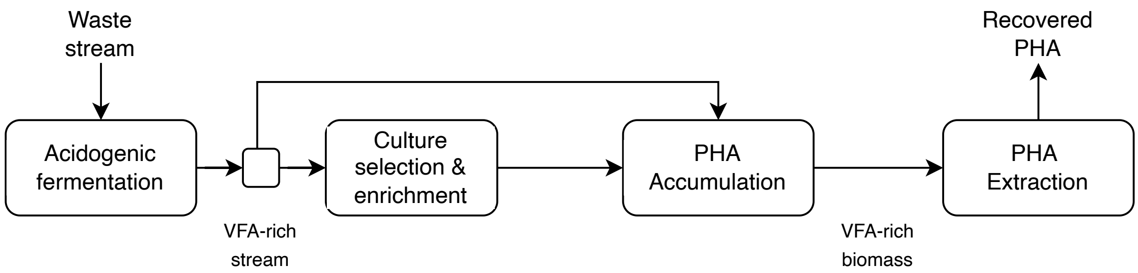

Figure 2. PHA production process from mixed-microbial culture (Khatami et al., 2021).

Every step of PHA production from MMC and wastewater is frequently researched with the aim of increasing process efficiency, improving the quality of the final product, and eventually decreasing the production costs. For example, Palmieri et al. (2021) investigated four different options for pre-treatment of wastewater and two separate PHA extraction methods, and found that homogenization with high pressure improves the extraction yield by 15% compared to other methods used in that research. Some of the factors impacting the PHA production include carbon/nitrogen and carbon/phosphorus ratio, pH control, and feedstock composition (Khatami et al., 2021).

PHA extraction is one of the consequential steps of PHA production, since due to energy demand, it has high impact on the cost of the final product. There are two main paths in PHA extraction: PHA recovery using solvents, and PHA recovery using cellular lysis. In the first approach, the PHA in the bacteria cell are solved using a solvent, whereas in the second approach, it is the biomass holding the PHA cells that goes through cell disruption and is later removed (Pagliano et al., 2021). Both paths have advantages and drawbacks with regards to PHA purity and recovery rate, as well as in cost and environmental friendliness. Other extraction methods such as mechanical disruption have been used in laboratories but have not succeeded for deployment in large industrial scale (Mannina et al., 2020).

Efficiency of PHA production from wastewater is measured using several values, among which PHA Accumulation Potential (PAP), sometimes referred to as Biomass PHA Content, is the most common one. PAP is defined as the weight ratio of PHA produced per volatile suspended solid in a waste material (gPHA/gVSS) (Estévez-Alonso et al., 2021). PAP of 0.4 gPHA/gVSS is generally considered the threshold for a wastewater flow to be suitable for financially feasible production of PHA (Bengtsson et al., 2017). Morgan-Sagastume et al. (2020) reported PAP of 0.40 to 0.70 gPHA/gVSS in a pilot plant, which produced PHA from wastewater of a potato-starch factory.

Pratt et al. (2019) identify organic waste as a suitable source for PHA production due to high presence of fatty acids, carbohydrates, and proteins, while also mention two conditions for actualizing such a value chain: organic waste has to be collected and stored to create a constant and uninterrupted flow, and a pretreatment technology has to be implemented for producing VFA and handling the undesired parts of the biomass.

2.3.2 PHA and biogas interaction in WWTPs

In recent decades, countries in European Union (EU) have adopted production of biogas through anaerobic digestion in WWTPs. It can be construed that PHA production from wastewater will be in competition with biogas production, and since the market price of PHA is much higher than that of biogas it can be expected that the former will be prioritized as soon as the technology is market ready. Conca et al. (2020) suggested that production of up to 4.9 m^3CH_4/PE (population equivalent) per year accounts for 0.58 €/PE annually, whereas a combined production of PHA and biogas using anaerobic digestion can produce up to 1.2 kg PHA/PE per year and result in income of up to 6.5 €/PE per year (assuming PHA price of 4-5 €/kg).

Some research suggests that PHA and biogas can and should be produced simultaneously from wastewater. ‘RESources from URban BIo-waSte’, abbreviated as ResUrbis, was a project funded by EU, operating during 2017-19. The project’s goal was to integrate the processing of various urban organic waste streams using a single technology (Majone, 2019).

Currently, different municipal waste streams such as organic municipal solid waste, wastewater, garden and park waste, and food-processing waste are treated separately using different technologies and probably in different locations. ResUrbis process was based on the premiss that it is more effective and efficient to handle these waste streams all together, using an integrated technology. The main product of such process then would be PHA, alongside secondary outputs such as nutrients, biogas, bio-solvents, and fibres.

2.3.3 Cost estimation of PHA from wastewater

Cost of PHA produced from wastewater has been estimated in several articles (Crutchik et al., 2020; Fernández-Dacosta et al., 2015; Fernando-Foncillas & Varrone, 2021). Some of these publications are based on either software modelling or secondary values from literature. For example, Fernando-Foncillas and Varrone (2021) modelled the PHA production from sewage sludge in combination with other organic waste in the Scandinavian countries, and concluded that the production cannot be profitable without subsidies. Moreover, they suggested that gate fees and the amount of treated material have key roles in increasing the revenue.

A few projects have estimated the cost of PHA produced from wastewater, using detailed techno-economic assessment, and based on long-run pilot projects.

2.4 Examples of notable wastewater PHA projects

During the past few years, interest in material extraction from wastewater has spawned many projects, which have engaged in laboratory or pilot PHA production from wastewater. The following includes a review of couple of notable wastewater PHA projects in recent years.

2.4.1 PHARIO - PHA2USE

PHARIO (‘PHA uit RIOolwater’ in Dutch translating to ‘PHA from sewage water’) was a project running during 2015-17, funded mostly by the Dutch government and different stakeholders in Dutch wastewater management. The pilot ran for 10 months creating 52 accumulation batches. (Bengtsson et al., 2017)

Researchers in PHARIO project evaluated different criteria that would affect PAP. Though higher levels of COD (chemical oxygen demand) and BOD (biochemical oxygen demand) is expected to lead to higher PAP, PHARIO researchers did not find any correlation between the two. Rather, the way Readily Biodegradable COD (RBCOD) is contacted with the biomass was discovered to have been the most critical factor in PAP enrichment. The lifecycle assessment (LCA) performed in the project also showed that in comparison with monoculture PHA, the wastewater PHA can have 70% lower environmental footprint, mostly due to using waste feedstock. (Bengtsson et al., 2017)

According to PHARIO project, wastewater PHA can be produced at 3.4 €/kg PHA. The production cost would include capital expenditure (CAPEX) of 80.3 M€ and annual operating expenditure of 10.4 M€, which would translate to 1.3 €/kg PHA and 2.1 €/kg PHA, respectively. For commercial viability, a minimum production level of 5,000 tons PHA/a was assumed. This amount will necessitate wastewater availability of one million population equivalent (PE) according to the PHARIO researchers. (Bengtsson et al., 2017)

In the continuation of the PHARIO project, a new project called PHA2USE is being pursued, where during 2022-23 a consortium of five water boards in the Netherlands alongside other partners are going to produce about ten tons of a type of PHA called PHBV (Biobased Delta, 2021). PHBV can be used in agriculture and horticulture applications, such as biodegradable pots, and also can be mixed into concrete for creating self-healing qualities (Biobased Delta, 2021). After laboratory and pilot stages of testing, this demo is considered the last step before full commercialized deployment of wastewater PHA production and will explore whether there is a market interest in this material.

2.4.2 WOW!

Wider business Opportunities for raw materials from Wastewater, or in short WOW!, was a project mostly funded by EU, running between 2018-21. The project had wide-ranging goals, including identification of potential value chains of sewage raw material, running pilots for production of several bioproducts from sewage, developing a Decision Support Tool for WWTP operators interested in biomaterial recovery and production, and creating policy action plans in both national and EU level (WOW!, 2022).

In three separate pilots of the WOW! project, five products were produced from three extracted material: biodiesel from lipids, bio-oil, biochar, and acid acetic from cellulose, which is present in wastewater from toilet papers, and finally PHA from waste activated sludge. The wastewater PHA production process used in the WOW! project (figure 3) is explained below.

2.4.2.1 WOW! PHA production process

Primary sludge from the WWTP will go through acidogenic fermentation, the result of which is fermented sludge, which is rich with VFA. Using a centrifuge, 77% of the VFA-rich solution is recovered and the rest exits the system as solid. The solution is then divided into two streams, where 36% of it is sent to a selection reactor. Extra sludge and water are added into the mix with ratios of 50% and 100% of the incoming sludge weight, respectively. Suitable biomass for PHA accumulation are enriched in this process and are then sent to the accumulation reactor, where they are fed with the other stream of VFA-rich solution of the first centrifuge. The resulting PHA-rich biomass then goes through a second centrifuge, where 97% of its weight is removed as effluent.

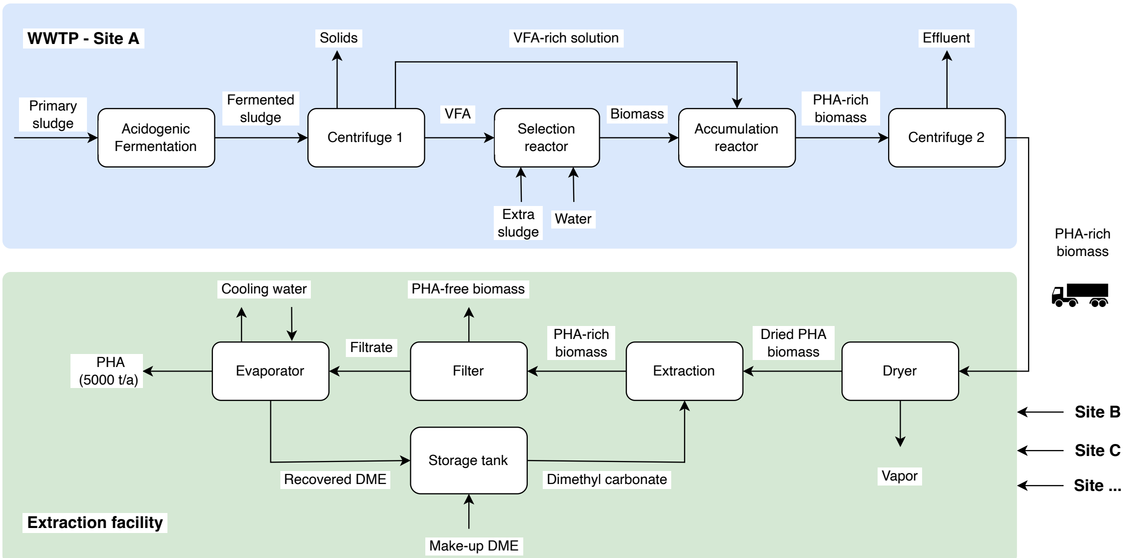

Figure 3. WOW! PHA production process (Khan et al., 2021).

Using trucks, the dewatered PHA-rich biomass is transported to a central extraction facility and is further dried at 100°C to a moisture content of 10%. The dried PHA-rich biomass is then mixed with a solvent called dimethyl carbonate, which is used at a ratio of 19 to 1 unit of biomass. The solution is mixed at 90°C for one hour and then goes through a filter, where the biomass is removed. The filtrate mixture of PHA and dimethyl carbonate is then sent to an evaporator, where 99.5% of the solvent is recovered and stocked in a storage tank. The pure PHA is recovered as the final product.

Same as in the PHARIO project, a minimum of 5,000 tons of PHA per year is assumed in the WOW! project as the threshold for economic feasibility of the wastewater PHA production. Based on the results of this project, the 5,000 tons of PHA requires WWTP flow of 2,168,518 PE per year. As there are not many WWTPs in Europe with such capacity, several WWTPs are needed for making the minimum required tonnage. Further details of the operation can be found at Khan et al. (2021) and Uhrig et al. (2022).

2.4.2.2 WOW! project results

In WOW! PHA pilot project, only wastewater sludge was used, and no aid flows or chemicals were added. The produced PHA was composed of PHB and PHV, and the ratio of the two in the output remained stable during all seasons. (Uhrig et al., 2022)

In the WOW! project's Techno-Economic Assessment for production of wastewater PHA, it was assumed that 10 WWTPs with the same capacity and all with a 50 km distance from a central extraction facility, will participate in a combined production of 5,000 tons PHA/a. Results showed that in such a scenario, PHA can be produced with the cost of 3.57 €/kg. The annualized capital expenditure (CAPEX) and operating expenses (OPEX) of this scenario were 3.87 M€ and 13.97 M€, respectively. Sensitivity analysis of the results showed that PHA yield and cell disruption efficiency were the two factors with the highest impact on the PHA unit price. (Khan et al., 2021)

In a policy report, recommendations were proposed both at EU and the national levels, with intention of facilitating material recovery from wastewater. Some of the recommendations are as follows: providing a new definition for waste so the material are not considered as waste after one time usage, passing the legal obligations to utilities and manufacturers for material recovery, harmonizing the legislation related to interpretation, assessment, and processing of waste, and creating market incentives for processing and trading of recovered material. (Best, n.d.)

A likely second phase of the WOW! project will further explore other possibilities of PHA production. As the current technology setup has high capital costs for participating WWTPs, feasibility of producing PHA in small to medium size WWTPs (with capacities lower than 50,000 PE) will be explored. Possibility of utilizing other residual streams such as those from the food processing industries as well as industrial wastewater will also be explored. (WOW!, 2021b)

3 Materials and methods

This chapters presents the materials and methods used in this research. Section 3.1 introduces techno-economic assessment as the main approach of this research. Section 3.2 exhibits the formulas used in the calculation of matter flow and energy consumption during the wastewater PHA production process. Section 3.3 discusses the criteria for selecting the WWTPs to be included in the production scheme, while that process is continued in section 3.4, where several scenarios are built based on the available WWTPs. Section 3.5 describes the methods used for calculations related to the transportation, and section 3.6 explains the procedures for calculating the operating and capital costs, and consequently the unit cost of wastewater PHA. Sensitivity analysis is briefly discussed in sections 3.7.

3.1 Techno-economic assessment

For feasibility study of producing a chemical at industrial levels, techno-economic assessment is an important and useful approach. A techno-economic assessment (TEA) creates a link between the process and financial parameters with the purpose of evaluating the financial feasibility of project and identifying the factors that affect its profitability. TEA consists of process modelling, capital cost modelling, operating cost assessment, and potentially cash flow analysis. Sensitivity analysis is usually used to identify threats and opportunities in the project. (Burk, 2017)

In this research, TEA is used for the assessment of the feasibility of PHA production from wastewater sludge in Finland's WWTPs. The technical and economic assumptions are based on the most recent similar assessments.

3.2 Matter and energy balance calculation

From among several projects and PHA production set-ups, WOW! project's PHA production process was selected as the basis for this techno-economic assessment. The reasons for this selection are as follows: the project was well-funded and was performed over several years, it was recent and had integrated the results of previous projects, there were several institutional participants in the endeavour, it was based on actual pilots and not just literature, and finally, it was documented in detail. The assumed wastewater PHA production process was shown in figure 3. The equipment' type and specification are presented in table 1.

Table 1. PHA plant equipment and their operational data (Khan et al., 2021).

Plant equipment	Type	Energy requirements		
		Electricity (kWh/m^3)	Heat (kWh/m^3)	Steam
Fermentation reactor	Heated anaerobic batch	96.9	23.4	-
Centrifuge 1	Continuous	1.88	-	-
Selection reactor	Sequencing batch	2.51	-	-
Accumulation reactor	Sequencing batch	2.4	-	-
Centrifuge 2	Continuous	1.88	-	-
Dryer	Falling curtain	0.16 kWh/kg-evap	1.45 kWh/kg-evap	-
Extraction reactor	Heated batch reactor	0.006	-	1.1 t/t dried PHA
Filter	-	-	-	-
Evaporator	Rotary	-	-	0.06 t/t filtrate

It is assumed that 5,000 tons of PHA per year needs to be produced at the extraction facility. There are not any WWTPs in Finland that could provide enough sludge for this capacity, and consequently, several WWTPs need to be involved in the production of PHA-rich biomass and its dispatchment to a central extraction facility.

Matter and energy balance was calculated in each WWTP and in the PHA extraction centre. The reference for most of the assumptions is Khan et al. (2021). The formula and calculation procedure in matter and energy balance are presented in appendix 1. Using the assumptions in table 1, the electricity, heat, and steam demand of each different step was calculated for all Finnish WWTPs.

3.3 WWTP selection

There are 152 Finnish WWTPs in the European Commission Urban Waste Water Website (n.d.) , from which the geolocation (latitude and longitude) and the annual receiving load for all these WWTPs were acquired. As expected, the WWTPs are close to Finland's population centres (figure 4).

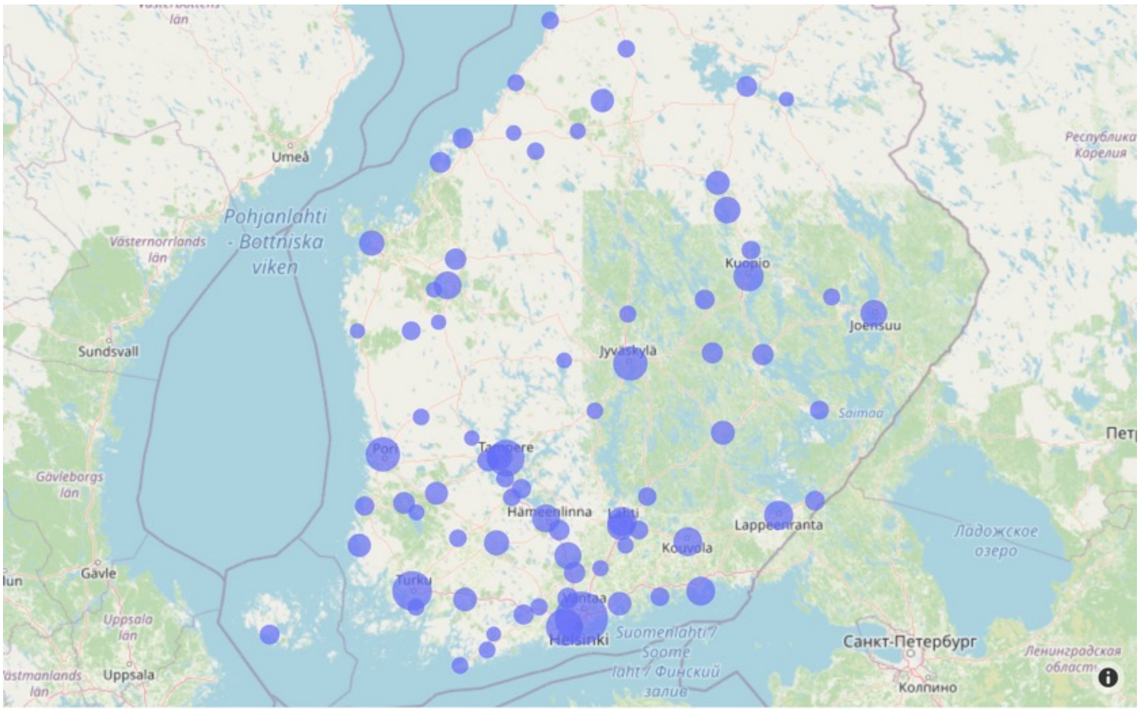

Figure 4. Distribution and annual receiving load of WWTPs in Finland (European Commission urban waste water website, n.d.).

Vast majority of the Finland's WWTPs have low annual receiving load, while few WWTPs account for most of the national wastewater load (figure 5). Meanwhile, using current technology, smaller WWTPs might not be suitable for PHA production, as annual PHA output might not justify the CAPEX costs. Therefore, to be considered for PHA production scheme, a cut-off for minimum PE for a WWTP needs to be assumed. This was achieved using Decision Support Tool, an output of the WOW! project (WOW!, 2021a).

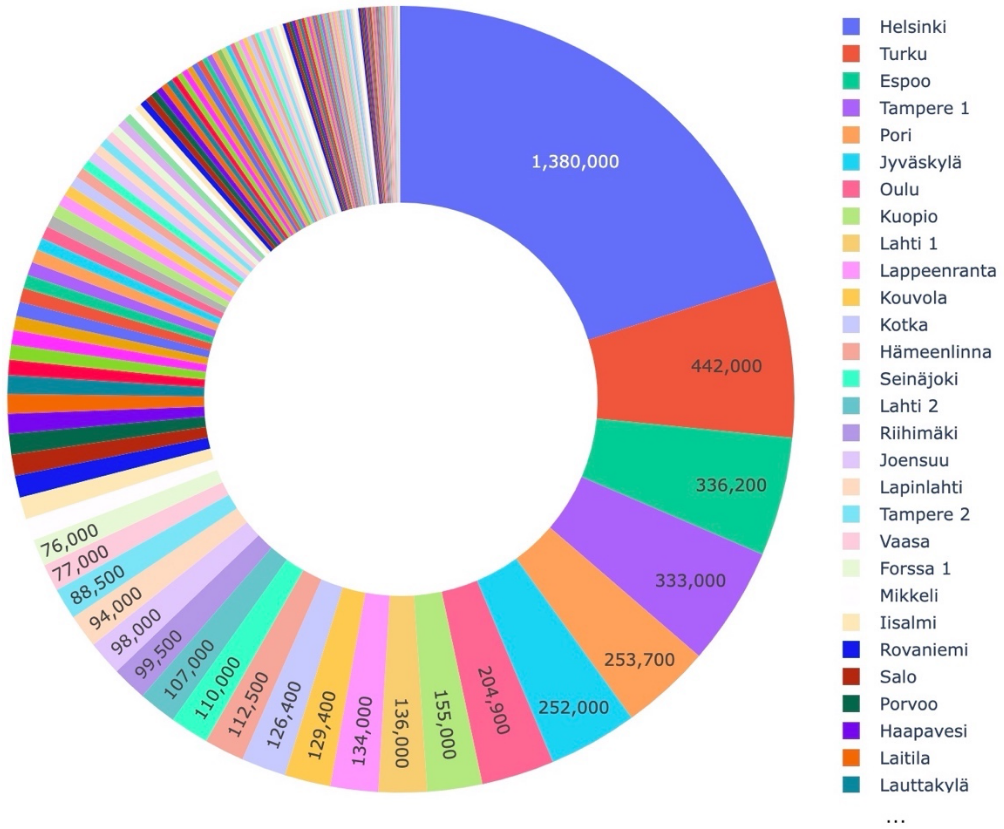

Figure 5. Annual load of Finland's WWTPs in 2018 in population equivalent.

WOW! project's Decision Support Tool (WOW!, 2021a) assists decision makers in selecting suitable WWTPs for production of either PHA, lipids, or cellulose, by dividing the WWTPs in three groups according to their PE. WWTPs in the first group with large PE are assumed to be promising for using the chosen technology. In the second group, decision cannot be made merely based on a plant's PE and other details are to be considered. Smaller WWTPs of the third group are not considered suitable on their own for the chosen product.

For performing an analysis of PHA production, four criteria are considered as inputs in Decision Support Tool: presence of primary treatment in the WWTP, as well as the plant's PE, BOD, and COD. Primary treatment is present in all of Finland's sizeable WWTPs, while PE information was also available as mentioned earlier. BOD and COD were further calculated.

Recent data and characteristics of the two Lahti WWTPs were available through the city's application for the European Green Capital Award 2021 (City of Lahti, n.d.). Using that data, the average BOD7 and COD of Kariniemi and Ali-Juhakkala WWTPs between 2012 and 2017 was calculated to be 414 mg/l and 816 mg/l, respectively. Average water consumption in Finland is about 155 litre per person (*Vedenkulutus*, n.d.), which means the aforementioned BOD7 and COD values are about 64 g/day and 126 g/day, respectively. Other WWTPs in Finland were assumed to have about the same values for BOD7 and COD.

Based on the above-mentioned values, from the scenarios available in the Decision Support Tool, Finland is closed to Luxembourg, with BOD of 60 g/day, COD of 120 g/day, and average water consumption of 150 litres per person per day. Using these assumptions in the tool resulted in the cut-off value of 50,000 PE, as the minimum capacity for a WWTP in Finland to be considered feasible for production of PHA. Accordingly, ranging from Helsinki WWTP with annual load of 1,380,000 PE to Lauttakylä WWTP with 52,200 PE, 29 of the 152 WWTPs were selected. With an aggregate load of 5,211,800 PE, the 29 selected WWTPs account for 76% of the total wastewater received in 152 WWTPs in Finland (figure 5). Various combinations of these plants were used for creation of different PHA production scenarios, further discussed in the next section.

3.4 PHA production scenarios

To meet the minimum 5,000 tons PHA production capacity per year, five scenarios were created, where in each scenario between 3 to 16 WWTPs were chosen (figure 6). In all the scenarios, it is assumed that the PHA extraction facility will be based in Lahti, within 10 kilometres of the Lahti train station. In each scenario, WWTPs are ordered from bottom to top by their proximity to this location.

Scenario 1 consisted of Finland's three biggest WWTPs, Helsinki, Turku, and Espoo; this is the minimum number of participating WWTPs for wastewater PHA production in Finland. In scenarios 2-5, Lathi's two WWTPs, Kariniemi and Ali-Juhakkala, were included. In scenario 2, Lahti and capital region's WWTPs were joined with two closest plants in Riihimäki and Kouvola, making a total of 6 participants. Scenarios 3-5 explore the possibility of WWTPs of the capital region not joining the PHA production. Scenario 3 consists of WWTPs closest to Lahti, regardless of their size and excluding the two treatment plants of the capital region, resulting in 14 participants. These WWTPs are Ali-Juhakkala and Kariniemi plants in Lahti, Viinikanlahti and Rahola plants in Tampere, and WWTPs in Riihimäki, Kouvola, Hämeenlinna, Porvoo, Forssa, Kotka, Mikkeli, Lappeenranta, Jyväskylä and Turku. In Scenario 4, five small WWTPs in scenario 3, consisting of plants in Porvoo, Mikkeli, Forssa, Hämeenlinna, and Rahola in Tampere, are replaced with two bigger yet farther away plants in Pori and Kuopio, reducing the number of participants to 11. Scenario 5 explores the possibility of Turku WWTP not participating alongside the capital region's WWTPs, in which case it is replaced by WWTPs of Pori, Kuopio, and Lauttakylä, resulting in a total of 15 participating WWTPs.

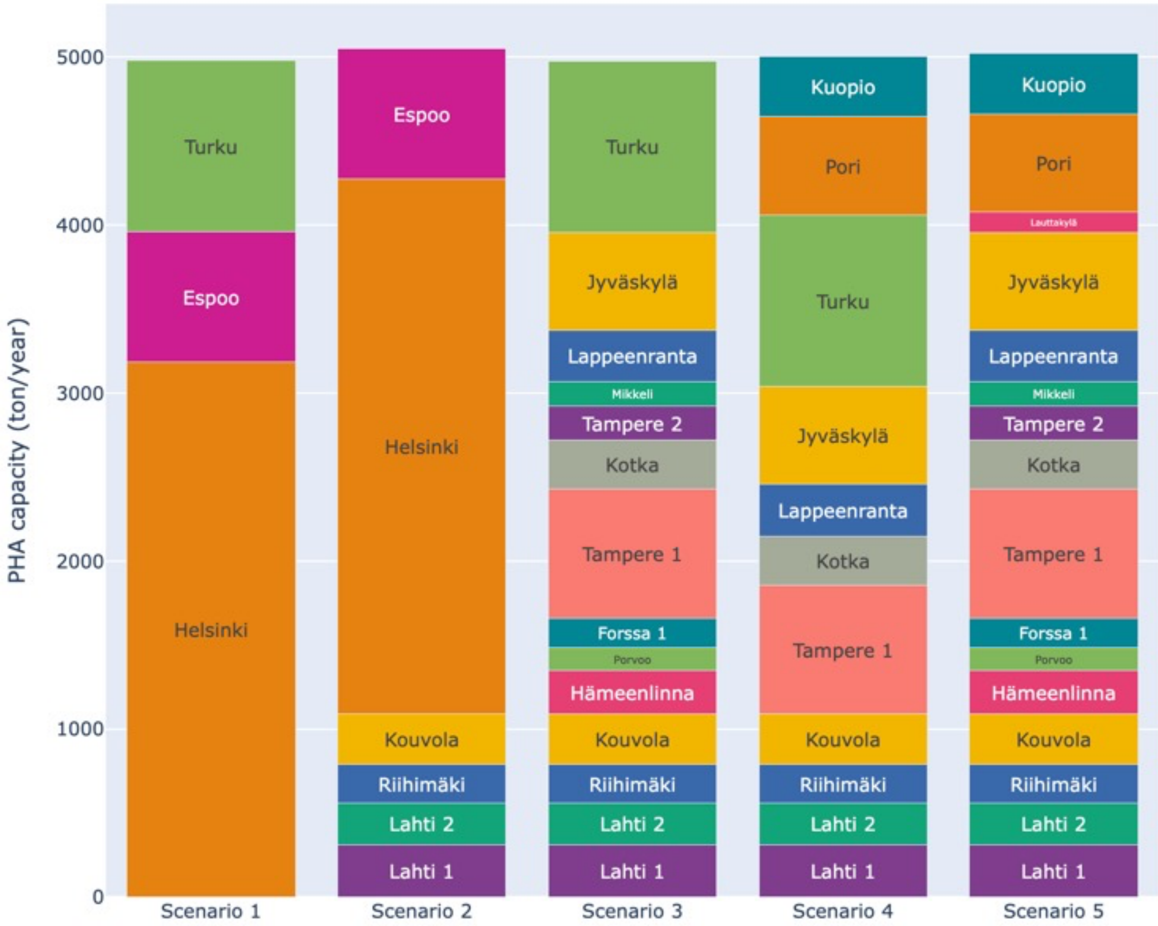

Figure 6. Scenarios for PHA production from wastewater in Finland's WWTPs.

While other combinations are possible, the five mentioned scenarios test the most important criteria on selecting WWTPs, such as PHA production capacity, distance to Lahti, impact of big WWTPs participating or not, and the impact of number of plants present in the production.

3.5 Transportation cost calculation

Due to dispersity of the population centres in Finland, it was important to calculate the cost of the PHA-rich biomass transportation from different WWTPs to the central extraction facility. It was assumed that the extraction facility would be located in the Päijät-Häme region and within 10 km from the Lahti train station in order to cover industrial areas such as Kujala and Hollola.

The distance between each WWTP and the assumed destination close to Lahti was calculated twice using Here Routing API, as well as by Google Maps' Direction API. The two results were similar, and the latter was used as the basis for distance calculation. The missing distances not covered by the API were calculated using Google Maps. Cost of transport and loading/unloading were assumed to be 0.08 €/ton.km and 1 €/t, respectively (Khan et al., 2021). Using these assumptions and the annual amount of dewatered PHA-rich biomass produced at each WWTP, the total annual transportation cost and consequently, the average transportation cost per kg of PHA was calculated.

3.6 Economic calculations

To calculate the unit cost of PHA, investment or capital expenditure (CAPEX) and operating expenses (OPEX) for all WWTPs and the extraction facility needs to be calculated. The economic assumptions in this section are based on Khan et al. (2021).

For the equipment in the WWTPs, flow of each equipment was divided by the operating hours, which assumed to be 8,000 hours per year, though expected to increase in future after the production process is balanced. Using each equipment's capital cost, reference capacity, and scale factor presented in table 2, cost of each equipment in every WWTP was calculated using formula 1.

$$C_2 = C_1 \left(\frac{S_2}{S_a}\right)^n \qquad \textbf{(1)}$$

where, C_1 is the cost of equipment at capacity S_1, C_2 is the cost of equipment at capacity S_2, and n is a scale factor varying between 0.3 and 1.2, depending on the equipment. The well-known rule of six-tenth states that the scale factor in the equation (1) can assumed to be around 0.6. The scale factor for various chemical process equipment have been suggested by different researchers and most of them fall between 0.6 and 0.8. (Couper, 2009)

Beside the cost of equipment, CAPEX included other costs related to the installation. These costs which were calculated as percentages of CAPEX are as follows: piping, instrumentation/electrical, engineering costs, civil works, and start up, which were estimated as 15%, 25%, 10%, 34%, and 12% of the CAPEX, respectively. Together these will add 96% to the cost of equipment, the result of which is the total CAPEX.

Table 2. Assumptions for equipment and operating labour (Khan et al., 2021).

Plant equipment	Capital cost (€)	Reference capacity	Scale factor	Lifetime (yr)	Personnel (per shift)
Fermentation reactors	185 000	125 m^3	0.75	40	0.02
Centrifuge 1	235 000	4 m^3/h	0.6	25	0.35
Selection reactor	263 947	30 m^3/d	0.78	40	0.5
Accumulation reactor	263 947	30 m^3/d	0.78	40	0.5
Centrifuge 2	235 000	4 m^3/h	0.6	25	0.35
Dryer	118 000	51.6 kg-vapor/h	0.6	25	0.5
Extraction reactor	50 255	125 m^3	0.78	15	0.2
Filter	341	100 m^3/day	0.6	1	0.15
Rotary evaporator	2 550	0.02 m^3/h	0.6	15	0.25

The capital cost of the equipment used in the extraction facility, which includes dryer, extraction reactor, filter, and evaporator, were obtained from Khan et al. (2021), since the annual production in different scenarios are close to 5,000 tons of PHA, same as in the WOW! project.

The total cost of CAPEX for the equipment were annualized using formula 2, where equipment lifetime is acquired from table 2 and the weighted average cost of capital (WACC) was assumed to be 4.1%. (Khan et al., 2021)

$$Annualized\ cost = \frac{equipment's\ CAPEX\ over\ lifetime}{\frac{1-(1+WACC)^{equipment\ lifetime}}{WACC}} \qquad \textbf{(2)}$$

OPEX was calculated based on the assumptions in table 3. Labour costs were calculated by multiplying the personnel demands of the equipment (table 2) by the operating hours and the average labour cost of 31.2 €/h. Maintenance costs assumed to be 67% of the labour, while insurance costs assumed to be 0.5% of the total CAPEX cost.

The unit cost of electricity, natural gas, and steam assumed to be 93 €/MWh, 34 €/MWh, and 24.6 €/t, respectively (Khan et al., 2021). Using these and the energy demand of each process, which was calculated as explained in section 3.1, the aggregate energy costs were determined. Transportation cost was computed as explained in the section 3.4.

Table 3. CAPEX and OPEX assumptions (Khan et al., 2021).

Item	Unit	Value
Plant lifetime	y	25
Base year	-	2019
Piping	% CAPEX	0.15
Instrumentation/Electrical	% CAPEX	0.25
Engineering costs	% CAPEX	0.1
Civil works	% CAPEX	0.34
Start-up	% CAPEX	0.12
Operating hours	h/y	8000
Insurance	€	0.005 of investment
Maintenance	€	0.667 of labour costs
Labour cost	€/h	31.2
Electricity	€/MWh	93
Natural gas	€/MWh	34
Steam	€/t	24.6
Cooling water	€/m^3	0.5
Process water	€/m^3	1
Dimethyl carbonate	€/kg	1
Biomass transport distance	km	50
Biomass transport cost	€/t	0.08
Loading/unloading cost	€/t	1 (each)

Using CAPEX, OPEX and the annual PHA output, the unit PHA cost can then be calculated using formula 3 (Khan et al., 2021).

$$Unit\ cost\ of\ PHA = \frac{Annualized\ CAPEX + OPEX}{Annual\ output\ (kg/a)} \qquad (\mathbf{3})$$

The salvage value of some of the equipment, which outlast the 25-year lifetime of the plant, were not taken into the account in this research.

3.7 Sensitivity analysis

The technical and economic factors effecting the total cost of PHA production have been analysed in detail by Khan et al. (2021). In this research, the focus of the sensitivity analysis was given to economic factors and mainly to electricity and heat, which are the factors with the highest contribution to the cost of PHA. Impacts of changes in the amount of CAPEX and the number of participating WWTPs were also studied. The inspection was carried out using what-if analysis in Excel.

4 Results and discussion

The results of the research are presented in sections 4.1-4.4. Sensitivity analysis results for some of the important factors affecting the cost of wastewater PHA is shown in section 4.5. Discussions are concluded by exploring the road ahead in section 4.6.

4.1 Finland’s total wastewater potential

From the 152 WWTPs in Finland, 29 with the individual load of 50,000 PE and above are more suitable for PHA production, using the current technology. PHARIO project had estimation of 200 PE of annual load for production of one ton of PHA, while the later WOW! project has that number closer to 430 PE. Based on these estimations, the 29 WWTPs with a combined load of 5,211,800 PE can produce between 12,000 and 26,000 tons of PHA per year. Based on 430 PE/ton PHA per year, the potential annual PHA output of the selected 29 WWTPs are shown in figure 7.

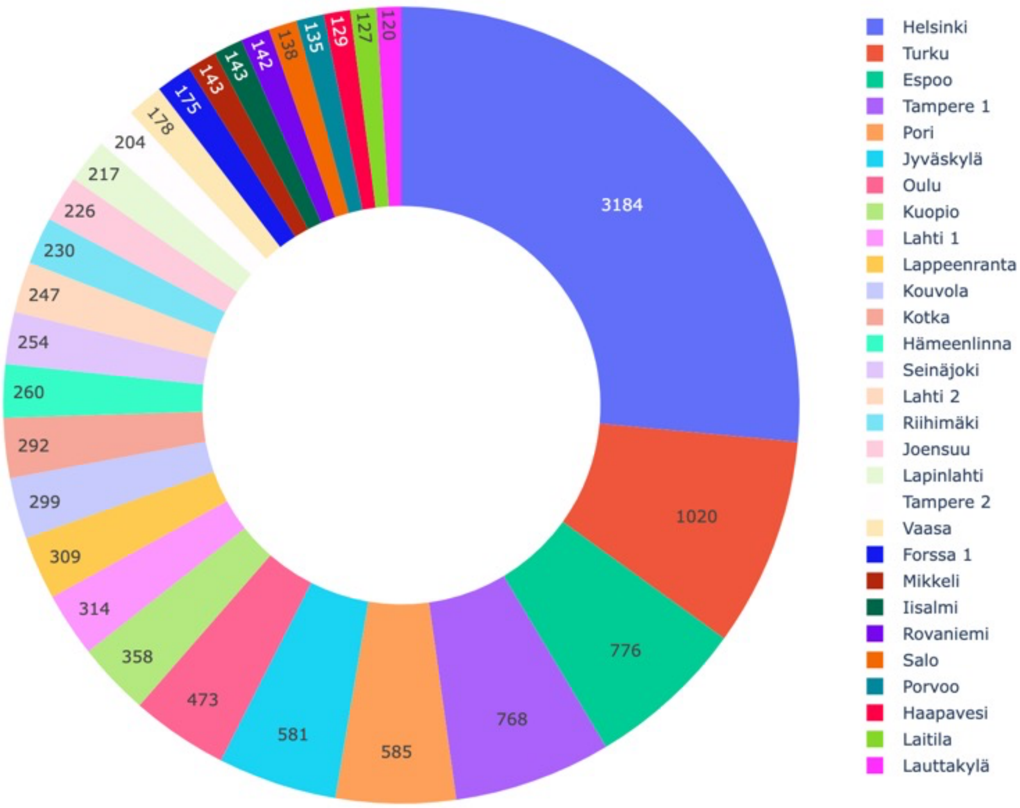

Figure 7. PHA output potential (tons/a) of WWTPs with loads higher than 50,000 PE.

As the range of Finland's annual PHA production potential vary significantly from 12,000 t/a to 26,000 t/a, it is interesting to see which one of these numbers will be closer to reality based on the results of PHA2USE, which is the next phase of the PHARIO project and will run during 2022-23.

Based on the assumption of 200 PE load per one ton of PHA, the Helsinki WWTP can produce 6,900 tons PHA per year, which means it can pursue PHA production without participation of other WWTPs.

4.2 PHA cost in different scenarios

The production cost of PHA was calculated for all the five scenarios defined in section 3.3 and the results can be seen in figure 8. PHA cost for scenarios 1 to 5, were 3.4 €/kg PHA, 3.45 €/kg PHA, 3.72 €/kg PHA, 3.68 €/kg PHA, and 3.76 €/kg PHA, respectively. The results seem to be in the same range of the literature, notably 3.4 €/kg PHA in PHARIO project (Bengtsson et al., 2017) and 3.57 €/kg PHA in WOW! project (Khan et al., 2021). Considering the estimated market price of 3.5 - 4.5 €/kg, scenarios 3, 4 and 5 are not considered favourable and the first two scenarios have better of chance of realization. This means that participation of the big capital region's WWTPs is key in lowering the production cost and enhancing the feasibility of PHA production from wastewater in Finland.

Since the production capacities in all the five scenarios are about 5,000 tons/a, there is not a sizeable difference in the OPEX values, ranging from 13,950,703 €/a to 14,243,373 €/a or 2.79 €/kg PHA to 2.84 €/kg PHA (table 4). The deciding factor in the cost variation of different scenarios is CAPEX, which is directly connected to the number of WWTPs participating in PHA production. Scenario 1 with only 3 WWTPs has annualized CAPEX of 2,958,596 €/a or 0.59 €/kg PHA, while scenario 5 with 16 participating WWTPs has annualized CAPEX of 4,654,862 €/a or 0.93 €/kg PHA.

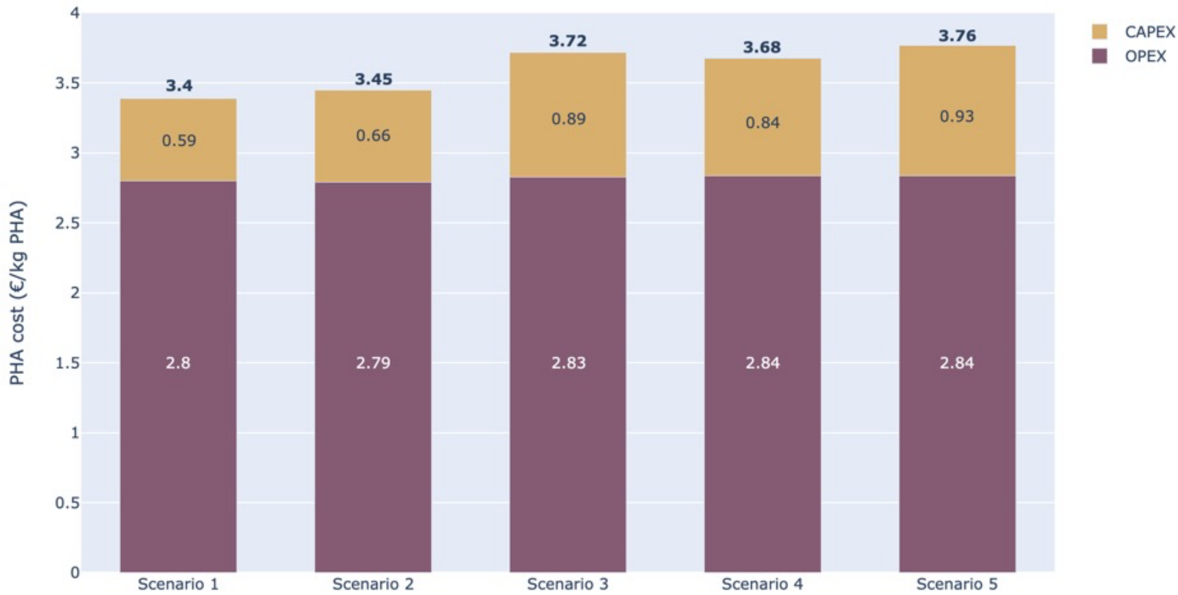

Figure 8. Cost of PHA in different scenarios.

It is important to note that authors of WOW! project's techno-economic assessment, the process of which was used in this research, admit that since part of the cost calculation methods is based only on the literature, there is a possibility that CAPEX results are more optimistic than reality, and therefore, even the attractiveness of the first two scenarios need to be handled with caution.

Table 4. PHA cost comparison between scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Number of WWTPs	3	6	14	11	16
Production capacity (ton/s)	4980	5050	4977	5003	5020
CAPEX total (€)	54 396 367	60 891 770	80 577 153	76 980 739	84 831 372
CAPEX annualized (€)	2 958 596	3 320 499	4 417 872	4 214 774	4 654 862
OPEX (€)	13 950 703	14 084 190	14 076 362	14 202 096	14 243 373
CAPEX unit (€/kg PHA)	0.59	0.66	0.89	0.84	0.93
OPEX unit (€/kg PHA)	2.80	2.79	2.83	2.84	2.84
PHA cost (€/kg PHA)	3.40	3.45	3.72	3.68	3.76

While scenario 1 with participating WWTPs of Helsinki, Turku and Espoo has the lowest production cost of 3.40 €/kg PHA, for practical reasons it can be assumed that Lahti WWTPs will be participating in the production. Hence, scenario 2 with 6 WWTPs and cost of 3.45 €/kg PHA is considered the mostly likely scenario and is further used for analysis of production cost breakdown and sensitivity analysis.

4.3 PHA production cost breakdown

Different components of CAPEX and OPEX of scenario 2, as the most realistic scenario, are discussed in this section. OPEX of scenario 2 stands at 14,084,190 €/a (figure 9). With 62%, 12%, and 4% of the total OPEX, respectively, electricity, heat, and steam account for sizeable total of 78% of OPEX. Energy price variation can swing the PHA production cost considerably and as a result, their price range needs to be addressed during the project design phase. Cost of material, which includes solvent and water, together represent 9% of the OPEX, while labour, maintenance, and insurance, together account for 12% of that cost. Transportation, which will be discussed in detail in section 4.4, account for 2% of the OPEX.

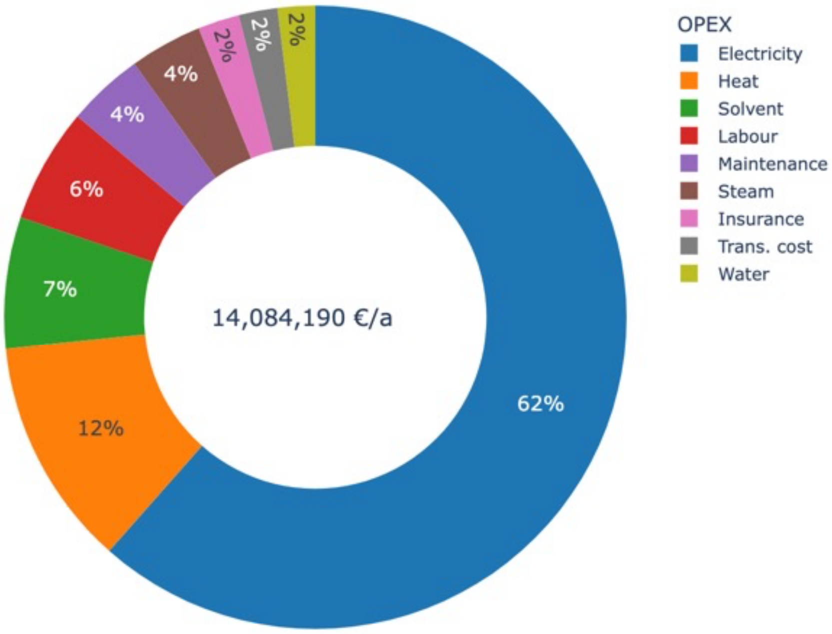

Figure 9. OPEX components in scenario 2.

The total CAPEX of scenario 2 was calculated as 60,891,770 €, which based on the 25-year lifetime of the project will translate to annualized CAPEX of 3,320,499 €/a (figure 10). The extraction facility, consisting of dryer and PHA extraction, accounts for merely 3% of the annualized CAPEX, while most of the cost occurs in the 6 WWTPs present in this scenario.

Table 5 shows the combined share of CAPEX and OPEX components in cost of PHA in scenario 2. From the total cost of 3.45 €/kg PHA, CAPEX accounts for 0.66 €/kg (or 19% of the cost), while OPEX represents 2.79 €/kg PHA (or 81% of the cost). PHA production and biomass selection have the highest shares of CAPEX, with 7% and 5% of the total cost, respectively.

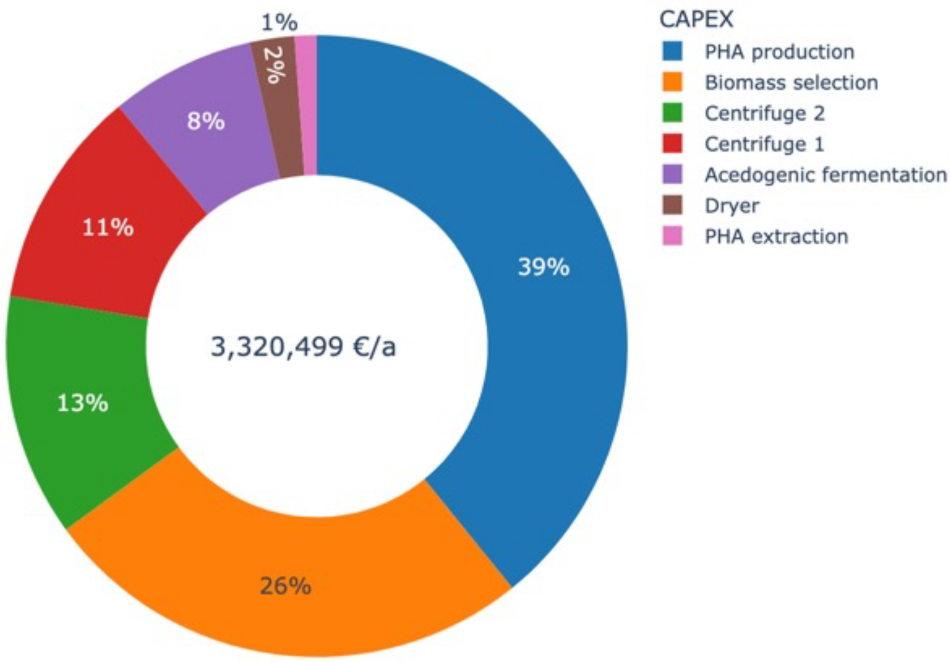

Figure 10. Annualized CAPEX components in scenario 2.

Table 5. Share of different components in cost of PHA in scenario 2.

	Share (%)	Cost (€/kg PHA)		
Transport	2 %	0.06	OPEX	81% 2.79 €
Water	2 %	0.05		
Solvent	6 %	0.19		
Steam	3 %	0.10		
Heat	10 %	0.33		
Electricity	50 %	1.72		
Insurance	2 %	0.06		
Maintenance	3 %	0.11		
Labour	5 %	0.17		
PHA extraction	0.2 %	0.01	CAPEX	19% 0.66 €
Dryer	0.4 %	0.02		
Centrifuge 2	2 %	0.08		
PHA production	7 %	0.26		
Biomass selection	5 %	0.17		
Centrifuge 1	2 %	0.08		
Acedogenic fermentation	1 %	0.05		
Total		**3.45**		

Since electricity, heat and steam together stand for 63% of the PHA cost, it is important to explore the ways to reduce these expenses, as even marginal cost reduction in these fields will have a noticeable effect on the PHA price. In scenario 2, about 90 GWh of electricity is used in WWTPs every year, a majority of which is used during acidogenic fermentation (table 6). Electricity consumption of the extraction facility is about 3.2 GWh per year. Acquisition of cheaper electricity in each of the 6 WWTPs will impact the cost of PHA, while this impact will be higher in bigger WWTPs such as Helsinki and Espoo.

The aggregate heat demand of the six WWTPs is about 20 GWh per year, which is mostly used in the acidogenic fermentation step at temperature of 35°C. The extraction facility uses 29 GWh of heat per year at 80-100°C for drying the biomass, as well as about 21 GWh of steam at 90°C for the extraction and evaporation.

Table 6. Annual energy consumption in WWTPs and in the extraction facility in scenario 2.

		Electricity (MWh/a)	Heat (MWh/a)	Steam (MWh/a)
WWTPs	Helsinki	56 714	12 567	-
	Espoo	13 817	3 062	
	Lahti 1	5 589	1 238	
	Kouvola	5 318	1 178	-
	Lahti 2	4 397	974	-
	Riihimäki	4 089	906	-
Extraction facility		3 201	29 000	21 338
Total		**93 125**	**48 925**	**21 338**

Using suitable waste heat in the operation can lead to cost reductions. Moving WWTPs is not feasible, hence efforts can be made to use any waste heat source close to each plant. Extraction facility, however, can be located anywhere based on different criteria, one of which is proximity to waste heat resources, such as industrial facilities and data centres. As a result, pursuing industrial symbiosis is crucial in lowering the PHA cost. Impact of price differences of electricity and heat on PHA cost is examined in more detail in section 4.5.

4.4 Transportation cost

The unit cost of PHA-biomass transportation in each of the 29 selected WWTP is presented in figure 11. The width of each bar represents the size of annual PHA output, and the height represents both the unit cost of transportation per kilogram of the produced PHA (left axis), as well as the distance of the WWTP from the industrial area Kujala in Lahti (right axis). The average cost of PHA-biomass transportation is 0.10 €/kg PHA. It is seen that the transportation cost of 75% of possible tonnage (that is 9,000 tons of the total possible 12,000 tons) is about 0.10 €/kg PHA, or less. Considering the final price of 3.45 €/kg PHA, the cost of transportation is marginal and is not a prohibitive factor for participation of most of the WWTPs in PHA production.

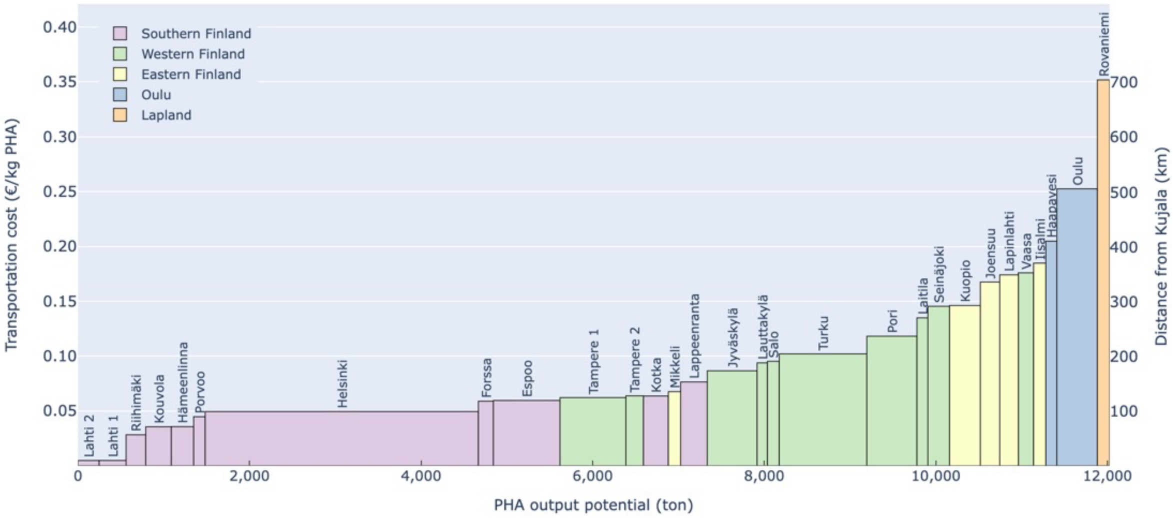

Figure 11. Cost of PHA biomass transportation from WWTPs to Lahti region.

In the five evaluated scenarios, the cost of transportation ranged from 0.06 to 0.09 € for every kilogram of PHA produced, accounting for between 1.6% to 2.4% of the total cost. It is seen that there is no sensible variability between different scenarios with regards to the transportation cost. Consequently, it can also be argued that the location of the extraction facility does not have a noticeable impact on the total cost, since at best it will save less than 0.06 € from the cost of one kilogram of PHA. As a result, it is reasonable to consider locating the centralized extraction facility based on other factors, such as proximity to waste heat sources, possibility of industrial symbiosis, and such. Using rail transportation, wherever possible, can lead to marginal cost reduction as well.

4.5 Sensitivity Analysis

As seen in section 4.3, with 50% and 10% respectively, electricity and heat had the highest contribution to the total PHA cost. Consequently, their price variability will have significant impact on PHA production's loss or profitability. For purpose of comparability, the prices of electricity and natural gas for heating were assumed to be the same values as in the WOW! techno-economic assessment (Khan et al., 2021), that is 34 €/MWh for fossil gas for heating demand and 93 €/MWh for electricity.

PHA price is very sensitive to electricity prices, as price variation of ±10 €/MWh for electricity results in ±0.18 €/kg of PHA (figure 12). Change in heat cost also has an impact on PHA cost, albeit to a lesser extent; ±10 €/MWh variation in heat cost leads to ±0.10 €/kg of PHA. It is worth noting that as Finland moves to carbon neutrality, many industrial processes are expected to be electrified, and as a result, in future cost of electrified heat needs to be evaluated in PHA production.

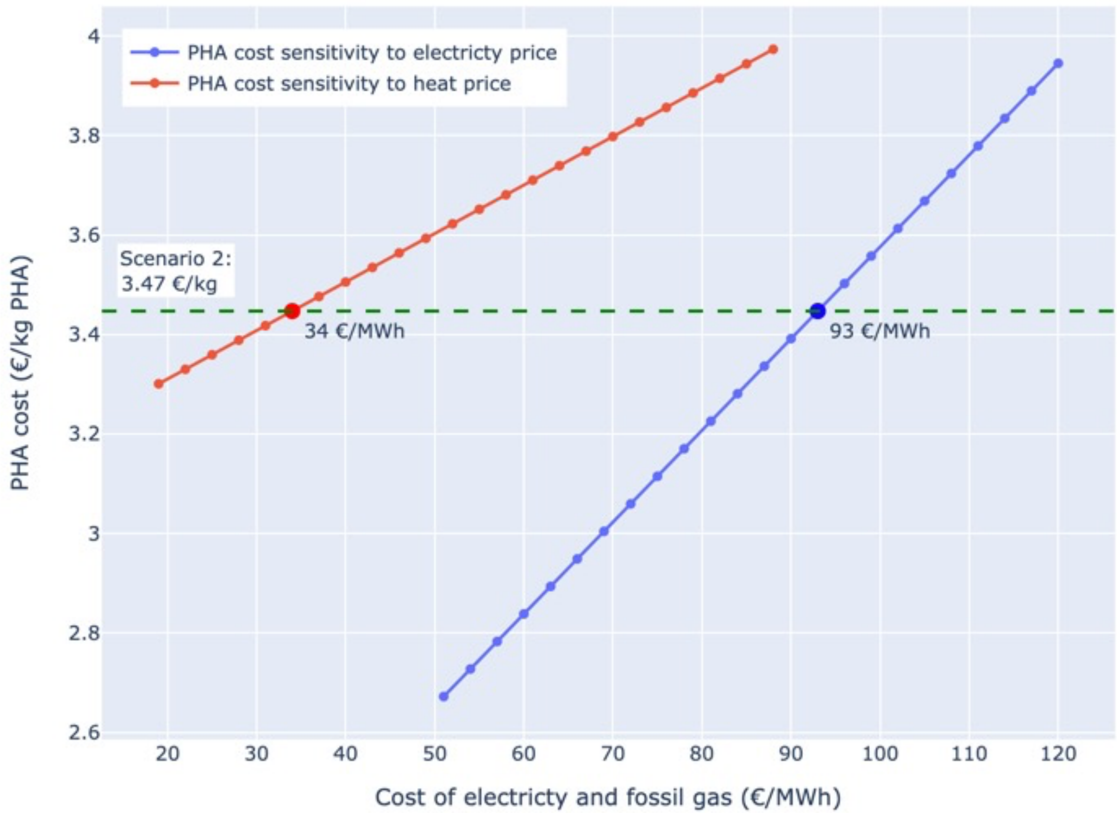

Figure 12. Impact of electricity and fossil gas cost on the cost of PHA in scenario 2.

As mentioned in 4.2, there is a possibility that CAPEX costs in this research are underestimated. Hence, it is necessary to determine the impact of CAPEX cost increases on the cost of PHA. As CAPEX accounts for 19% of the PHA cost, its increase leads to a notable PHA price elevation. An increase of 10% in CAPEX cost results in 0.065 € price rise in every kilogram of PHA (figure 13).

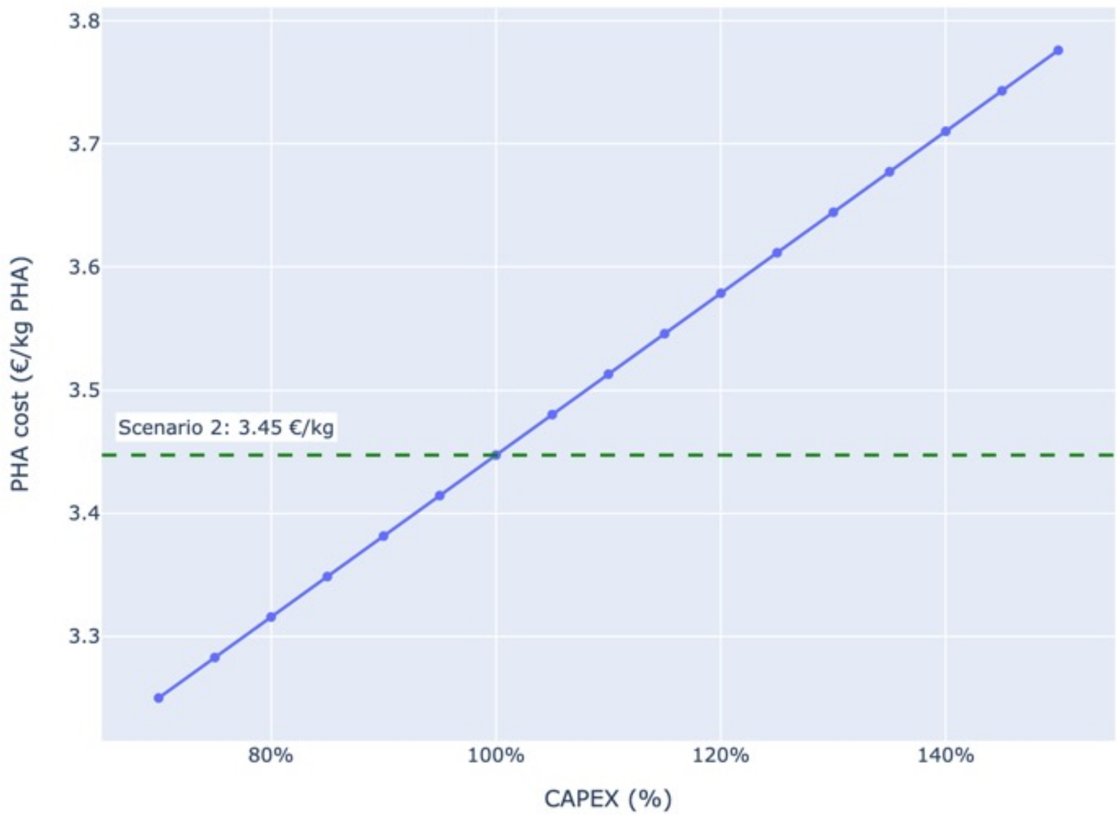

Figure 13. Impact of CAPEX on PHA cost in scenario 2.

Finally, the impact of the number of participating WWTPs in PHA production is examined. Unit cost of PHA increases with the increase in the number of WWTPs (figure 14), where the expansion of WWTPs from 3 to 16 leads to increase of PHA unit cost from 3.40 €/kg to 3.76 €/kg. The price elevation is not linear, however, as the unit PHA cost increase rapidly when the number of participating WWTPs increases up to 11 and then the cost increase is smoother.

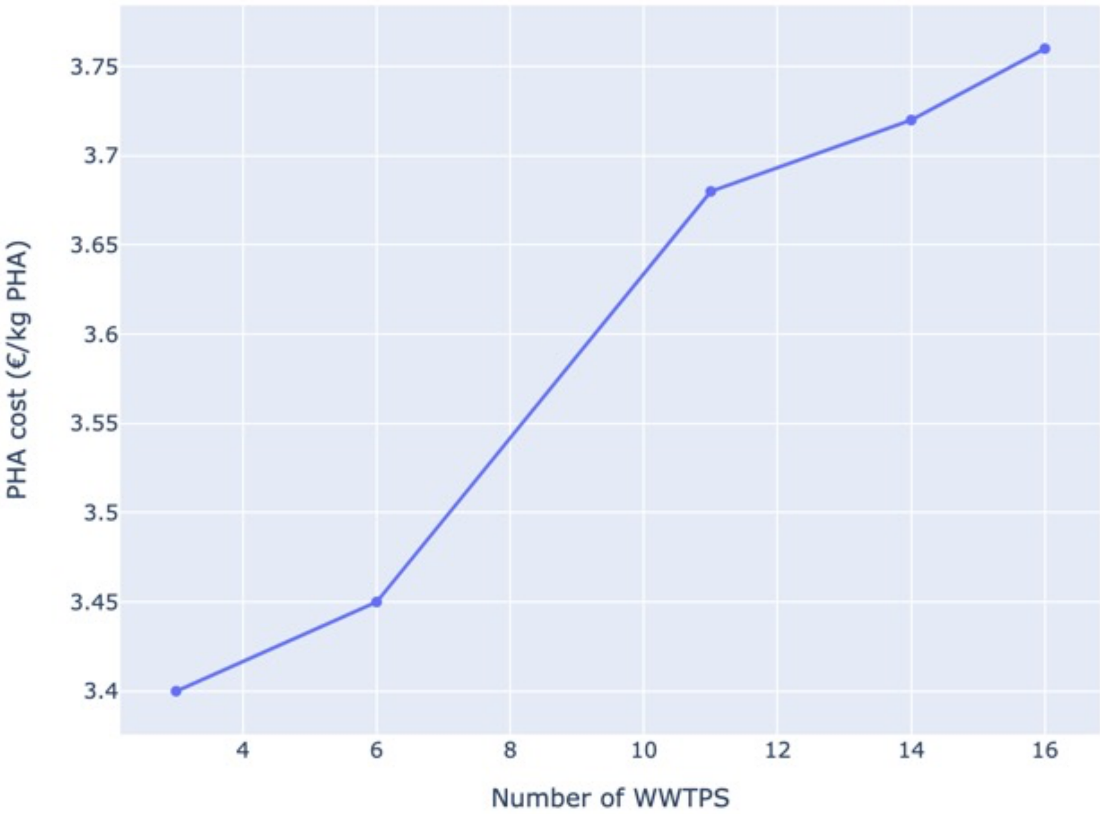

Figure 14. Impact of the number of participating WWTPs on the cost of PHA in scenario 2.

Based on the evaluations so far, though in its infancy, wastewater PHA has a potential of entering the markets by 2030's. Its impact on transition from fossil plastics and the future ahead is discussed further below.

4.6 Outlook

It is essential to put into perspective how much of an impact wastewater PHA can have in replacing fossil plastics. Based on the assumptions of this research, for every population equivalent, 2.307 kg of PHA can be produced. There are 3,885 WWTP with the incoming load of above 50,000 PE in the 27 EU member states (European Commission urban waste water website, n.d.). The annual loads of these WWTPs add up to 674 million PE, which can be used in production of 1.556 million tons of PHA/a, if all of WWTPs participate in PHA production. Considering the plastic demand of 58 million tons in Europe in 2019, the impact of PHA production from wastewater treatment plants in replacing fossil plastic is negligible. The same comparison can be made for Finland, where the wastewater PHA potential is calculated to be between 12,000 - 26,000 tons per year, compared with the national annual demand of 0.7 million tons in 2019. It is, therefore, to be seen in future whether this type of plastic will outgrow serving more than a niche market. There are, however, reasons to be optimistic about the future trajectory of wastewater PHA.

As PHA is fully biodegradable in different environments, it can provide new use cases that the traditional fossil plastic cannot. For example, PHA can be used in biodegradable pots and self-healing concrete, as mentioned in 2.4.1. Such usages create the necessary demand that is necessary for making a business case for producing PHA, including from wastewater. Moreover, production of PHA from wastewater needs to be looked at from a bigger perspective of PHA production from mixed-microbial culture versus from monoculture.

Compared to PHA production from monoculture sources such as corn, sugar cane and sugar beet, producing PHA from waste streams has both advantages and some challenges. Unlike monoculture resources, waste streams do not carry significant land-use and environmental challenges and are not in competition with other sectors with high land demand. On the other hand, it is not obvious whether global plastic demand can be completely supplied with waste-sourced PHA, so plant-based PHA might be still needed to cover such demand. Possible quality variations of PHA from MMC also can be seen as another challenge compared to PHA based on monoculture, though this issue can be resolved over time through further research and technology maturation.

As PHA from waste does not have material cost, it is expected that it will be less expensive than the PHA from monoculture once the production process has been stabilized and the technology has matured. Waste sourced PHA should also have less price volatility compared to both monoculture and fossil plastics. Evaluation of market prices of the most common plastics during the past ten years shows high price fluctuations. These variations can be due to the actions of market players, but also due to price instability of the fossil sources. It can be expected that PHA, or at least PHA from wastewater, can have more stable prices as it is not bound to oil and gas price fluctuations.

By overcoming the challenges of PHA production from mixed-microbial culture, more streams that are currently considered as waste can be integrated into PHA production. Such streams include organic municipal waste, livestock faeces, industrial wastewater, food processing waste, oil and biowaste from food service industry and more. From such perspective, it is important to see PHA production from wastewater and biowaste as a pursuit of bio-circularity and industrial symbiosis. Moreover, utilizing these streams can lead to increase in renewable plastics' potential and scalability in future.

To succeed, production of PHA from MMC needs to overcome several vital challenges. The production processes need to be optimized to achieve stability of PHA quality from different types of feedstocks. The process also needs to reach industrial scale. Finally, the waste-PHA has to become cost competitive with fossil plastics, or at least meet the market valuation of PHA.

5 Conclusions

Transition from fossil fuels also necessitates moving from fossil-based plastics to renewable sources for production of this modern material. Biodegradability of plastics is also another critical factor in addressing plastic pollution in nature. Polyhydroxyalkanoates (PHAs) are one of the most promising family of renewable and biodegradable plastics and their production from both mono- and multi-culture resources is increasingly researched.

This research managed to present realistic feasible scenarios for production of PHA from wastewater in Finland, using geolocation and annual load of all of Finland's wastewater treatment plants (WWTP). By using wastewater from six major WWTPs in southern Finland, PHA can be produced in a centralized facility in the Lahti region at 3.45 €/kg. This price is in line with the reported price in recent major pilot projects in Europe.

Based on the current technology, Finland has a potential of producing 12,000 – 26,000 tons of wastewater PHA per year from 29 wastewater treatment plants, which handle 76% of the total wastewater in the country.

To be price competitive, it is essential that at least two of the three largest wastewater treatment plants in Finland (Helsinki, Turku, and Espoo) participate in the PHA production venture, since feasibility of the project requires a minimum annual production of 5,000 tons/a and increase in the number of participating wastewater plants to reach this number raises the capital expenditure and consequently the PHA's price. The research also showed that dispersity of wastewater treatment plants in Finland is not a deterring factor in feasibility of PHA production from wastewater, as the transportation costs are negligible in the final cost of PHA.

5.1 Contributions

As one of first studies in topic of producing wastewater PHA in Finland, this thesis provided an overview of current developments of the field. It also proposed realistic scenarios for producing wastewater PHA in Finland and in the Lahti region specifically, utilizing real data from the country's WWTPs. Additionally, it explored opportunities for cost savings, which can improve project's feasibility.

5.2 Limitations

The calculations regarding some sections of CAPEX in the main reference were estimated using literature. As a result, there is a possibility that CAPEX and consequently the price of PHA are underestimated. An in-depth CAPEX calculation might lead to more accurate results.

In this research, BOD7 and COD were assumed to be the same for all the participating WWTPs. Using individual measurements for these items can lead to more precise estimation on whether a WWTP is suitable for wastewater PHA production.

5.3 Future Research

This research is a preliminary exploration of wastewater PHA production in Finland and there are quite a few aspects that can be further explored. Since share of transportation cost is insignificant in the price of PHA, there are many options for where the extraction facility can be located. Several candidates can be chosen based on different criteria, such as proximity to waste heat and possibility of industrial symbiosis with other close industries. The impact of these choices on the PHA unit price can then be explored.

There is ongoing research on different types of feedstocks that are suitable for production of PHA, either separately or in combination with wastewater. Exploration of these resources might lead to PHA production in combination with wastewater, which might improve both the output and the cost of PHA.

Further study on future cost of electricity and electrification of industrial heat assists on producing more accurate projections of the wastewater PHA cost, since cost of energy is a significant part of the PHA price. Energy consumption of the production process may also decrease in future through technological developments, which then needs to be considered in the economic calculations.

This research assumed that production of wastewater PHA will be performed as a consortium between few WWTPs and an extraction facility. It was also discovered that in reaching the minimum 5,000 tons/a output, the fewer the number of participating WWTPs are, the lower cost of PHA will be. This model excludes the rest of potential WWTPs interested in participating in PHA production. It is interesting to explore the idea of the extraction facility as a separate entity, which buys dried PHA-rich biomass from various WWTPs and sells the

PHA output to customers based on the market price. This way, more WWTPs can decide individually whether to invest in PHA production process based on the direct financial return and possible cost reduction in wastewater treatment operations. The feasibility of such a model needs to be verified with further research.

References

Aldor, I. S., & Keasling, J. D. (2003). Process design for microbial plastic factories: Metabolic engineering of polyhydroxyalkanoates. *Current Opinion in Biotechnology*, *14*(5), 475–483. https://doi.org/10.1016/j.copbio.2003.09.002

Anjum, A., Zuber, M., Zia, K. M., Noreen, A., Anjum, M. N., & Tabasum, S. (2016). Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: A review of recent advancements. *International Journal of Biological Macromolecules*, *89*, 161–174. https://doi.org/10.1016/j.ijbiomac.2016.04.069

Bengtsson, S., Werker, A., Visser, C., & Korving, L. (2017). *Stepping Stone to a Sustainable Value Chain for Bioplastic Using Municipal Activated Sludge* (STOWA 2017-15).

Best, J. de. (n.d.). *EU Roadmap – call for action*. Retrieved April 22, 2022, from https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/#tab-4

Biobased Delta. (2021, April 30). *PHA2USE - Test plant for biodegradable bioplastic from organic waste streams* [PHA2USE]. Circular Biobased Delta. https://biobaseddelta.com/news/pha2use/

Biodegradable plastic. (n.d.). Wikipedia. Retrieved September 11, 2021, from https://en.wikipedia.org/wiki/Biodegradable_plastic

Burk, C. (2017). Techno-Economic Analysis for New Technology Development. *Advanced Materials*, *1*, 266–269.

City of Lahti. (n.d.). *Application Form for the European Green Capital Award 2021*.

Conca, V., da Ros, C., Valentino, F., Eusebi, A. L., Frison, N., & Fatone, F. (2020). Long-term validation of polyhydroxyalkanoates production potential from the sidestream of municipal wastewater treatment plant at pilot scale. *Chemical Engineering Journal*, *390*, 124627. https://doi.org/10.1016/j.cej.2020.124627

Couper, J. R. (2009). *Process engineering economics* (Repr). CRC Press.

Crutchik, D., Franchi, O., Caminos, L., Jeison, D., Belmonte, M., Pedrouso, A., Val del Rio, A., Mosquera-Corral, A., & Campos, J. L. (2020). Polyhydroxyalkanoates (PHAs) Production: A Feasible Economic Option for the Treatment of Sewage Sludge in Municipal Wastewater Treatment Plants? *Water*, *12*(4), 1118. https://doi.org/10.3390/w12041118

Ellen MacArthur Foundation. (2016). *The New Plastics Economy—Rethinking the future of plastics*. https://ellenmacarthurfoundation.org/the-new-plastics-economy-rethinking-the-future-of-plastics

Estévez-Alonso, Á., Pei, R., van Loosdrecht, M. C. M., Kleerebezem, R., & Werker, A. (2021). Scaling-up microbial community-based polyhydroxyalkanoate production: Status and challenges. *Bioresource Technology*, *327*, 124790. https://doi.org/10.1016/j.biortech.2021.124790

European Bioplastics. (n.d.). *What are bioplastics?* European Bioplastics. Retrieved September 30, 2021, from https://www.european-bioplastics.org/bioplastics/

European Bioplastics. (2020). *Bioplastics Market Development 2020* (p. 2).

European Commission urban waste water website. (n.d.). *UWWTD*. UWWTD. Retrieved April 25, 2022, from https://uwwtd.eu/

Fernández-Dacosta, C., Posada, J. A., Kleerebezem, R., Cuellar, M. C., & Ramirez, A. (2015). Microbial community-based polyhydroxyalkanoates (PHAs) production from wastewater: Techno-economic analysis and ex-ante environmental assessment. *Bioresource Technology*, *185*, 368–377. https://doi.org/10.1016/j.biortech.2015.03.025

Fernando-Foncillas, C., & Varrone, C. (2021). Potential of the sewage sludge valorization in Scandinavia by co-digestion with other organic wastes: A techno-economic assessment. *Journal of Cleaner Production*, *324*, 129239. https://doi.org/10.1016/j.jclepro.2021.129239

Hassan, M. A., Yee, L.-N., Yee, P. L., Ariffin, H., Raha, A. R., Shirai, Y., & Sudesh, K. (2013). Sustainable production of polyhydroxyalkanoates from renewable oil-palm biomass. *Biomass and Bioenergy*, *50*, 1–9. https://doi.org/10.1016/j.biombioe.2012.10.014

Kehrein, P., van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., & Posada, J. (2020). A critical review of resource recovery from municipal wastewater treatment plants – market supply potentials, technologies and bottlenecks. *Environmental Science: Water Research & Technology*, *6*(4), 877–910. https://doi.org/10.1039/C9EW00905A

Khan, M. N., Uhrig, T., Steinmetz, H., Best, J. de, & Raingue, A. (2021). *Techno-economic assessment of producing bioplastics from sewage* (WPT1 Deliverable 3.1 Techno-Economic Assessment).

Khatami, K., Perez-Zabaleta, M., Owusu-Agyeman, I., & Cetecioglu, Z. (2021). Waste to bioplastics: How close are we to sustainable polyhydroxyalkanoates production? *Waste Management*, *119*, 374–388. https://doi.org/10.1016/j.wasman.2020.10.008

Li, Z., Yang, J., & Loh, X. J. (2016). Polyhydroxyalkanoates: Opening doors for a sustainable future. *NPG Asia Materials*, *8*(4), e265–e265. https://doi.org/10.1038/am.2016.48

Majone, M. (2019). *RES URBIS Closing meeting* (p. 10). Research Centre for Protection of Environment and Cultural Heritage. http://www.resurbis.eu/sites/default/files/ResUrbis_Overview_final_meeting.pdf

Mannina, G., Presti, D., Montiel-Jarillo, G., Carrera, J., & Suárez-Ojeda, M. E. (2020). Recovery of polyhydroxyalkanoates (PHAs) from wastewater: A review. *Bioresource Technology*, *297*, 122478. https://doi.org/10.1016/j.biortech.2019.122478

Morgan-Sagastume, F., Bengtsson, S., De Grazia, G., Alexandersson, T., Quadri, L., Johansson, P., Magnusson, P., & Werker, A. (2020). Mixed-culture polyhydroxyalkanoate (PHA) production integrated into a food-industry effluent biological treatment: A pilot-scale evaluation. *Journal of Environmental Chemical Engineering*, *8*(6), 104469. https://doi.org/10.1016/j.jece.2020.104469

Pagliano, G., Galletti, P., Samorì, C., Zaghini, A., & Torri, C. (2021). Recovery of Polyhydroxyalkanoates From Single and Mixed Microbial Cultures: A Review.

Frontiers in Bioengineering and Biotechnology, *9*, 624021. https://doi.org/10.3389/fbioe.2021.624021

Palmieri, S., Tittarelli, F., Sabbatini, S., Cespi, M., Bonacucina, G., Eusebi, A. L., Fatone, F., & Stipa, P. (2021). Effects of different pre-treatments on the properties of polyhydroxyalkanoates extracted from sidestreams of a municipal wastewater treatment plant. *Science of The Total Environment*, *801*, 149633. https://doi.org/10.1016/j.scitotenv.2021.149633

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M. W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., & Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environmental Science & Technology*, *56*(3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158

PlasticsEurope. (2020). *Plastics – the Facts 2020*. https://plasticseurope.org/knowledge-hub/plastics-the-facts-2020/

Pratt, S., Vandi, L.-J., Gapes, D., Werker, A., Oehmen, A., & Laycock, B. (2019). Polyhydroxyalkanoate (PHA) Bioplastics from Organic Waste. In J.-R. Bastidas-Oyanedel & J. E. Schmidt (Eds.), *Biorefinery* (pp. 615–638). Springer International Publishing. https://doi.org/10.1007/978-3-030-10961-5_26

Raza, Z. A., Abid, S., & Banat, I. M. (2018). Polyhydroxyalkanoates: Characteristics, production, recent developments and applications. *International Biodeterioration & Biodegradation*, *126*, 45–56. https://doi.org/10.1016/j.ibiod.2017.10.001

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Tullo, A. H. (2019, September 8). *PHA: A biopolymer whose time has finally come*. Chemical & Engineering News. https://cen.acs.org/business/biobased-chemicals/PHA-biopolymer-whose-time-finally/97/i35

Uhrig, T., Zimmer, J., Bornemann, C., & Steinmetz, H. (2022). *Report on optimised PHA production process layout*. https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/#tab-4

Vedenkulutus. (n.d.). Ympäristöosaava Ammattilainen. Retrieved April 6, 2022, from https://www.ymparistoosaava.fi/sosiaali-ja-terveysala/index.php?k=22672

Wang, S., Lydon, K. A., White, E. M., Grubbs, J. B., Lipp, E. K., Locklin, J., & Jambeck, J. R. (2018). Biodegradation of Poly(3-hydroxybutyrate- *co* -3-hydroxyhexanoate) Plastic under Anaerobic Sludge and Aerobic Seawater Conditions: Gas Evolution and Microbial Diversity. *Environmental Science & Technology*, *52*(10), 5700–5709. https://doi.org/10.1021/acs.est.7b06688

WOW! (2021a). *Tool launched for circular use of sewage*. Interreg North-West Europe. https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/news/tool-launched-for-circular-use-of-sewage/

WOW! (2021b, June 29). *WOW! maximizes impact with Interreg NWE capitalisation call*. Interreg North-West Europe. https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/news/wow-maximizes-impact-with-interreg-nwe-capitalisation-call/

WOW! (2022). *Biobased Products from Sewage—Final Results*.

Wupperverband. (2019). *WOW State of the Art Report*.

Wupperverband. (2020). *Designing value chains for carbon based elements from sewage—Market Potential Study*. Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH. https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/news/designing-value-chains-for-carbon-based-elements-from-wastewater/

Appendix 1. Formula and calculations for matter and energy balance

Primary sludge:

To calculate the amount of primary sludge in each WWTP, first the sludge generation ratio per population equivalent (PE) was calculated using the following assumptions: average sludge generation: 35 g solid/PE.day, solids ratio: 3%, and operational hours per year = 8,000 hours (Khan et al., 2021).

$$Sludge\ ratio = \frac{Average\ sludge\ generation\ (\frac{g.solids}{PE.d})}{Solids\ ratio\ (\%) \times 10^6 \frac{g}{ton}} = \frac{35\ (\frac{g.solids}{PE.d})}{3\% \times 10^6 \frac{g}{ton}} \tag{1.1}$$

$$= 0.00167\ \frac{tons\ sludge}{PE.d} \times 365 \frac{d}{a} \times \frac{8{,}000\ (hours\ operational)}{8760\ (hours\ in\ year)}$$

$$= 0.389156\ \frac{tons\ sludge}{PE.a}$$

Consequently, the total annual primary sludge in each WWTP is calculated:

$$Primary\ sludge = Annual\ wastewater\ inflow\ (PE) \times Sludge\ ratio\ (\frac{t}{PE.a}) \tag{1.2}$$

Centrifuge 1:

$$VFA\ rich\ output = 77\%\ \times activated\ sludge \tag{1.3}$$

$$Solids\ removed = 23\%\ \times\ activated\ sludge \tag{1.4}$$

Selection reactor:

$$VFA\ input = 36\%\ \times Centrifuge\ 1\ VFA\ output \tag{1.5}$$

$$Added\ excess\ sludge = 50\%\ \times VFA\ input \tag{1.6}$$

$$Added\ water = 100\%\ \times VFA\ input \tag{1.7}$$

$$Total\ enriched\ biomass\ output = VFA\ input + Excess\ sludge + water \tag{1.8}$$

Accumulation reactor:

$$VFA\ input = 64\%\ \times VFA\ rich\ output\ from\ Centrifuge\ 1 \tag{1.9}$$

$$PHA\ rich\ biomass\ output = VFA\ input + enriched\ biomass \tag{1.10}$$

Centrifuge 2:

$$\text{Dewattered PHA rich biomass output} = 3\% \times \text{PHA rich biomass from Accumulation reactor} \quad \textbf{(1.11)}$$

$$\text{Efluent} = 97\% \times \text{PHA rich biomass from Accumulation reactor} \quad \textbf{(1.12)}$$

Dryer:

Assumptions: Dry matter content of the incoming PHA rich biomass: 30%, and moisture content after drying: 10%.

$$\text{Dried PHA biomass output} = \frac{\text{Dry matter of incoming biomass} \times \text{Incoming biomass}}{1 - \text{moisture content after drying}} \quad \textbf{(1.13)}$$

$$\text{Water vapor output} = \text{Enriched biomass} - \text{Dried PHA biomass output} \quad \textbf{(1.14)}$$

Extraction:

Assumptions: Solvent (dimethyl carbonate) to dried biomass ratio: 19

$$\text{Dimethyl carbonate demand} = 19 \times \text{dried PHA biomass input} \quad \textbf{(1.15)}$$

$$\text{PHA solution output} = \text{Dimethyl carbonate} + \text{dried PHA biomass input} \quad \textbf{(1.16)}$$

Filter:

Assumptions: PHA output yield: 50%, cell disruption efficiency: 100%, and solvent recovery: 99.5%.

$$\text{PHA rich filterate out} = \text{Dried PHA rich biomass} \times 0.5 \times 1 + \text{PHA rich solution} \times 0.995 \quad \textbf{(1.17)}$$

$$\text{PHA free biomass efluent} = \text{PHA rich solution} - \text{PHA rich filterate output} \quad \textbf{(1.18)}$$

Evaporator:

Assumptions: cooling water demand: 0.39 t/t filtrate.

$$\text{PHA output} = \text{Dried PHA rich biomass} \times 0.5 \times 1 \quad \textbf{(1.19)}$$

$$\text{Recovered solvent} = \text{PHA rich filterate} - \text{PHA output} \quad \textbf{(1.20)}$$