MASTER THESIS

CIRCULARITY IN WASTEWATER TREATMENT PLANTS: DRIVERS AND BARRIERS TO THE COMMERCIALISATION OF BIOPLASTICS FROM WASTEWATER

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ABSTRACT

Wastewater treatment plants (WWTPs) can become essential players in the global transition to a circular economy. The circular economy is a model that promotes the sustainable management of materials and energy by minimizing waste generation and ensuring the recycling and reuse of waste in a closed-loop system. This is gradually being achieved in WWTPs through the integration of resource recovery and energy generation in wastewater treatment processes, resulting in a circular reuse of water, valuable resources, nutrients and energy. One of such valuable resources is polyhdroxyalkanoates (PHAs), a type of bioplastics that is both biobased and biodegradable. PHAs can be produced and accumulated in bacteria that treat organic pollutants in wastewater. These bioplastics not only have some similar properties with unsustainable fossil-based plastics, they also have unique properties that make them suitable for other applications. The focus of this research was to assess the drivers and barriers to commercialisation of PHAs produced from wastewater. The PESTLE framework was used as the analytical tool to assess these factors in the six categories (political, economic, social, technological, environmental and legal) of the framework. This provided a comprehensive approach to the research. Primary data collection was through in-depth interviews with relevant actors such as representatives from WWTP, research institute, industries, and solid waste management company, while literature and government reports served as secondary data sources. Content analysis was the method of data analysis adopted. From the study, the major barrier to the commercialisation of PHA is the lack of sufficient capital funds for its upscaling from pilot scale to commercial, while the main drivers include allocation of subsidies for PHA production by the government and the biodegradability advantage of PHA.

Keywords: bioplastics, circular economy, PESTLE analysis, polyhydroxyalkanoates, resource recovery, (PHA), sustainability, wastewater.

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WWTPs:	Wastewater treatment plants
GHG:	Greenhouse gas
CE:	Circular Economy
EPS:	Extracellular polymeric substances
VFAs:	Volatile fatty acids
PHAs:	Polyhydroxyalkanoates
CO_2:	Carbon dioxide
EU:	European Union
PLA:	Polylactic acid
PE:	Polyethylene
PET:	Polyethylene terephthalate
PA:	Polyamides
PTT:	Polytrimethylene terephthalate
PP:	Polypropylene
PBS:	Polybutylene succinate
PBAT:	Polybutylene adipate terephthalate
PCL:	Polycaprolactone
PVC:	Polyvinyl chloride
P3HB:	Poly (3-hydroxybutyrate),
P(3HBco-3HV):	Poly (3-hydroxybutyrate-co-3-hydroxyvalerate), P(3HBco-3HV)
SDE+:	Stimulering Duurzame Energietransitie
STOWA:	Stichting Toegepast Onderzoek Waterbeheer

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CHAPTER 1: INTRODUCTION

This chapter gives an overview of the background of the research while further expounding the problem statement and stating the research objective and questions. Lastly, the organisation of the thesis is presented.

1.1 Background

Wastewater treatment plants (WWTPs) were developed to safeguard downstream water users from health risks by treating wastewater to meet effluent discharge quality [1]. However, in the last few decades, subjects such as their greenhouse gas (GHG) emissions, maintenance costs and wastage of potential resources (such as carbon, nitrogen, phosphorus and heavy metals from wastewater) are becoming issues of major concern [2]. Moreover, research increasingly highlights their potential contributions to national circularity goals [1]. Therefore, a paradigm shift towards circularity, particularly via resource recovery, is highly crucial, thus, transforming WWTPs to wastewater resource recovery factories [1,3]. Circular Economy (CE) is a concept that strongly advocates the sustainable management of raw materials and energy by limiting waste generation and ensuring the recycling and reuse of unavoidably generated waste [4]. It is in direct contrast to the linear take-make-dispose system of our society where waste is perceived as the valueless last stage of product life cycle. Wastes, co-products, and process residues should become secondary materials for other processes.

Resources that can be recovered from municipal wastewater include water, phosphorus, nitrogen and multiple carbon-based products, such as energy in the form of biogas (methane), cellulose, extracellular polymeric substances (EPS), volatile fatty acids (VFAs)[1], polyhydroxyalkanoates (PHAs), single-cell proteins, carbon dioxide (CO_2), among others [1,3]. Currently, sewage sludge[2] from WWTPs are mostly digested to produce biogas [5]. This does not fully agree with the concept of CE, which seeks to valorise wastes and make the most of them. Although renewable energy generation is important in a sustainable economy, it does not receive a high priority in the ladder of circularity; it should only be an option when the recovery of valuables is not feasible [6]. One of such valuable resources is bioplastic, namely, PHA, which is a biodegradable polymer that can be produced and accumulated in bacteria that treat wastewater [7]. Bioplastics, broadly defined as biobased and/or biodegradable plastics [8], are interesting because of their unique potential to help reduce the numerous negative impacts of traditional plastics.

[1] VFAs are also the building blocks for PHAs. However, they can also be used to produce other materials.

[2] Sewage sludge: Solids, semi-solid or liquid residues generated during biological wastewater treatment processes.

Plastics are an important and indispensable part of our daily lives and economy. Their versatility makes them the preferred material in a lot of applications, ranging from automobiles to electronics, food packaging and even biomedical purposes [9]. However, the current methods of producing plastics and the way they are disposed of pose huge environmental challenges that require urgent intervention. This is because traditional plastics are non-biodegradable and can remain in the environment for hundreds of years, leach into waterbodies, and have even been found in the intestines of some aquatic organisms [10]. Various stakeholders are increasingly becoming concerned about this plastic menace as it is one of the most noticeable forms of environmental pollution. These concerns are thus driving producers into the search for sustainable alternatives that capture the convenience and other unique properties of fossil-based plastics without the associated environmental burden [11]. Biobased and biodegradable plastics seem to be a viable solution to this dilemma, as they allow the conservation of limited depletable resources, and their biodegradability makes them fit into the concept of sustainability. The problem, however, is that the most common methods of producing these bioplastics are by using starchy crops like maize as raw materials, which make them also burdensome when land usage, competition with food resources and other associated problems such as nutrient leaching, are considered [12]. PHA bioplastics, however, do not have these problems as they can be produced from wastewater (either municipal or industrial wastewater[3]) and are fully biodegradable [13,14]. The development of technologies to produce biodegradable plastics that can address the environmental concerns of both wastewater treatment and traditional plastics is an impressive innovation in the wastewater sector. It advances the concept of CE in WWTPs by making more efficient use of wastewater as a resource while also satisfying the CE principle of replenishing the soil with nutrients. Therefore, exploring this potential resource (wastewater) is a promising approach that can turn WWTPs to bioplastic-producing factories [15] and provide solution to the increasing worry of the society about the environmental problems associated with plastic disposal [14].

1.2 Problem statement

Although the scientific community has increasingly offered technological solutions in the area of resource recovery to establish a more circular water sector, the large-scale implementation of these resource recovery technologies is still very weak [1]. Therefore, to advance the idea of sustainability and uphold the CE principles in WWTPs, it is imperative for all stakeholders involved to stimulate the recovery of valuable resources, such as PHAs, which is the major focus of this research.

[3] Municipal wastewater refers to wastewater from non-industrial buildings such as households, farms and offices while industrial wastewater refers to wastewater from industries such as the chemical industry, food industry and petroleum industry.

The environmental impacts associated with fossil-based plastics from their production to their end-of-life disposal have necessitated the development of more sustainable alternatives. Some bioplastics have similar physical properties with the traditional plastics and are often used in similar applications. However, not all bioplastics are as environmentally friendly as they are touted to be. Although they may be biobased materials, some degrade poorly in the environment while some degrade only under specific non-ambient conditions [16]. Furthermore, the production process of some of these bioplastics are energy or resource-intensive [17].

PHA bioplastics from wastewater are not only biobased, they are also readily biodegradable in the natural environment [18]. Moreover, they possess properties similar to those of some traditional plastics [13,19]. Their production process fits into the CE principle since they are produced from the residuals in WWTPs. Wastewater is employed as a valuable resource to produce eco-friendly plastics, thereby closing a resource loop (carbon recovery[4]) in WWTPs. However, despite the fact that PHA bioplastics have been discovered for decades [20] and their production from WWTPs has long been recognised as a valorisation[5] path for organic wastewater [21], one would expect that they would already be commercially available, but unfortunately, this is not the case. Therefore, this thesis investigated the key drivers and barriers that facilitate or impede the deployment of this innovative wastewater-based plastic into the market.

1.3 Research objective

The objective of this research was to improve the scientific knowledge on the different factors that affect the commercialisation of bioplastics from WWTPs by assessing the main drivers and barriers from an interdisciplinary perspective.

1.4 Research questions

To achieve the research objective, the thesis sought to answer the following research questions:

Main research question

How does PHA production contribute to circularity in WWTPs and what factors drive or hinder its commercialisation?

[4] Carbon recovery: the recovery of materials based on carbon, such as biopolymers, methane, and organic chemicals.

[5] Valorisation: To make something valuable. In this context, it is waste valorisation: making valuable product from waste.

Research sub-questions

1. How is the production of PHA in WWTPs a more circular route for carbon valorisation than the conventional biogas production?
2. What political and legal factors impact the commercialisation of bioplastics from wastewater?
3. What are the environmental impacts of PHAs' end-of-life options on its commercialisation?
4. What are the impacts of the social perception of PHAs on its adoption?
5. What are the technological factors impacting the commercialisation of PHAs from WWTPs?
6. What are the economic factors impacting the commercialisation of PHAs from WWTPs?

1.5 Organisation of the thesis

The thesis is organised as follows:

The second chapter focuses on the literature review and the theoretical framework that provided the basis for the execution of this research. The third chapter elaborates on the design of the research methodology, including the research framework, research strategy, data collection, data analysis, and the analytical framework. The fourth chapter presents the findings of the research (primary data from interviews), while the fifth chapter discusses the results and answers the main research question by analysing the findings in the light of applicable secondary data. The last chapter concludes the report with recommendations.

CHAPTER 2: LITERATURE REVIEW

This chapter elaborates the theoretical framework and preliminary research that make up the research perspective of this thesis. The theories and models on various concepts related to the research topic and objective are introduced. The first section discusses the general concept of the CE and further narrows it down to the WWTP context, especially in the light of resource recovery. The second section introduces traditional plastics and its shortcomings, the different bioplastics, and then PHA bioplastics which is the focus of the research. The last section describes the theoretical framework, introducing the PESTLE framework, which is the main analytical compass of this research. This framework was chosen because it provides a comprehensive approach to the analysis by considering several important aspects that impact the research object.

2.1 Circular Economy

Wastes, as opposed to conventional resources, until recent times were considered useless because they were thought to be of generally low value with associated burden of disposal. They are mostly regarded as economically unreasonable or technologically restrictive for value extraction [22]. However, considering the aggressive promotion of green economy and increasing technological advancements in resource efficiency, wastes actually represent underutilised resources [22]. Regulations regarding wastes mostly treat them as environmental hazards and therefore, seek to ensure that waste management bodies dispose them as safely as possible without considering the possibility of these wastes being sources of valuable resources. This, consequently, creates regulatory or legal barriers to sustainable activities that promote recovery, reuse and redesign of products and materials [23].

The concept of CE encourages ‘closed loop’ cycling of materials throughout entire supply chains [24], such that post-use materials are regarded as valuable assets and resources, rather than being regarded as wastes [25]. Biobased products when returned to the environment can serve as replenishment for nutrient stocks, thereby restoring the health of the ecosystem [26]. Aside environmental impacts and the development of new economic models, CE also seeks to address social concerns by curbing environmental externalities, such as toxic chemical use and air pollution, which pose a threat to human health [24].

Since the onset of the industrial revolution in the early 19th century, the European economy has recorded unparalleled prosperity, but despite this success, the use of resources in Europe is regarded as very wasteful [23]. The main drivers of the transition to a CE in Europe are problems of increasingly scarce resources, dependence on the importation of raw materials, which subject the European economy to challenges such as market volatility, exorbitant prices, uncertainty in political circumstances of countries, among others [4]. Thus, the European Union (EU) is dedicated to promoting the transition to a CE through its CE Action plan [27]. The goal is an economy that will foster competitiveness, boost sustainable economic growth and facilitate the creation of jobs. The EU plastic sector is a necessary inclusion in this vision. Bioplastics have been recognised for their crucial role in this transition due to their wide range of features and applications, as well as the renewability of their sources [13]. The 1987 Brundtland Report on sustainability has indeed been the key driver for the development of policies, favouring the production of biodegradable polymers both in Europe and America [22]. In the same vein, the Netherlands aims to develop a CE by 2050 and there is a Government-wide program in place for this. The goal of the cabinet is to achieve a 50% reduction in the use of virgin materials (fossil, minerals and metals) by 2030 [28].

2.1.1 Circular Economy in WWTPs

WWTPs are traditionally known for the treatment of wastewater and sewage sludge but research increasingly shows their great potential to become resource recovery facilities [4]. The European Energy Agency stated that the utilisation of municipal waste as resource has the potential of reducing GHG emissions by 62 million tons of CO_2 equivalent by 2020 relative to 2008 [29]. Within this progressive thinking approach lies the active strive for bioeconomy in our society, birthing numerous innovative ideas. To this end, many practical studies have been and are still being carried out within the water management and technology sectors in the Netherlands [5]. Circularity can be effectively incorporated into the processes of WWTPs by actively integrating resource recovery and energy production without compromising clean water production [4]. Global nutrient needs, as well as water scarcity and clean energy demands are motivations for this kind of forward thinking in WWTPs, which are expected to become technological systems of high ecological sustainability in the near future [4].

2.1.2 Resource Recovery in WWTPs

Scarcity of resources is steering a change in current systems of production in our society. The focus is fast changing from treatment of residues and wastewater towards resource recovery [3]. Dutch water boards are becoming leaders in cutting-edge developments that consider WWTPs as sites that create vast opportunities for the production of renewable raw materials, both energy and resources [5]. Biotechnological systems provide an economic and adaptable way of concentrating and converting these resources into valuable products, which is a requirement for the technological advancement of a cradle-to-cradle[6] bioeconomy [3].

[6] Cradle-to-cradle is a sustainable business strategy that mimics the regenerative cycle of nature in which waste is reused.

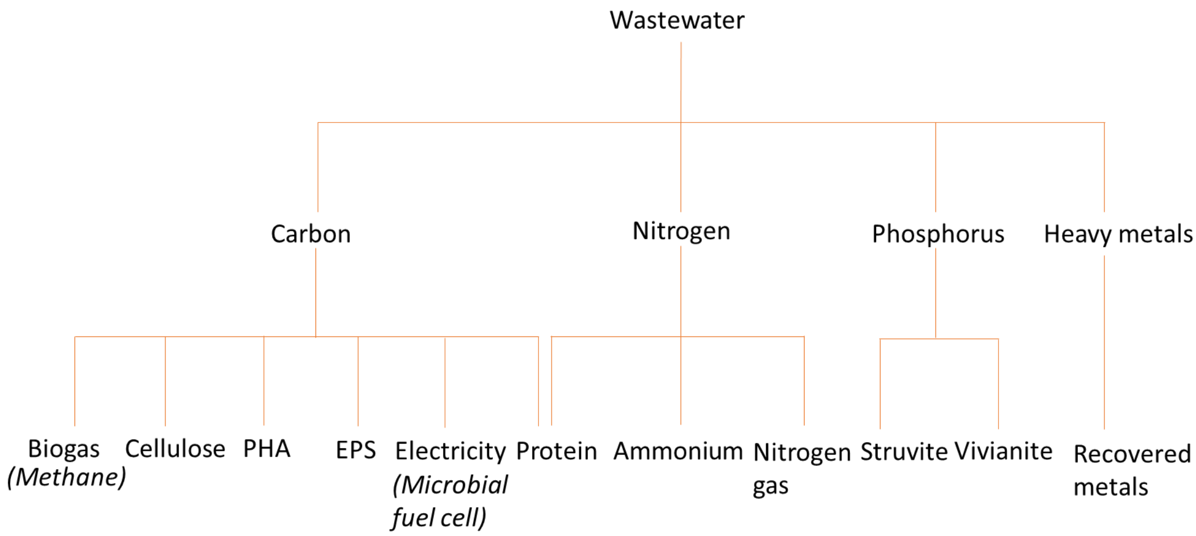

Figure 1: A schematic classification of the most common resources that can be recovered from wastewater (own elaboration). (PHA: Polyhydroxyalkanoates; EPS: Extracellular Polymeric Substances).

As shown in figure 1, municipal wastewater is rich in resources such as carbon, nitrogen, phosphorus and heavy metals, which can be potentially recovered as valuable products [3,30]. For instance, wastewater carbon can be valorised to biogas (methane), cellulose, PHA, EPS, among others. Nitrogen can be recovered as ammonium salts (e.g. ammonium sulphate), single-cell protein or fixed as nitrogen gas [1]. Phosphorus, on the other hand, is largely recovered as struvite ($NH_4MgPO_4{\cdot}6H_2O$), which is primarily used in agriculture as fertilisers [31], although some WWTPs are now valorising phosphorus to vivianite ($Fe_3(PO_4)_2{\cdot}8H_2O$) [32]. Furthermore, heavy metals such as copper, gold and lead are also valuable resources that can be recovered from wastewater [3]. Unfortunately, the bulk of these (especially carbon) are destroyed during the conventional aerobic wastewater treatment processes [33]. The associated high cost (~ 45 billion annually) of treating just a fraction of this waste strongly demands a sustainable modification of wastewater treatment systems [33]. It was estimated that the degradation of organics during wastewater treatment processes in 2010 contributed approximately 0.77Gt CO_2-equivalent GHG emissions, which is about 1.57% of the global emissions (49 Gt CO_2-equivalent) [34]. However, WWTPs are gradually, though slowly, being transformed into resource factories for the recovery of carbon (in form of biopolymers, energy, and organic chemicals) and nutrients (nitrogen and phosphorus) [35]. Cellulose and PHA bioplastics are some of the valuable biopolymers on the verge of commercialisation [36,37]. Their unique properties make them suitable in several applications, ranging from commodity to specialty products [3,38]. However, the recovery of resources such as PHA from wastewater demands that the production process competes financially with those of other polymers and with other value-adding processes that utilise wastewater such as the production of biogas [12].

2.2 The incentive for switching from traditional plastics to bioplastics

In the last fifty years, plastic use has risen twenty-fold with increasing expectations that its use will double in the next twenty years [28]. In 2013, the global production of plastics rose to 299 million tons, of which Europe alone produced 20% [28]. In recent years, new plastic materials with exceptional durability and physical properties have been created with remarkable and rapid advancement being made in the science and technology of polymers. However, the bulk of these plastic products are employed in single use applications, especially in medical and food packaging applications, and their non-biodegradable property implies their undesirable and damaging stability in the environment [14]. This unhealthy accumulation of plastic waste in the environment keeps growing exponentially, with a yearly accumulation rate of approximately 25 million tons [14]. The effect of such accumulation is strongly felt by the surrounding fauna whose feeding or habitat is affected negatively, and sometimes, this leads to the death and extinction of certain species [10]. Moreover, plastics degrade over time into increasingly smaller micro and nanoparticles, which end up impacting the ecosystem and the food chain negatively [28]. In light of these plastic challenges, more biobased and biodegradable alternatives to fossil-based plastics are increasingly being developed and marketed, most of which are used specifically and increasingly in situations that pose high environmental risks [28].

2.3 Bioplastics

Bioplastics is a term loosely used to describe two distinctive types of polymer, namely biobased polymers and biodegradable polymers [17]. Biobased polymers are produced wholly or partly from renewable resources such as cellulose, sugar, vegetable oils, starch and also from food residues [39]. The idea came from the need to move from fossil-based products to renewable products in a bid to reduce GHGs and contribute to climate change mitigation. Biodegradable polymers, on the other hand, which may either be biobased or from petrochemical origin, are polymers with a certain degree of intrinsic biodegradability [22,39]. This means that they can be decomposed biologically, for example through bacterial or fungal actions, and thus produce natural metabolic products [39]. Biodegradability is therefore mostly concerned with end of life and disposal of polymers, majorly focusing on techniques of waste management [39]. Biodegradable polymers are part of the budding portfolio of sustainable raw materials promising to deliver environmental, economic and social benefits [22]. However, this does not mean biobased polymers cannot be biodegradable or vice versa. Polylactic acid (PLA) and PHA are examples of polymers which are both biobased and biodegradable while Polycaprolactone is an example of a non-renewable biodegradable polymer [39]. A general classification of bioplastics as presented by the European Bioplastics is presented in figure 2.

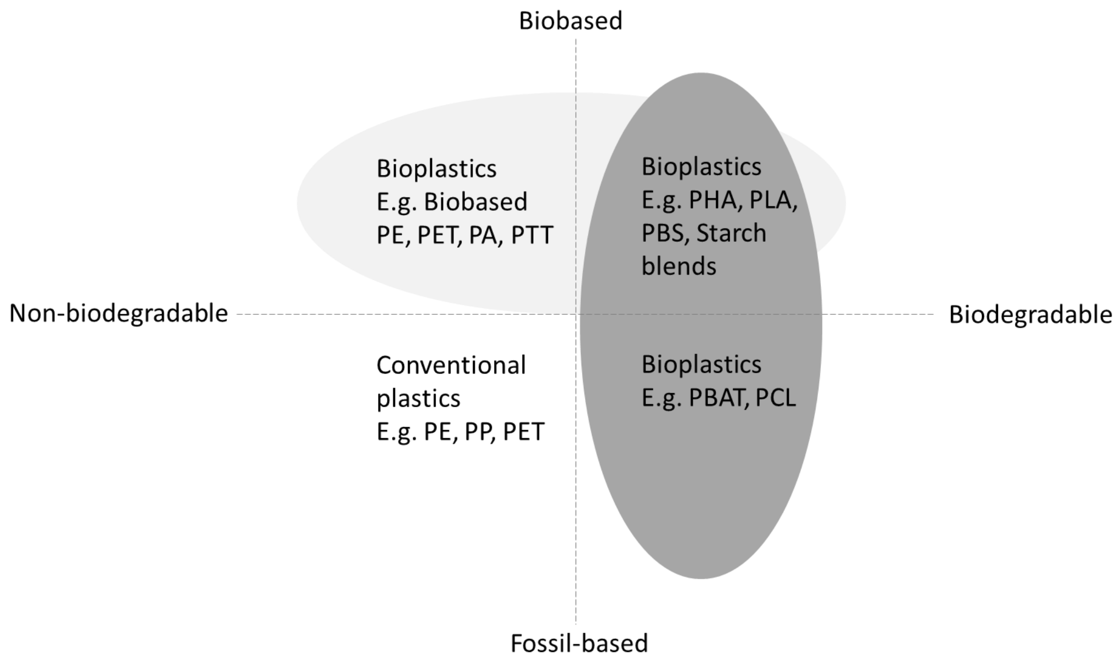

Figure 2: Classification of bioplastics
(Adapted from European Bioplastics [8]*)*
*(**PE**: Polyethylene, **PET**: Polyethylene terephthalate, **PA**: Polyamides, **PTT**: Polytrimethylene terephthalate, **PP**: Polypropylene, **PHA**: Polyhydroxyalkanoates, **PLA**: Polylactic acid, **PBS**: Polybutylene succinate, **PBAT**: Polybutylene adipate terephthalate, **PCL**: Polycaprolactone)*

The global capacity for bioplastics production is projected to increase from about 2.1 million tonnes in 2019 to about 2.4 million tonnes in 2024. This growth is being driven by innovative biopolymers like PLA and PHA [40]. Dutch companies rank among the pioneers in the processing and production of bioplastics in the growing global market [28]. The EU bioplastic market is actually expanding by about 20% every year as the global bioplastic market is being driven by the increasing demand for sustainable and innovative solutions [13]. This increase is likewise anticipated for PHA bioplastics to quadruple by 2023 [7,40].

PLA, one of the most exploited and commercially available bio-derived bioplastics, is an aliphatic polyester made mostly from starch or sugar-rich crops. Its characteristics such as surface gloss and high transparency, as well as other physicochemical properties such as chemical resistance to fats and oils makes it a suitable substitute for conventional plastics such as polyethylene terephthalate (PET) and polyvinyl chloride (PVC) [41]. However, the exceptional high-temperature performance of PHAs appreciably expands the addressable number of applications for bioplastics beyond those that can be served by the more common PLA [11].

2.3.1 Waste management options for bioplastics

Bioplastics can be recycled either mechanically or organically as shown in figure 3. They offer more waste treatment options than traditional plastics, thus, steering resource efficiency and helping to create a real circular bioeconomy in Europe [42].

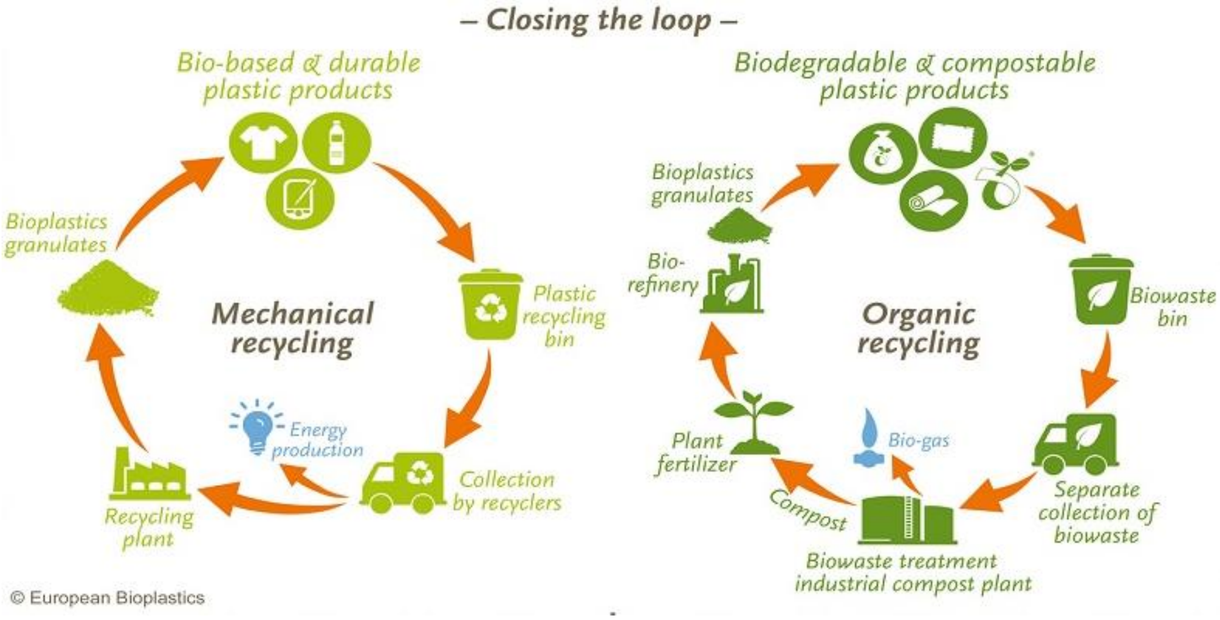

Figure 3: End-of-life options for bioplastics
(Adapted from European Bioplastics [8]*)*

Anaerobic digestion and composting (industrial or home composting) are some biological waste treatment options offered by biodegradable plastics for the recovery of materials and the production of valuable products such as biogas and compost, respectively [42,43]. Both Anaerobic Digestion and composting play crucial roles in the diversion of organic wastes from landfills [41].

Furthermore, waste-to-energy procedure by incineration is considered a suitable option for all types of bioplastics as it contributes to the generation of renewable energy. Landfilling is strongly discouraged and the EU's Landfill Directive (Landfill Directive, 1993/31/EC) aims to limit the total quantity of biodegradable wastes being sent to landfill [41].

Regarding mechanical recycling of bioplastics, although this is technically possible, the absence of a reliable and continuous supply of the bioplastic wastes makes recycling not attractive economically [41]. This is because bioplastics currently represent only about 1% of the total yearly plastic production [40]. Another concern is the contamination of conventional plastic recycling streams. However, there have been technological advancements, though still expensive, in the aspects of different plastic wastes sorting [41].

2.3.2 Polyhydroxyalkanoates (PHAs)

There are several types of biodegradable plastics but a group of over 40 PHAs and their copolymeric derivates have turned out to be highly desirable because of their full biodegradability [14]. PHAs are naturally-occurring polyesters produced by several species of bacteria in response to nutrient shortage, usually inorganic nutrients, in the presence of excess carbon [5,19,22]. One of the sources of this PHA is activated sludge, the biological materials derived from WWTPs processes, as metabolic products [14]. At the onset, the bulk of the work done on the development of PHA for a full-scale production mostly used virgin raw materials, for example, corn-derived glucose [22]. The major drawback of this approach is the high production cost involved, which is primarily due to the high cost of the substrate [13]. This makes competition with fossil-based plastics impractical [20]. A more sustainable strategy is to use cheap and readily available carbon substrates that will both facilitate microbial growth and efficient PHA production [20]. In the last few years, a plethora of studies have been carried out to produce PHAs from municipal and industrial wastes, which are residuals now considered as vital resources for bio-economy [22]. PHAs have naturally useful properties which make it unnecessary to compromise their real biodegradability property for improved properties, unlike their other biodegradable counterparts such as fossil-based polymers, PLA and even starch-based polymers [12]. PHAs can be grouped into 2 main types: the short-chain PHAs containing monomer units with 3 to 5 carbon atoms and the medium-chain PHAs with monomer units of 6-18 carbon atoms [19]. Poly (3-hydroxybutyrate), P3HB and poly (3-hydroxybutyrate-co-3-hydroxyvalerate), P(3HBco-3HV) are the most common PHAs. They possess mechanical properties similar to those of polyethylene and polypropylene but they are more brittle and have much lower elongation-to-break [19].

The PHAs available commercially in the market are usually from pure cultures[7] which are comparatively expensive because they require high level of sterility [19]. This has impacted their market penetration negatively [12,28]. However, this price can be reduced by lowering the production costs, for instance, by integrating their production into the operation of existing facilities that can produce these PHAs [5]. Municipal and Industrial WWTPs and sludge management facilities are identified to have such attractive prospects [5,44]. Mixed culture[8] production has the added advantage of not requiring sterilization of feedstocks and equipment [22]. However, the quality control of the produced polymer has been a cause for concern [5]. The technical feasibility of PHA production from mixed culture system

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[7] Pure Culture refers to a population of cells growing in the absence of other species or types (https://www.scientistcindy.com/ex-12--8203-pure-culture-technique.html)

[8] Mixed culture contains two or more different bacteria (https://milnepublishing.geneseo.edu/suny-microbiology-lab/chapter/bacteriological-culture-methods/)

in wastewater treatment processes has been repeatedly shown by several studies but the production of sufficient amount to assess their quality and large-scale potential was only recently possible [5].

One of such demonstration projects was the PHARIO project which was a collaboration of several Dutch water authorities [21]. Since 2011, the potential for PHA production from municipal wastewater treatment sludge has been repeatedly explored in locations both within and outside the Netherlands. However, more research into the quality of product that could be produced from this sludge was needed and this was the driver for the PHA production and value-chain demonstration project, the PHARIO project. The project was based on the knowledge that full-scale municipal WWTPs are potential process units for the production of activated sludge with PHA-accumulation capacities without making any modification to the WWTPs. The pilot operation ran for 10 months at the full-scale WWTP in Bath, the Netherlands. The results showed that PHA polymer with significant application potentials can be produced consistently. A life cycle assessment (LCA) was also conducted and the result showed that the environmental impact of the polymer produced is 70% lower compared to the PHA bioplastics available currently [21].

The extensive range of prospective applications of PHA, due to its unique features such as biocompatibility, insignificant toxicity to cells and biodegradability, increasingly makes it gain attention in various sectors that involve packaging, agriculture, coating and medical materials [20]. Its biocompatibility makes it highly desirable in tissue engineering, where compatibility of foreign materials with the human body is extremely crucial (Chee et al., 2010).

2.4 Theoretical Framework

Alongside the theories and concepts presented earlier in this chapter, the research will employ the PESTLE framework for the analysis of the research object. The PESTLE framework helps to consider the Political, Economic, Social, Technological, Legal and Environmental aspects surrounding a business, which need to be understood to facilitate strategic decision making [45]. It enables a holistic and interdisciplinary approach to the research from a business perspective. De Boer et al. [31] employed the framework in their work on assessing the drivers and barriers for the deployment of urban phosphorus technologies to the Dutch market. Song et al. [46] also adopted the framework for the analysis of the development of the waste-to-energy incineration industry in China. However, for this research, not all possible sub-categories under the PESTLE framework will be considered, the aspects assessed are considered in the context of the CE concept, particularly resource recovery from WWTPs. The interconnectedness between these aspects is evaluated to achieve the research objective. This is elaborated in figure 4 and further in the research framework.

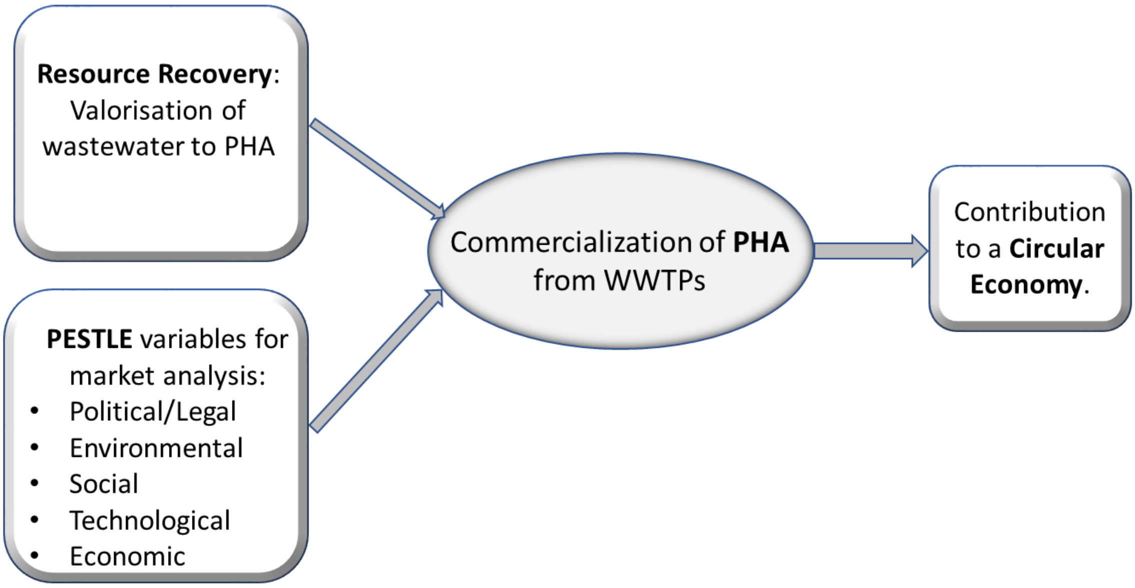

Figure 4: The theoretical framework for assessing the factors affecting PHA commercialisation

CHAPTER 3: METHODOLOGY

This chapter describes the activities that were conducted to achieve the research objective. It presents the research framework, research strategy, the methods applied to collect and analyse data and the analytical framework.

3.1 Research Framework

Research framework is a schematic and highly visualised representation of the steps that need to be taken in order to achieve one's research objective [47]. The research object was PHA from WWTPs' sludge. The objective of the research was to improve the scientific knowledge on the different factors that affect the commercialisation of bioplastics from WWTPs by assessing the main drivers and barriers from an interdisciplinary perspective. The research assessed these drivers and barriers through a PESTLE-guided framework. This enabled the analysis to cover the Political, Economic, Social, Technical, Legal and Environmental aspects involved, and the interlinkages among them, where present. The analysis was, however, applied in the context of the CE concept. These helped give an overview of areas that need to be addressed to make a headway in the further upscaling of the product into the market while making WWTPs more circular. The research used scientific literatures and preliminary research to develop a contextual model as shown in the research framework below (figure 5).

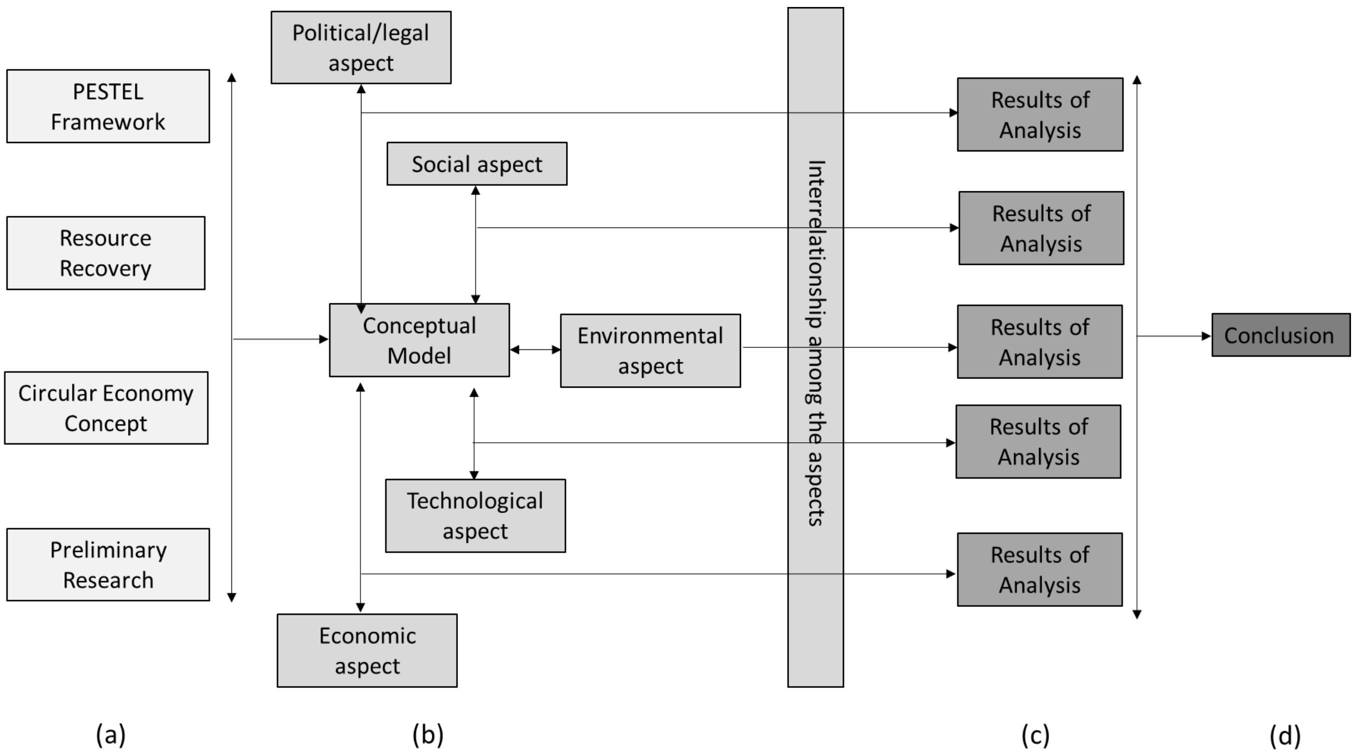

Figure 5: A schematic representation of the research framework

3.2 Research Strategy

The research was qualitative and it employed the single case study approach as its strategy, focusing on only one case which was the commercialisation of PHA from WWTPs. This was done by conducting semi-structured interviews with various stakeholders. The stakeholders were identified based on the different aspects the research focused on. These stakeholders were vital in the data collection process. They included: representative from an industry currently working on PHA from wastewater; researchers/experts in PHA technology both from the private industry and WWTP, final product manufacturers as shown in figure 6; representative of a solid waste management company (for recycling possibilities of product after use).

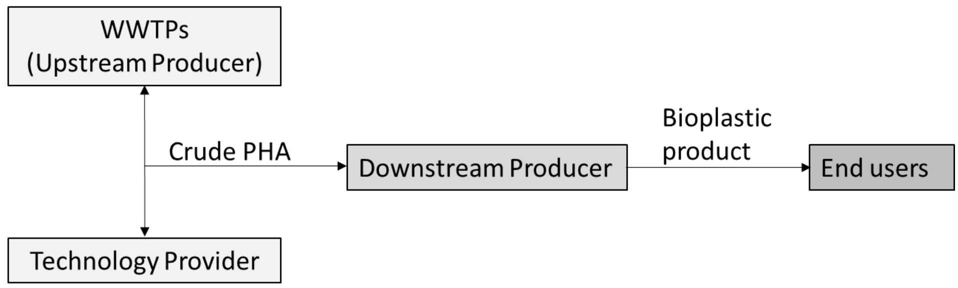

Figure 6: A schematic representation of the Actors in the production chain of PHA bioplastics from WWTPs.

3.2.1 Actors in the production chain of PHA bioplastics from WWTPs

The WWTPs, in collaboration with technology providers, produce the crude PHA. The downstream producer (the plastic manufacturer) represents the companies that refine the crude polymer to produce the final bioplastic product and the end users are the 'consumers' which could be retailers or niche market players.

3.3 Data Collection

Five semi-structured interviews were conducted for this study. The interview questions for each session (appendix II) was tailored to the expertise of each respondent. The elements of the analytical framework (figure 7) served as the basis of the interview questions. In addition to investigating the contribution of PHA production to WWTPs in terms of circularity, the objective of each interview session was also to explore the drivers and barriers to the commercialisation of PHA by discussing past developments, current hurdles and future developments. Four out of the five interviews were recorded with consent while note-taking was done for one (as preferred).

3.3.1 Selection of Interviewees

The researcher was able to gain the needed insight into the study by gathering information from different perspectives. The perspective of the informant from WWTP was crucial in shedding light into the realities surrounding PHA production and commercialisation beyond what is found in literatures. This covered almost all the aspects of the PESTLE framework. The researcher/PHA expert interviewed was selected based on his active involvement with the PHARIO project (section 2.3.2), in which he led the technical developments and deliverables. His perspective was important especially in the technical aspect but also in environmental and economic aspects. The industrial expert from Paques BV[9] was selected because of his company's continued interest in PHA, and his personal involvement with the technology as part of his job role in the company. Thus, his opinions on all the PESTLE categories were crucial to the research. Likewise, the informant from PEZY group[10] was chosen because of his company's involvement with the PHARIO project as downstream producers. It was vital to get his opinions about the technical, economic and mostly social aspects of the research. Lastly, the perspective of an expert on the end of life management possibilities for PHA and their impact on its commercialisation was crucial to the study and this led to the selection of a respondent from the solid waste management company.

As part of the research framework, it was important to get the first-hand perspective of a government representative to cover the political and legal aspects but due to the COVID-19 situation, this was not possible. However, these aspects were dealt with through the data obtained from some of the interviewees and through secondary data, particularly government published reports. The list of the interviewees, their roles in the study and their affiliations are presented in table 1.

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[9] Paques is a wastewater technology provider specialised in anaerobic wastewater treatment and resource recovery (www.paques.nl).

[10]PEZY group is a hands-on innovation company in the Netherlands, which was involved in the product testing phase of the PHARIO project.

Table 1: List of Interviewees, their roles in the study and their affiliations

Name of Interviewee	Role in the study	Affiliation
Mr. Yede van der Kooij	Expert from a WWTP	Research and Project Manager at the Wetterskip Fryslan[11]
Alan Werker	Researcher/Expert on PHA technology	Researcher and Expert on PHA technology from Wetsus[12].
Joao Sousa	Industrial expert (PHA upstream producer/Technology provider)	Head of Emerging Technologies at Paques BV.
Joop Onnekink	Industrial expert (downstream producer)	Senior consultant at PEZY group
Aucke Bergsma	Expert from a solid waste management company.	Sustainability advisor at Omrin[13]

3.3.2 Data required and Accessing method

To guide the interview preparation, the data and information required and its accessing method were identified through the set of research sub-questions, as displayed in Table 2.

[11] The Wetterskip Fryslân (*Water Board Friesland*) is the water authority in the Dutch province of Friesland.

[12] Wetsus, European centre of excellence for sustainable water technology is a part of Water campus Leeuwarden (www.wetsus.nl). Leeuwarden is a city in the north of the Netherlands.

[13] OMRIN is the solid waste management company of the Friesland province in the Netherlands (www.omrin.nl).

Table 2: Data and information required for the research and accessing methods

Research Sub-Questions	**Data/Information Required**	**Sources**	**Accessing Data**
RQ1: How is the production of PHA in WWTPs a more circular route for carbon valorisation than the conventional biogas production?	-The benefits of PHA production over biogas production to the circularity of WWTP in terms of sludge reduction, CO_2 emission and waste resource (carbon) efficiency.	-Experts, especially from the WWTP -Researcher -Literature	-In-depth Interviews -Content Analysis
RQ2: What political and legal factors impact the commercialisation of bioplastics from wastewater?	-The existing policies about PHA and other types of bioplastics -The role, perspective and influence of government and policymakers	-Literature -Government reports. -All interviewees	-Content Analysis
RQ3: What are the environmental impacts of PHA's end-of-life options on its commercialisation?	-The feasibility of separation from other plastic wastes and possible recycling. -The extent of biodegradability and under which conditions. -Safety of degraded material to the soil	-Experts, especially from solid waste management industry -Researcher -Literature	-In-depth Interviews -Content Analysis
RQ4: What are the impacts of the social perception of PHA on its adoption?	- The effects of the bias of downstream producers and end-users on the adoption of the product. -The role of sustainability consciousness on the adoption of PHA	-Industrial experts -Literature	-In-depth interviews -Content Analysis
RQ5: What are the technological factors impacting the	-Consistency of crude PHA polymer -Purity of crude PHA polymer	-Researcher -Experts -Literature	-In-depth interviews -Content Analysis

commercialisation of PHA from WWTPs?			
RQ6: What are the economic factors impacting the commercialisation of PHA from WWTPs?	-The unique properties of PHA that gives it an edge over other types of bioplastics and traditional plastics. -The realistic scale of production and the economic/market impact of that. -The available niche markets for PHA	-Experts -Researcher -Literature	-In-depth interviews -Content Analysis

3.4. Data Analysis

The initial stage of the research involved a qualitative exploration of various documents and literatures relevant to the research. The findings from this stage provided the foundation for the analysis stage, which helped to achieve the objective of the research. The primary data from interviews were accessed through content analysis of transcripts. Content analysis is a research technique used to make reproducible and valid inferences by interpreting and coding textual materials [48]. For this research, manual coding was done. This entailed the labelling and categorisation of codes generated to identify themes and the relationship between them.

3.4.1 Validity of findings

To ensure validity of the results, the interviews were recorded and notes were taken for the only one that was not recorded (due to interviewee's preference). The interviews were transcribed word for word while the note taken was revisited immediately after the session and all thoughts were better reported in the form of transcript. Interpretative reliability was ensured by both iterating statements during the interview sessions and sending the chapter where these data were reported (chapter 4) to the interviewers for further clarifications. Table 3 shows the data required to answer the questions and the method of analysis.

Table 3: Data required and method of analysis

Data/Information Required to Answer the Questions	**Method of Analysis**
RQ1 -The benefits of PHA production over biogas production to the circularity of WWTP in terms of sludge reduction, CO_2 emission and waste resource (carbon) efficiency.	<u>Qualitative:</u> comparatively analysing the economic and environmental sustainability values of PHA production and biogas production to WWTPs
RQ2 -The existing policies about PHA and other types of bioplastics -The role, perspective and influence of government and policymakers	<u>Qualitative</u>**:** analysing the legal and regulatory context surrounding PHA in the Netherlands and in the EU. <u>Qualitative</u>: analysing the position of government and policymakers in PHA commercialisation
RQ3 -The feasibility of separation from other plastic wastes and possible recycling. -The extent of biodegradability and under which conditions -Safety of degraded material to the soil	<u>Qualitative:</u> analysing the available recycling options for end-of-life management of PHA. <u>Qualitative</u>: analysing the environmental impacts of PHA disposal into the environment.
RQ4 -The effects of the bias of downstream producers and end-users on the adoption of the crude polymer and final bioplastic product respectively. -The role of sustainability consciousness on the adoption of PHA.	<u>Qualitative:</u> analysing the attitude of consumers towards its adoption and its impact on commercialisation.
RQ5 -Consistency of crude PHA polymer -Purity of crude PHA polymer	<u>Qualitative:</u> analysing the feasibility of achieving a highly pure and consistent quality crude PHA polymer and its impact on its commercialisation

RQ6 -The unique properties of PHA that gives it an edge over other types of bioplastics and traditional plastics -The economic impacts of the realistic scale of production -The available niche markets for PHA.	 Qualitative: analysing the exclusive properties of PHA and their role in its market penetration. Qualitative: analysing the 'demand versus supply' context of PHA and the consequent market impact. Qualitative: identification of the strategic markets for PHA and the willingness of market players to consider this product.

3.4.2. Analytical Framework

The schematic representation of analytical framework is shown in figure 7.

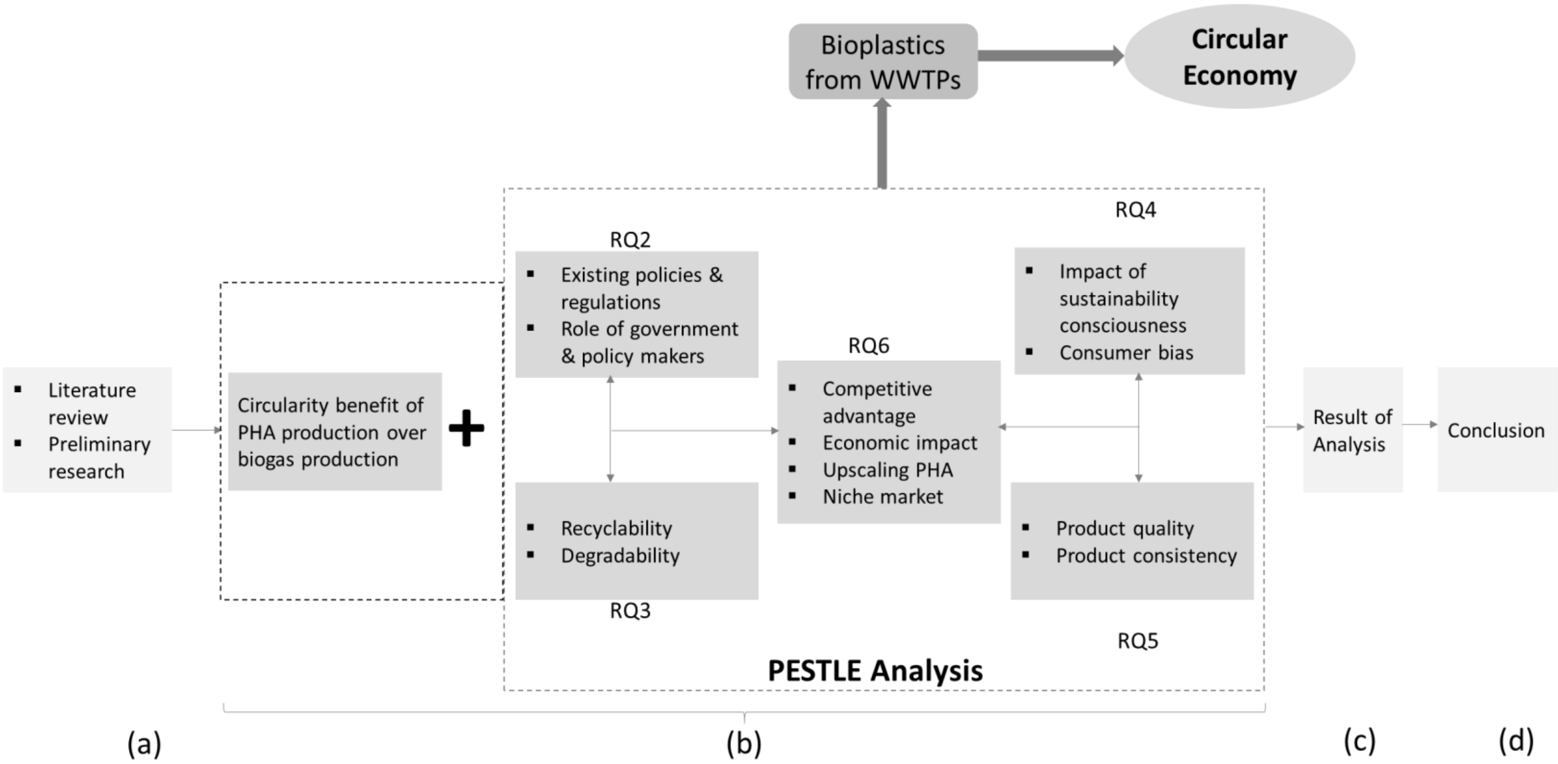

Figure 7: A schematic representation of the analytical framework

The data analysis was conducted in the following sequence:

a. The first step of the analysis was done by studying relevant documents and literatures. The document review helped shed some lights on research sub-question 2 about the existing policies and the role of government in facilitating the commercialisation of PHA bioplastics while the literature, alongside the primary data, was crucial to answering all the research questions.

b. The next analysis was content analysis of the data generated from the interviews. This was to first explore the circularity benefits of PHA production to the WWTP, and then to carry out a PESTLE-guided market analysis.
c. The third step was the analysis of the results from (a) and (b).
d. The result of (c) was used to draw conclusions which ultimately helped to answer the main research question.

3.5 Ethical Considerations

This research involved the gathering of information from humans in form of interviews. It was therefore imperative to seek the consent of participants before conducting the interviews. The information provided in advance to the interviewees addressed the following: the voluntariness of participation; the nature and purpose of the investigation, the right to decline participation and withdraw from the research at any time without any negative consequences, and name and details of the researcher.

The informant's approval: the informants volunteered to become involved in the research process, and were informed about the aim of the study. In addition, the informant was offered the right to interrupt their involvement in the course of the research. This contributed to ensuring that the informants had control over their own participation in the research process. Therefore, a written consent form was issued to the participant prior to the interview, to read and sign where necessary. All signed consent forms can be found in appendix I.

Confidentiality: If an informant requested that any information be kept confidential or his/her anonymity be preserved, the researcher ensured this.

Consequences: The interviews were conducted in a way that preserved the informants' integrity by taking into consideration the informants' interests and reputation.

CHAPTER 4: FINDINGS

This chapter presents the research findings based on the content analysis of the data collected from the primary data sources, namely, the semi-structured interviews conducted. The profiles of the interviewees have been presented in section 3.4.1 (table 1). No discussion or interpretation of results takes place in this chapter. The information needed to answer the research sub-questions and ultimately the main question is presented sequentially. The first section deals with the contribution of PHA production to circularity in WWTP in comparison to biogas production while the next section deals with the PESTLE categorization of findings to address the market-related concerns.

4.1 Carbon circularity in WWTPs: a field to further explore

Carbon is a valuable resource in wastewater and its efficient recovery is crucial in facilitating circularity in WWTPs. The currently favoured route of carbon valorisation in WWTPs is biogas (specifically, methane) production and this is primarily due to the subsidies received from the Dutch government [5,49]. However, considering the waste hierarchy[14] and the bio-based pyramid [50], energy recovery is at a lower level compared to material recovery. One of the interviewees, Yede van der Kooij, a Research and Project Manager at the Wetterskip Fryslan mentioned that the major benefit of biogas production for WWTP is sludge reduction. He stated that the business case is not so much about energy production but about the reduction in sludge disposal costs. After sludge dewatering, the dewatered sludge is transported to an incinerator. This operation costs the Frisian water board €4.7 - 5 million annually. However, through biogas production from about 25% of the produced sludge, about € 1 million is saved and therein lies the business case for biogas. The energy component of the operation has become interesting only because of the subsidy, which has made stakeholders further develop the business case of biogas generation from WWTPs. However, Yede van der Kooij noted that the effect of biogas production (from sludge) on sustainability is little. Only about 25% of the organic matter in wastewater is converted to methane, and most of the remaining organic fraction is oxidised to CO_2. This is not just a wasteful approach but also unsustainable. Alan Werker supported this by stating that maximizing the conversion of wastes to renewable resources is highly important in the transition to a circular economy. He highlighted that the main focus of a lot of WWTPs are wastewater treatment, not so much about resource recovery. However, after these treatments, the surplus sludge should be optimized by converting them into valuable resources such as PHA, which extend the circularity of carbon and are more beneficial for the society. This should be considered in place of the current

[14] The Waste hierarchy introduced by the EU Directive 2008/98/EC on waste (Waste Framework Directive) provides a priority order for waste management with waste prevention as the first priority, followed by re-use, recycling, recovery and disposal.

practice of destroying most of the organic matter via oxidation. The same thought was reiterated by almost all the interviewees.

4.1.1 Comparison of the economic value of biogas and PHA productions to conventional WWTPs

Instead of oxidising (to CO_2) most of the organic matter in the wastewater (conventional WWTPs employ the aerobic biological process[15]) [3], a more sustainable and economic strategy is to valorise these organics to useful biopolymers such as PHA. Figure 8 shows the relatively low value of biogas (methane) production compared to PHA production from an equal amount of organic matter (3 kg chemical oxygen demand[16]). Even with the subsidy, the revenue from producing biogas is only about 20% of what could be realised with PHA production.

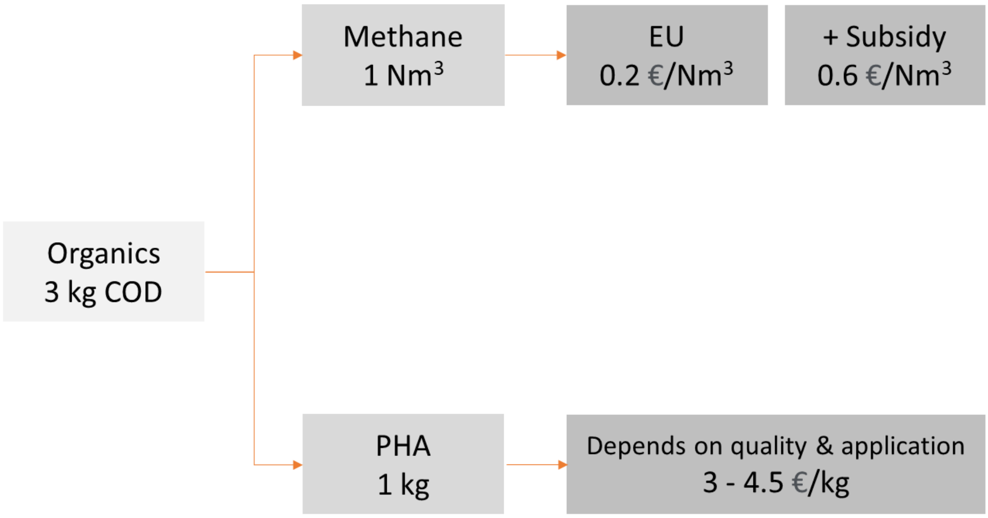

Figure 8: Comparison of the economic value of biogas (methane) and PHA productions (adapted from Joao Sousa's presentation at the Wetsus Congress, 2019).

4.1.2 How does PHA production compare with biogas production at WWTPs in terms of sustainability? A case study of Wetterskip Fryslan

Using Wetterskip Fryslan as a case study, data was obtained from Yede van der Kooij about CO_2 emission, sludge production and sludge disposal to compare the impacts of PHA production and biogas production, in terms of circularity and sustainability on the WWTPs in Frsylan. Wetterskip Fryslan employs the conventional aerobic wastewater treatment process. It produces about 15,000 tonnes of dry sludge (about 400,000 tonnes of wet sludge) per year. If a conservative estimate of 28% of the

[15] Aerobic biological process is the use of bacteria to break down organic pollutants in the presence of oxygen.
[16] Chemical Oxygen Demand (COD) in the context of wastewater treatment is the energy available for bacteria to consume and utilise for their growth and other metabolic activities such as producing PHA.

sludge is used for PHA accumulation and considering that PHA accumulation in biomass is about 60% sludge dry weight, then about 2500 tonnes of PHA will be produced, with a reduction of approximately 10,000 tonne CO_2-eq. The total CO_2 footprint of Wetterskip Fryslan for the year 2017 with active biogas production was 47600 tonnes per year (Figure 9). Considering this, PHA production with only a quarter of the sludge can reduce the CO_2 footprint by about 21%.

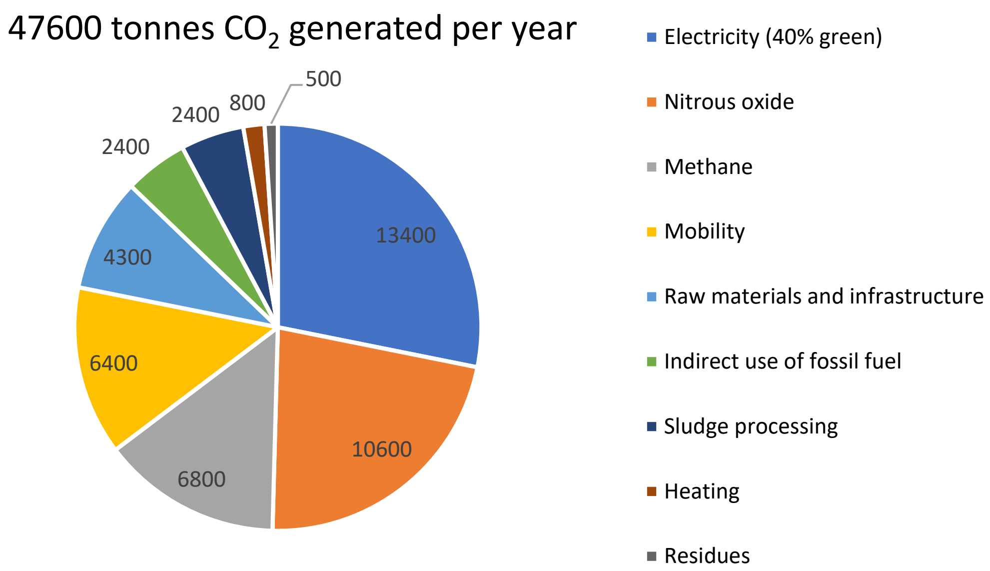

Figure 9: The total CO_2 footprint of Wetterskip Fryslan in 2017

(received from Yede Van Der Kooij)

Moreover, Yede van der Kooij was of the opinion that energy production is still possible with PHA production. The empty cell mass left after extracting PHA from the biomass (the microorganism that accumulates the PHA) can be further used for energy production via incineration or even for biogas production if there is sufficient organic carbon left. The combination of PHA extraction from PHA-rich biomass and subsequent energy generation will further reduce the amount of waste sludge and the consequent cost of sludge disposal.

Considering that for a commercial PHA plant producing 6000 tonnes PHA/year (as calculated by the PHARIO process [21], the sludge produced from about 1.2 million population equivalents is needed. Altogether, the Netherlands treats the wastewater of about 24 million population equivalents. Therefore, this implies that only about 5% of the total wastewater treated in the Netherlands is required for a first commercial plant. However, not all the WWTPs are large enough for an economically feasible scale of PHA production. With biogas, virtually all the WWTPs can successfully incorporate its production into their treatment processes and Yede van der Kooij suggested that the best option will be for small WWTPs (typically less than 100 000 population equivalents) that are already in business with biogas production to continue with that and not try to incorporate PHA production. However, the plants that are large enough for PHA production should strongly consider it, taking into account the higher score of PHA as a resource over biogas, in terms of CO_2 emission, sludge management and circularity.

4.2 Pestle categorisation of findings

This section presents the findings from the interviews in a PESTLE-guided framework. The political and legal aspects are grouped together and reported first, followed by the environmental, technological, social and economic aspects.

4.2.1 Political and Legal Aspects

The intervention of the government of any country is to stimulate, among other things, economic growth. Moreover, their legal power could have a strong influence on business operations and consumer behaviour. Hence, the role and perspective of the Dutch government and the European Union towards the commercialisation of PHA from WWTPs were investigated in this section.

The influence of the government and the power of legislation

At the moment, there is not a lot of direct and active attention received from the Dutch and EU government for PHA production from wastewater (Yede van der Kooij). All the interviewees unanimously agreed that the major role of the government will be in legislation, majorly to place stricter regulations on unsustainable materials and encourage the use of sustainable alternatives. So, a strong push towards biodegradable polymers because of the necessity of the property, for instance, will definitely favour PHA since it is one of the few polymers that fit well into that category. Alan Werker highlighted a legislation under consideration, through which, strict restrictions will be placed on the use of non-biodegradable plastics for fertilizers in a bid to mitigate microplastic pollution [51]. Such legislation would mean that the market will be forced to look to materials that are biodegradable such as PHA, thereby expanding the market for such sustainable products.

Aucke Bergsma also suggested the introduction of regulatory instruments that oblige producers to have a certain percentage of their products produced from biodegradable plastics, similar to the present EU directive on incorporating recycled plastics into newly produced plastics [52]. Alan Werker further noted that there is a need for the government to be realistic in their approach – all opportunities and possibilities should be considered and the rules should be such that potential investors will not be discouraged. Joao Sousa had a similar thought and gave an example of a regulation against the use of single-use plastics [53]. This kind of generalization in policy-making, without any distinction, becomes a problem for sustainable and natural polymers like PHA which somewhat fall under that category when used for applications that harness their biodegradability. He, therefore, mentioned that changing the status or category of this kind of polymers, as it is already being advocated by a pro-PHA organisation, the Global Organization for PHA [54], is one of the ways to overcome this challenge.

Another crucial point pointed out by Joao Sousa and Yede van der Kooij regarding the status of PHA is the 'end-of-waste' criteria. When resources are produced from waste, including wastewater, then the status 'end-of-waste' is given to the resource. This label becomes a big legal bottleneck for most circular products, including PHA because it warrants enormous testing procedures, which are both expensive and cumbersome. Yede van der Kooij believed this juridical aspect needs to be looked into to achieve a smooth transition to a circular economy.

Another way the government can play a strategic role is through subsidies on renewable resources. Three out of the five interviewees suggested that subsidy would be a useful financial instrument to facilitate the commercialisation of this product. Yede van der Kooij argued that a level playing field is needed between subsidies on energy and those on resources such as PHA. The SDE+ (Stimulering Duurzame Energietransitie) subsidy is the Dutch government subsidy on energy, from which biogas production highly benefits [49]. The price of biogas is about 20 cents/m^3 but with subsidy, it becomes about 60 cents/m^3, – three times the normal price (Joao Sousa). Yede van der Kooij, therefore, opined that having a somewhat similar subsidy on resources could help stimulate the development of the technology and market for PHA, especially for the associated capital cost, which is the major drawback to its commercialisation (discussed in section 4.2.5.3). If the Dutch government or the European Union can guarantee this kind of subsidy on resources, then it will be easy for the relevant WWTPs to convince their own Water Boards[17] to put more efforts, capital and means into this resource project. Joao Sousa had a similar opinion that the advantages associated with the production of much more circular and sustainable products, like PHA should facilitate a fair competition between the compensation received from the government for energy and for resources. However, Joao Sousa further noted that the SDE+ is beginning to expand the range of products being subsidised and even though PHA is not included yet, the action towards expansion looks like a promising step. On the other hand, Joop Onnekink argued that providing subsidies is not always the best way to go but flipping it over and having taxes on unsustainable products would be a more strategic action. However, that will be related to subsidies provided on products, not that provided as aids for production processes.

[17] Dutch water boards (Dutch: *Waterschappen* or *Hoogheemraadschappen*) are regional government bodies charged with managing water barriers, waterways, water levels, water quality and sewage treatment in their respective regions (https://en.wikipedia.org/wiki/Water_board_(Netherlands)).

Finally, regarding the influence of government, Yede van der Kooij noted that the government has a role to play in societal education. The government here might mean the Waterboards, as they are the government authorities responsible for wastewater management. They need to provide education through information campaigns to the general public, industries and consumers about circular products like PHA, initiating dialogues, actively incorporating lessons on circular economy into primary and secondary school curricula, organizing technical and academic trainings, among others. He gave the example of the big campaigns initiated on the separation of wastes in households and industries in the 90's and the subsequent legislation developed about the waste hierarchy within the next 10 years. He highlighted that those moves have proven to be highly effective in encouraging openness and good behaviour in the society.

Summary of key findings on Political and Legal Aspects is presented in Table 4.

Table 4: Results on Political and Legal Aspects

Political and Legal Aspects	# interviewees
Drivers	
• Favourable legislation such as prohibiting the use of non-biodegradable plastics in some applications	5
• Regulatory instruments like taxes on unsustainable products.	1
• Subsidies	3
• Societal education	1
Barriers	
• Unfavourable legislation such as restriction of single-use plastics without exemption of biodegradable single-use plastics like PHA and the end-of waste status.	2

4.2.2 Environmental Aspects

In a circular economy, the environmental impacts of new innovations, especially at their end of life, need to be strongly looked into before they are pushed into the market. Biodegradability is one key property of PHA that sets it apart from most other bioplastics. However, recycling seems to be a more sustainable and less wasteful route for these products. Hence, it was important to investigate the recycling possibilities and the involvement of solid waste management companies, who might be dealing with these products at their end of life.

4.2.2.1 Recycling of PHA

Polylactic acid (PLA), being the biggest type of bioplastic currently on the market, was thought to be a good benchmark when considering the current state of bioplastic recycling. As PLA market expands, one major limitation it faces is the current lack of recycling facility due to its relatively small volume [41]. As a result, some of the interviewees were asked for their opinion about how PHA could circumvent the recycling drawback, which is a major barrier to PLA's sustainability claim. Alan Werker was of the opinion that it is a mistake to try to introduce materials that might cause complications for some sectors such as the recycling sector. He noted the enormous resistance from the society against the introduction of new things. People are used to operating in a certain way and therefore, find it difficult to adopt new developments. Using the recycling industry as an example, he stated that this already has established operation processes for traditional plastics and are therefore not ready for any disruption by bioplastics. More so, the percentage of bioplastics is very small (∼1%) compared to the volume of traditional plastics that can be recycled [40]. A similar position was taken by Aucke Bergsma, he mentioned that biodegradable plastics cause a lot of trouble in the traditional plastics recycling processes because of their bad influence on the properties of the recyclates[18]. He noted that, though it is technically possible to sort bioplastics from traditional plastics, every sorting step has a certain efficiency and this means that small amounts of bioplastics still end up in the fossil plastic stream. He further confirmed that there is currently no separate recycling process for bioplastics in the Netherlands because it is not regarded as being worthwhile to sort and recycle them, for the same reason of small volume. Taking this to PHA, Alan Werker opined that it is too early for PHA to start striving for recycling, it should rather remain in its unique lane first. However, this does not mean it cannot be recycled in theory; recycling is possible. There are several research efforts going into PHA recycling, but the industry is not likely to take it up until there is a substantial amount in the market (Aucke Bergsma).

Furthermore, Aucke Bergsma noted that although biodegradable plastics are marked with the 'kiem plant' logo in the Netherlands to facilitate proper disposal by consumers, composting them with other organic wastes poses a lot of problems for composting companies because of the much longer degradation time when compared to the other green waste. The products end up being sieved out and incinerated. Joop Onnekink was of a similar opinion about recycling: he noted that the relatively limited amount of these products, in comparison with the huge fossil plastic waste stream, means that they will often end up being burnt or landfilled and not recycled, despite being expensive to produce. Aucke Bergsma, therefore, suggested keeping these products apart and conducting more research on how to better manage all the associated end-of-life management problems. Joao Sousa supported this by stating that the recycling industry will need to get on board in the research towards recycling of bioplastics. He, however, noted that PHA has a somewhat greater advantage over PLA as far as composting is concerned because if it ends up on an industrial compost, it will degrade and disappear

[18] Recyclates are raw materials processed in a waste recycling plant or materials recovery facility which will be used to form new products (https://en.wikipedia.org/wiki/Recycling)

quite faster than PLA. However, Aucke Bergsma stated that even the relatively short time of PHA degradation (2 – 3 months [55] is still too much for composting companies to handle.

Asides recycling, Alan Werker highlighted other sustainable options to consider for PHA at its end-of-life. He mentioned that it has been proven that it can be converted to biogas for energy production. Also, because it behaves like thermoplastics, it can be melted, pelletized and reused like other polymers. Although it stands the risk of reduced mechanical properties, it is of course, not different from how other polymers behave when recycled. Lastly, he mentioned degradation as another great end-of-life option worth noting, as long as it is used for purposes that strongly require that property such as for agricultural mulch films.

4.2.2.2 Involvement of solid waste management companies

The involvement of solid waste management companies in PHA research and development is crucial when considering its environmental impact at its end-of-life phase. Some of the interviewees were asked about their opinions on this.

Alan Werker mentioned the Dutch company, Slibverwerking Noord-Brabant (SNB), which is a sewage sludge processing company, as a potential supplier of VFAs for PHA production. Aucke Bergsma also revealed that Omrin has had some discussions about collaborating with Paques (the major company looking into PHA production from wastewater in the Netherlands) on being a potential supplier of VFAs to them. Joao Sousa likewise mentioned a few solid waste management companies they are working with, for instance, Omrin, HVC, Orga World and Attero. He stated that these companies are interested in playing a role as they are on both ends of the cycle, namely, to supply organic wastes as feedstock and to deal with the end-of-life phase of the plastic.

Alan Werker stressed the importance of commercial investments and industrial symbiosis in PHA commercialisation. This, he said, is a situation where different industries come together with the aim of combining and making the best use of resources, resulting in strong socio-economic relationships. However, because recycling is not really happening for now, the involvement of these solid waste companies is currently more in the production side than in the end-of-life management but the latter is also being looked into.

4.2.2.3 Biodegradability and sustainability

In a newsletter on sustainable business [56], a spokesman of the Dutch Waste Management was quoted as follows: 'biodegradable is not equal to sustainable and should therefore not be the major selling point of bio-based products.' Considering that biodegradability is indeed one of the major selling points of PHA, the opinion of the interviewees was sought regarding this statement and the market implication of such a notion on PHA commercialisation. Alan Werker argued that that was a misleading and oversimplified idea. He believed that having a more effective management of resources or the residuals of societal activities in a way that promotes circularity is the goal. Therefore, if biodegradability is a key requirement in some applications, then that makes it sustainable. Fundamentally, the most important thing is having a circular economy where wastes can be utilized in better ways, which could of course, mean in applications that require biodegradability. In the same vein, Joop Onnekink stated that considering the overall application of products is what makes it sustainable, not just about the material. If a product has an unavoidably high risk of ending up in the environment because of its usage form, then choosing a biodegradable material for such purposes will be the most sustainable thing to do.

On the other hand, Joao Sousa was of the opinion that as important as biodegradability is, it is not the only thing that will give PHA producers the market. It is, of course, a valuable property as it offers an extra end-of-life option but the polymer needs to be able to strive on other interesting properties like thermal and mechanical properties that are also interesting for the market. Biodegradability becomes more interesting when that particular property is really required. In terms of CO_2 footprint, Joao Sousa noted that PHA production has an advantage as its production is CO_2-neutral. They estimated that for every kilogram of PHA used, 4 kilogram of CO_2 equivalent is saved. So, beyond biodegradability, the production of this polymer from waste is sustainable in terms of CO_2 neutrality compared to traditional plastics. Nonetheless, recycling will always be a preferred end-of-life option compared to biodegradability because biodegradation leads to CO_2 release. Hence, the CO_2 saved during PHA production ends up being released again when biodegraded. So, like other interviewees, Joao Sousa agreed that biodegradability could be a part of sustainability but he thought it should not be seen as always equal to sustainability or the most sustainable solution to go for, but it could definitely be a great selling point when used in the right applications, namely those that highly require it.

Summary of key findings on Environmental Aspects is presented in Table 5.

Table 5: Results on Environmental Aspects

Environmental Aspects	# interviewees
Drivers	
• Biodegradability/Compostability	5
• Sustainable (circular) production process	2
Barriers	
• Current lack of mechanical recycling options	3

4.2.3 Social Aspects

Since PHA is produced upstream as a crude polymer that needs to be fashioned into end-products by downstream producers, the perspective of the downstream producers and end-users will be vital in its acceptance.

The impact of sustainability consciousness on product preference by downstream producers and end-users

According to Joao Sousa, the sudden realization of the enormous negative impacts of fossil plastics in recent years has led to increased societal awareness and the emergence of several legislations that have resulted in a big shift towards biodegradable polymers like PHA and PLA. Investors and producers are beginning to show great interest in PHA because of its necessity in their business applications, for example, in the agricultural sector where there is a plan to legislate in favour of the use of biodegradable plastics [57]. Furthermore, Joop Onnekink stressed that there is often no end-user bias in choice making because marketers usually stress product benefit over product source. What is important is that it is bio-based, made by microbes, it is circular as it is made from waste and it has useful properties. Downstream producers, on the other hand, mostly look at the total picture, they consider the solution the product is providing and the cost of the crude PHA before thinking about its sustainability.

Regarding the end-users, most of the interviewees agreed that it would not be helpful to mislead consumers by simply stating that the product is biodegradable and could simply be dumped carelessly in the environment. The risk run here is that consumers end up not thinking any differently about the product, they simply treat it as plastic that can be littered in the environment since it is biodegradable, thereby constituting a nuisance in the environment before its degradation. Joop Onnekink also stressed the importance of honesty in the marketing of bio-based products. The poor public perception of fossil-based plastics is still a barrier to the acceptance of biobased plastics (for some, plastic is plastic irrespective of its source), so producers should be transparent and highly interested in the sustainable end-of-life management of their products. Joao Sousa was of the opinion that people are becoming open to sustainable products, although PHA from sewage sludge will still be limited for now in its acceptance for some applications, such as food packaging. A lot of work will have to be done to prove its safety in such applications. This associated risk in image makes such applications not the first focus for now but with time and proper societal education, the acceptance will come.

Summary of key findings on Social Aspects is presented in Table 6.

Table 6: Results on Social Aspects

Social Aspects	# interviewees
Drivers	
• Increasing societal awareness and openness to circularity and sustainability	2
• Green perception of biodegradable products like PHA	1
Barriers	
• The effect of the poor public perception of fossil-based plastics	1
• Bias against its source for certain applications	2

4.2.4 Technological Aspects

All the interviewees whose opinions were sought about the importance of the consistency and purity of the produced PHA all agreed that these were vital factors in PHA commercialisation. However, most of the interviewees stressed consistency as a more important factor than purity. From an industrial expert's perspective, Joop Onnekink argued that consistency and stability are crucial because these polymers come into applications with established processes, and no downstream producer will be willing to change their process due to inconsistency in material quality. Joao Sousa affirmed that consistency is one of the challenges of products from waste streams. However, he noted that focusing on applications where purity could be a bit lower and also working with partners that are willing to accept slight variations in PHA consistency are the focus for now. That does not in any way mean the crude PHA producers (such as Paques) will stop striving for better purity and consistency but to get the product to the market, it would be a good strategy to first focus on applications where high PHA purity and consistency are not needed. Yede van der Kooij was of a similar opinion that very sophisticated applications, such as medical, that require the highest purity should not be the primary target route for a product made from wastewater, as even legislation might not permit it.

Alan Werker stated that there are certain regulatory standards for chemicals such as its level of purity or a limit to the amount of harmful substances like heavy metals they should contain. The PHARIO pilot project [21], in which he led the technical developments and deliverables, demonstrated the possibility of achieving these requirements. The PHARIO project also demonstrated the technical feasibility to engineer the scaled-up production of PHA with consistent properties, even when using bacterial biomass produced as a by-product from municipal wastewater treatment (the surplus or waste activated sludge). This was achieved through the demonstration of predictability in the outcomes of the polymer properties related to potential influences from the bioprocess steps and the downstream polymer chemical recovery processes.

Furthermore, Joop Onnekink stressed that choosing the right technology for making products out of PHA is a crucial factor in its market success. Different products might require different technological processes. For instance, his company made business card holders for the PHARIO project with injection moulding technology. However, according to him, trying to make bottles with the same technology was a big failure, a different but suitable technology had to be employed for that purpose. He saw that as a limitation, in addition to some behavioural properties of PHA they experienced during production. PHA, when melted, has an incredibly low viscosity, lower than water, which results in a relatively low crystallization rate and a high stabilisation time. This causes long cycle times and quite undesirable product outcomes. However, Joao Sousa was of the opinion that this behavioural issue is relatively easy to overcome in the future via blending. Although he confirmed the low viscosity nature of the polymer, he mentioned that it changes with molecular weight and it is possible to modify the polymer to achieve a more desirable behaviour via blending. This, he further said, might mean there are certain boundaries of applications for the polymer but it is a pretty common occurrence in the polymer industry to have different blends of polymers to achieve the desired properties. It will therefore not be a peculiar problem of PHA.

Another technical consideration will be the undesired rapid degradation of PHA product when used in applications that require a little longer functional time before degradation. Joao Sousa argued that that would be considered a luxury problem because it is relatively easy to finetune the PHA to degrade at a much slower rate by either modifying some properties of the PHA itself such as its crystallinity or by blending it with other biodegradable materials with longer degradation time, such as PLA

Summary of key findings on Technological Aspects is presented in Table 7.

Table 7: Results on Technological Aspects

Technological Aspects	# interviewees
Drivers	
• Technical modification possibilities to achieve desired properties	3
• Possibility of achieving consistency and high purity	2
Barriers	
• Undesirable manufacturing behaviour due to properties such as low viscosity	1
• High technical costs of achieving consistency and high purity	3

4.2.5 Economic Aspects

PHA is still at the embryonic phase of the development stages of new polymers. However, it is now quickly accelerating and starting to get a name for itself in the market but this also means more demand than supply (Joao Sousa).

4.2.5.1 Competition with fossil-based plastics and other bioplastics

All the interviewees had the same thought about PHA competing with other bioplastics in the market. They unanimously agreed that competition was not the way to go. Alan Werker was of the opinion that PHA and other bioplastics are not in the market to totally replace traditional plastics, hence no need for competition. It should not be expected that they would break into the market to solve all the plastic problems at once. So, for instance, if some other polymer is more fitting for a particular application, then it is best to utilise it for such application so long as the materials are well-managed throughout the product's life – from cradle to cradle. He believed that seeking out the most interesting applications where the advantage of the unique properties of PHA are most needed is the best strategy for market success. Joop Onnekink reinforced that, with the argument that PHA, being of a comparatively small amount in the total volume of plastics produced and used, coupled with its relatively high cost, it is best to use it wisely in applications that require the typical and unique properties of the polymer and not try to compete with other materials that are much more suited for other applications. These unique properties, according to Alan Werker and Joao Sousa, are mechanical and thermal properties, and of course in combination with biodegradability, where the products remain where they are utilised without the fear of posing harm to the environment. Joao Sousa also thought that the enormity of the market for these polymers already discourages competition. Furthermore, Alan Werker talked about the potential for overlap in the services provided by different types of bioplastics. Furthermore, there are different types of PHA. Each type of PHA has distinguishing shades of differences in properties, and a given application may be very PHA-type dependent. Of course, specific respective properties (as well as market price) may favour some applications over others, however, they are not necessarily mutually exclusive. Sometimes, the properties of one type of bioplastic that make its use in some applications difficult can be easily compensated for or enhanced by another type of formulation used for the same bioplastic. For example, the brittleness of some polymers can be improved upon by blending in another polymer in order to influence the plastic microstructure, and resulting mechanical properties. He cited the case of the PHARIO project as an example, where PHA was used to enhance properties of Corbion PLA. The PHA acted as a toughness enhancer for the Corbion PLA [21]. He concluded that applications demand a spectrum of material properties within the boundaries of the economy of that application. Engineering materials used in products and services are developed as formulations of ingredients for which PHAs have a role to play, independently and in combinations with other ingredients. Meaningful considerations and explorations for that commercial role require reliability of material supply in quantity and quality. If the types of PHAs produced in PHARIO, for example, are not available in sufficient supply for the market of application developers, it is extremely difficult, if not impossible, for roles in unique applications to be realistically and broadly entertained and, for would-be entrepreneurs, to engage to establish commercial uses for these materials.

As regards pricing, Joop Onnekink saw price as a huge limitation in the market success and competitiveness of PHA. He highlighted a project his company was involved in, which was the production of biodegradable children's beach toys. According to him, though the project was a success from a technical point of view, the price of the play toy in the end was about 4 - 5 times the price it would be if produced out of traditional polyethylene or polypropylene. This price difference between biobased and fossil-based plastics therefore makes it difficult to make a profitable business case for biobased plastics for such applications. However, Alan Werker was of the opinion that social values and public policy come into play when comparing prices with other products such as fossil-based plastics. A culture that promotes comparison on just the basis of purchase price with products that fail to consider the associated common costs of environmental impact of their processes, as well as the burden and costs of mitigating environmental impacts is short sighted of governments, communities, and individuals alike. Alan Werker also thought that since PHA was just coming up, it would definitely start on a small scale and be more niched in the market but of course, often times, as production scale of a product gets bigger, then it becomes more economical to produce and to compete as a polymer for use more widely in mainstream applications. Hence, PHA producers have to first focus on niche markets where they can still have a meaningful business case and not try to compete, initially and directly, in mature markets. Besides, there are people who would not mind paying a higher price for such products because of the sustainability appeal. Joao Sousa further buttressed this idea using PLA as an example, that although PLA is still quite expensive, it is still in business. The important thing will be having a good business case, and a receptive and committed market to sell it to. On the other hand, Joop Onnekink argued that the best strategy for this polymer would be to not use it for stand-alone products but rather with other polymers, for example, as blends with other biobased polymers such as PLA for improved properties.

Another economic constraint is the high cost of downstream extraction of PHA accumulated in the biomass [58]. Joao Sousa noted that achieving a high purity PHA from wastewater biomass requires an expensive purification process. This purification process is capital intensive due to the need for big-scale reactors, solvent recovery plants, among others. The associated investment costs are therefore the setback, not so much the operational costs, since the solvent can be recycled and reused again for several cycles. However, Joao Sousa mentioned that work is currently being done on lowering the cost, which will most likely result in PHA price reduction and a better market placement. Presently, they have been able to achieve a price reduction below the current market price of PHA from pure cultures, which is about 5euro per kg.

4.2.5.2 Biodegradability and the market success of PHA

As a material choice expert, Joop Onnekink mentioned that the choice of a material over another similar material is based on the advantages of the properties of one over the other. He highlighted two reasons for choosing PHA. One is its biodegradability, which could be a commercial reason if used for products that highly require that property. An example he gave was the production of the beach toy for children. If lost on the beach, this plastic can easily break down without causing plastic pollution in the marine environment. He, however, mentioned that there are other materials with the same property that can serve the same function but a second consideration will then be safety. The impact resistant property of PHA ensures that it does not break and pose a risk of injury when dropped, it only bends and that might indeed be a safe property to look out for in a product made for children like a beach toy.

4.2.5.3 Scaling up

Joao Sousa and Yede van der Kooij both mentioned that scaling up PHA production, that is, meeting up with the market demand is the biggest barrier to its commercialisation. This, they both addressed as the 'chicken and egg' dilemma. There is a demand but there has to be a corresponding supply. Before downstream producers can be committed to invest in this product, they need prototypes of PHA in certain quantities (about 100 - 1000 kg) to conduct application tests. These amounts are much higher than the current pilot production scale and, therefore, necessitates the building of a larger scale plant (a demo scale) to produce practical amounts for testing. Until this is achieved, the commercialisation of PHA from wastewater might never become a success. Joao Sousa and Yede van der Kooij both stated that a demonstration plant is currently being built, from which a reasonable quantity (between 600 - 1000 kg) of the polymer can be produced for market testing. However, a commercially viable plant (a full-scale plant) as calculated from the PHARIO process should be able to produce around 5000 - 6000 tonnes of PHA per year [21]. This will require an enormous investment (largely the capital expenditure, CAPEX) and that is where governmental subsidies could be of tremendous help. This challenge is not peculiar to PHA from WWTPs but it is often the case with most circular products. The gap between innovation and commercialisation is always there, and relevant tools like subsidies to help bridge the gap are always needed. Usually, there are separate subsidies for pilot projects and full-scale plant building but the step in between these two stages of business development is always the most difficult and that is another reason for the government to look into new tools to aid development in this area.

4.2.5.4 Niche markets

All the interviewees mentioned the agricultural sector as the most promising niche market for PHA. One agricultural application is in its use as mulch films[19]. The use of traditional non-biodegradable plastics as mulch films presently pose a huge environmental problem because of the difficulty in recovering them. This results in unavoidable plastic contamination to the soil, and even when they are recovered, they are not easy to recycle, so they end up being burned or landfilled (Joao Sousa). Another interesting agricultural application mentioned is its use as coatings for controlled-release fertilizers, where the plastic serves as a kind of wrap for the fertilizers to ensure they are secure and not easily washed away or released to the soil too quickly. The advantage here is an efficient and sustainable use of resources, in this case, the fertilizers, as they are released in a highly controlled manner. Furthermore, using PHA, as an alternative to traditional plastic, for this purpose provides an added benefit of zero risk of plastic contamination to the soil since it degrades. Unlike PLA, which needs certain industrial composting conditions for degradation, PHA can biodegrade at ambient environmental conditions, and not pose a risk to the environment [59]. These markets are particularly interesting for PHA now because of the recent EU legislation in favour of the use of biodegradable polymers in these applications by 2025 [60]. This will mean a huge market shift towards biodegradable polymers like PHA and market size will therefore not be an issue for a new PHA producer (Joao Sousa).

In addition, Alan Werker mentioned that the biodegradation property of this polymer could make them useful in exploration mission trips, where things taken along for the mission might not be taken back. He also suggested applications in structural elements that require harmless dissolution of the material into the environment when no longer in use and as prebiotics in aquaculture [61]. Joop Onnekink likewise stressed the uniqueness of the biodegradability of PHA, not so much the fact that it is biobased, as he believed people do not really care about the latter as they do about the former. He saw a promising market in applications for garden products where it will be safely absorbed into nature with no environmental concern. According to him, the product might end up being more expensive but on the other hand, not having to remove it afterwards for proper disposal by the users could be a great marketing opportunity for the PHA industry. Joop Onnekink further talked about 3 classifications of products in the market: the disposables, the durables and the plannables as shown in Figure 10.

[19] Mulch films are used to modify soil temperature, limit weed growth, prevent moisture loss, and improve crop yield as well as precocity [93].

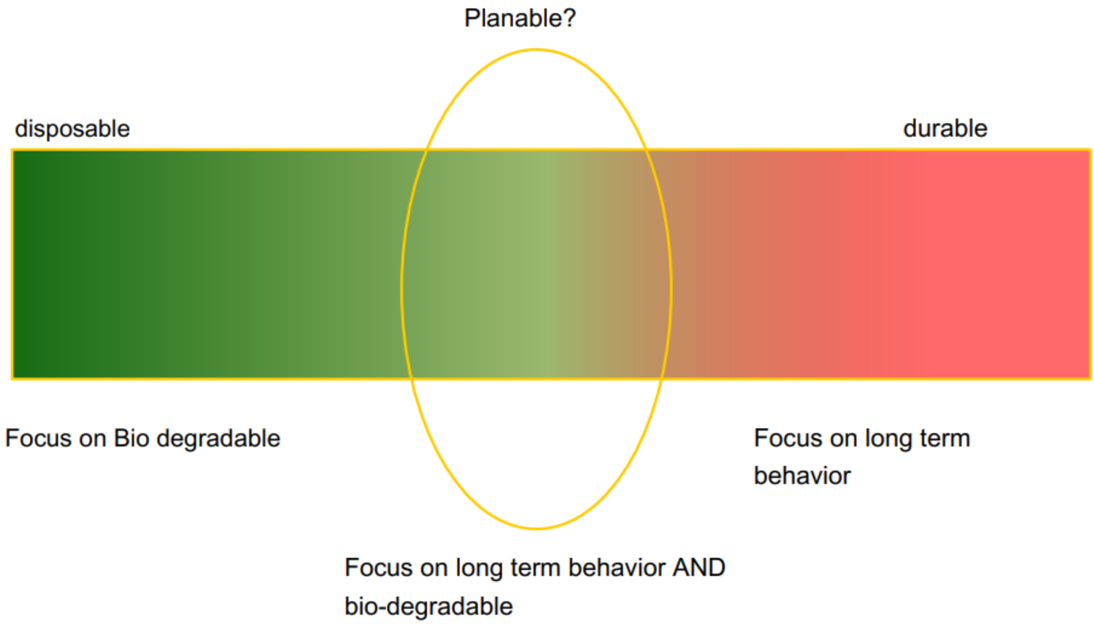

Figure 10: Classification of products in the market
(Source: Joop Onnekink, PEZY product innovation)

The disposables are the fast-moving consumer goods that are typically used, collected and reused over a short time while the durables are materials like cell phones, coffee machines, and the like, that are expected to last for a long time - these are typically repaired and reused. Joop Onnekink was of the opinion that biodegradability will not be the most suitable property to be considered for durables and hence, PHA might not be the best material of choice for the production of such products. Disposables, on the other hand, could use biodegradability as an essential property depending on the application, such as in agriculture or for garden products as stated earlier and shown in Figure 11.

The last category which are called the planables are products that last for a defined period of time. They function in the environment for a certain amount of time and then disappear without damage and with no need for special attention. They are called planables because they have some decay and plannable properties. Joop Onnekink thought this would be another valuable market for PHA, especially when blended with other materials like PLA or starch to extend its degradation time. Examples of such applications will be in temporary drainage or pipes, or as biodegradable wires in greenhouses.

Figure 11: Examples of PHA applications in agriculture (Source: Wageningen University and Research, 2011, via Joop Onnekink, PEZY product innovation)

Summary of key findings on Economic Aspects is presented in Table 8.

Table 8: Results on Economic Aspects

Economic Aspects	# interviewees
Drivers	
• Huge market demand	3
• Opportunities for PHA in niche markets based on unique properties, especially biodegradability	5
Barriers	
• High cost of production	2
• Relatively high market price	1
• Inability to meet market demand	2
• Lack of funding for scaling up	2

CHAPTER 5: DISCUSSION

This chapter focuses on answering the main research question based on secondary data and the analysis of the findings from the interviews (primary data) presented in chapter 4. The research sub-questions are discussed under different sub-headings and the interrelationship observed between the PESTLE aspects is discussed. Lastly, the answer to the main research question, as concluded from the major findings of the research, is presented in a figure.

5.1 PHA production: a more circular route for carbon valorisation in WWTPs compared to biogas production

This study shows that biogas production is currently the preferred route for carbon valorisation in WWTPs because it helps in reducing the costs of disposing sludge. However, this approach is actually a waste of resource because a lot of the organic carbon is not utilised [5]. Although anaerobic digestion for biogas production is a developed and deep-rooted technology for the valorisation of sewage sludge in WWTPs, research increasingly shows the expediency of exploring other technological opportunities for the production of end-products with much higher value [62–64]. The findings presented in Chapter 4 show the superior sustainability advantages of PHA production over biogas production. For instance, the 21% reduction in the CO_2 footprint of Wetterskip Fryslan, used as a case study, is a staggering number in view of the current global climate crisis. Moreover, the high inefficiency of the process of biogas production, whereby only about a quarter of the wastewater organics gets converted and the remaining fraction becomes oxidized to CO_2, shows the urgent need for a process change in WWTPs. Besides, PHA production equally promises a reduction in sludge handling costs [65], which is the major driver of biogas production.

Considering the current global stimuli for circularity, resource and energy efficiencies, as well as minimization of waste and GHG emissions, it is imperative for all sectors, including the wastewater sector to revisit their processes and incorporate the highest sustainable alternatives. This is the major reason for advocating the production of value-added materials over less sustainable resources, no matter how established the production of the latter is. It might definitely require time, taking into account the significant impacts of integrating new processes into existing and established treatment systems [65]. However, there is a need for forward thinking that promotes a willingness for change and an active pursuit of the same. Moreover, there is a technically proven possibility of incorporating PHA production with biogas production in WWTPs without compromising the overall sustainable conversion of the organics present in wastewater [64,66], just as the findings of this thesis show.

Asides environmental advantages, PHA production is shown to be of higher economic value, which is equally important in circular business models, than biogas. This is in agreement with a study conducted by Reis et al. [67] on the production of PHAs by mixed microbial cultures. The study showed that the potential returns from PHA production can be about 20-50 times greater than that obtained when biogas is produced. Although the costs associated with PHA production are significantly higher than those with biogas production, Reis et al. [67] concluded that it is highly unlikely that these production costs will offset the revenue benefit of PHA over methane. Besides, there are several research endeavours aimed at achieving PHA production, recovery and utilisation in the most cost-effective ways possible [62]. This superior economic benefit of PHA, coupled with the environmental advantages shown, makes it a more promising and circular route for the recovery of organic material (carbon) from wastewater.

5.2 The political/legal role and perspective of the Dutch government and the EU

The transition to a CE requires strong public-private partnerships for research and innovation [68]. Hence, this study shows that WWTPs cannot achieve circularity without the support of researchers, industries and most importantly, the government and policy makers. The major focus of policy makers should be to accelerate the transition to a CE in a manner that shows an active response to issues related to climate change and other global challenges [69]. A report published by the Dutch Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs on the government-wide programme aimed at achieving a CE by 2050 highlighted how upscaling of PHA bioplastics from sewage sludge is being worked on by support programmes such as 'the Green deal on the raw materials of the Water Boards' [28]. It was also noted that the vision of the business community to establish commercial-scale production of sustainable plastics in the Netherlands has the support of the Dutch Cabinet [28]. However, findings from this thesis show that the government support for PHA from wastewater is rather slow at the moment, though it is believed that the 2050 circularity vision will eventually help kickstart the required actions in favour of this biopolymer. Furthermore, Bluemink et al. [7] reported that the Dutch Water Boards are now giving more attention to waste valorisation in WWTPs in a bid to achieve circularity, by coming up with a 'Waste to Value' model. Likewise, in the Dutch Roadmap for 2030 (*Routekaart Afvalwaterketen tot 2030*) [70], the director of the Water Management Applied Research Foundation, STOWA (*Stichting Toegepast Onderzoek Waterbeheer*) wrote:

> '…we believe that wastewater treatment will always be necessary, but the future is found in resource thinking'.

This kind of forward thinking by the Dutch political board governing WWTPs is crucial to the circularity of WWTPs and, thus, favours the recovery and market push for resources like PHA. In the same vein, there are several initiatives and funding schemes for bioplastics by the EU. These include; Europe 2020/Innovation Union, Lead Markets Initiative for Biobased Products, Resource Efficiency Strategy, Key Enabling Technologies, Horizon 2020, Bioeconomy Strategy and CE Package [71]. These are political drivers for the commercialisation of this polymer.

Furthermore, this study shows the power of favourable legislation. Considering the shortcomings of traditional plastics, new government regulations are considered useful in promoting a market shift to bioplastics, thus, increasing the demand for them [72]. However, policy makers need to keep policies flexible to avoid knotty legal problems that might work against innovations [69,73], as revealed in the study. This implies that regulations can either be a driver or a barrier.

The most central political driver revealed in this study is the allocation of funds, primarily in the form of subsidies, in favour of PHA production from WWTPs, as it is for biogas today. PHA commercialisation from WWTPs is currently weakened by a lack of adequate funding. The subsidy on biogas production hinders the channelling of investments and efforts towards the recovery and production of value-added sustainable resources like PHA from WWTPs [5]. Provision of funds is one of the most important ways by which the Dutch government and the EU can support the development of value-added products like PHA from wastewater.

5.3 Recyclability and biodegradability of PHA bioplastics as environmental considerations in its commercialisation

Beyond functionality, some market-related environmental concerns for a biobased plastic economy are biodegradability and recyclability. Therefore, for PHA, like other biobased plastics, waste management at the product's end of life is one of the most important issues as far as CE is concerned. It will also be important in the product design phase to determine the most suitable applications [11]. This is more so because in a functional CE, producers have a great responsibility to consider the risks and costs related to the waste generated by their products [74]. Interestingly, the findings of this thesis show that the functionality most demanded and promising for PHA is its biodegradability. This is more so because there are no current mechanical recycling options available for bioplastics in general. As such, PHA products can both be designed to safely enter into the environment, as it is with agricultural mulch films, or to be industrially composted [11]. However, the rate of biodegradation depends on a number of factors such as composition, presence of additives, crystallinity, as well as environmental conditions such as moisture level, temperature and pH [75].

On the other hand, recyclability is still a more preferred option because it ensures the recirculation of the resource in a closed loop [74]. However, Song et al. [41] corroborated the findings of this thesis that for a sustainable mechanical recycling, a constant supply of large amounts of high-quality feedstock and a promising market for the recycled material are highly important. This is a challenge for now because PHA represents only 1.2% of the bioplastics market (the bioplastics market is also only about 1% of the total plastics produced) [40]. Nevertheless, findings from this thesis further show that the debate between recyclability and biodegradability is a matter of choosing the right application. The environmental advantage of the biodegradability property of PHA when used in applications that require this property, such as in agriculture, should not be devalued. In such applications, it might also be a beneficial way of soil replenishment [74]. However, as PHA market expands, recycling will become a critical issue to consider for a more functional CE. Therefore, the earlier this is factored into active research, the more manageable it will be. Before then, the contamination of existing traditional plastic waste stream must be prevented as much as possible [11,41] by measures such as proper labelling of products. This is to avoid compromised quality issues with products of traditional plastic recycling. Biodegradable plastics may alter the technical properties, such as durability and strength of the final products of conventional plastic recycling [43]. Therefore, for the same reason, it is noted that PHA would not be a suitable alternative for some everyday consumer products such as PET water bottles [11], as sorting for recycling might become a big problem. To conclude, when used in the right applications, PHA and similar innovative products can become a foundational part of a range of sustainable and CE-enabled products by helping to solve some of the urgent environmental issues regarding plastic waste treatment and disposal [76].

5.4 Impacts of the social perception of PHA on its adoption

The ultimate success of PHA-based products in the market will be determined by consumer acceptance. Unfortunately, not a lot of studies have been carried out in understanding the perception of consumers about waste-derived products like PHA bioplastics. Most studies have mainly focused on the technological and engineering aspects of these products [76]. However, the technological developments in sustainable transitions like the biobased economy operate at the crossroads between technological advances, political regulations and societal expectations. It is, therefore, vital to involve several stakeholders, including the wider public [77,78]. This implies that the zest and effort put by researchers and policy makers are not enough in this transition; consumer involvement and acceptance are equally important [79].

Just as the findings of this thesis show, consumers will be faced with the need to make judgments about bioplastics as they come into contact with them and this will be done in the light of their worries about the negative impacts of traditional plastics [80]. An exploratory study conducted by Sijtsema et al. [79] on the subject of consumer perception in some European countries showed that consumers are largely unfamiliar with biobased products and those that do mostly weigh the advantages and disadvantages of biobased products as it relates to their context and personal interests. On the other hand, another study by Lynch et al. [77] on the perception of Dutch citizens to biobased technologies found that consumers connect these products to positive ideas such as eco-friendliness, sustainability, naturalness and a 'green' feeling while a higher price and improper land use were some of the negatives associated with them. However, mixed culture PHA from wastewater does not have this problem of improper land use, as it is with bioplastics produced from crops, for instance. This is a major positive point for mixed culture PHA. Its production from waste, which makes it more sustainable, eradicates this concern. Moreover, PHA easily fits into all the positive ideas highlighted in the study of Lynch et al. [77]. Nonetheless, the higher price remains a major hurdle that needs to be tackled as much as possible for a much higher consumer acceptance. Furthermore, in the study of Sijtsema et al. [79], out of 21 keywords provided for biobased products, the most used keyword among participants was biodegradable, this shows how much consumers might be willing to consider products that are truly biodegradable over any other advantage a biobased product might have. This perspective will definitely favour products like PHA.

Lastly, consumers desire the production of bioplastics that are similar to traditional plastics in function, life span and aesthetics [77]. Findings from this research show that to a large extent, PHA can meet these requirements and even offer better properties, specifically thermal and mechanical properties, than traditional plastics. For example, European bioplastics reported that for over 15 years, there has been a high acceptance level for biodegradable mulch films, for instance, among European fruit and vegetable farmers [81]. This shows that PHA has an advantage as long as it caters to the specific needs of the targeted consumers.

5.5 Technological factors affecting the commercialisation of PHA from WWTPs

Although research continually shows that mixed culture PHA production from organic wastes is generally more sustainable and cost-effective than pure culture PHA production [7,22,44,82], the latter is still preferred because it leads to a more consistent product [83]. Therefore, consistency and purity of PHA from wastewater were the two technological factors initially considered in this thesis, to be important in the acceptance and commercialisation of PHA. However, the findings of the thesis further reveal the significance of manufacturing behaviour that could result from some inherent properties of the polymer, such as low viscosity. This concern about manufacturing behaviour is consistent with the report of Cambridge Consultants [11] about the comparatively low temperature (about 180^{o}C) for thermal decomposition of PHAs, which consequently demands careful processing and significant process development in production. These are some possible barriers to the product's acceptance by downstream producers, who have to deal with these hiccups in production, and also to the product's range of applications. However, to improve the material properties of PHA, their chemical configuration can be modified depending on the type of monomers[20] and their combinations [11,84]. This modification possibility provided by PHA is a technological advantage because it provides ample opportunities for the product to overcome some of the technical setbacks highlighted. Furthermore, the flexibility offered by the thermoplastic nature of PHA [84] makes it suitable for a number of standard production techniques such as injection moulding (which was the chosen method of producing the business card holders by the PEZY group within the PHARIO project), film forming technique, extrusion, blow moulding, among others [11].

Regarding consistency, because the PHA family contains a wide assortment of different polymers, which can be blended or copolymerised, the design scope offered by this material is broad [11,12,84]. This presents the possibility of engineering polymer blends that have the properties desired for a broad range of applications. This could also ensure consistency of the polymer's quality to a large extent. However, because the PHA focused on in this study is that produced from wastewater and municipal waste streams are largely inconsistent, a lot of work needs to be done downstream (that is, during the extraction of the PHA from the biomass to produce the crude polymer) to achieve reproducibility, which is what the market needs. Otherwise, the polymer will be too restricted in the market to only applications that can withstand this irregularity. The same argument goes for the purity of the polymer. As shown in the study, the market focus of this polymer is presently limited to applications that do not require an exceptionally high purity level. This is not a market advantage. For instance, PHAs are highly biocompatible and some are already being employed in biomedical applications [85–87]. However, it will be difficult for mixed culture PHAs to penetrate such markets unlike pure culture PHAs which are already being used for such applications [84]. Nonetheless, with the right techniques and use of (green) solvents for purification, it is technically possible to achieve a highly pure (≥ 98%) PHA from wastewater [88], but this study shows that the economics of this is not encouraging enough to be a worthy pursuit on a full-scale production.

5.6 Major economic influences on the commercialisation of PHA from WWTPs

Economic viability is one of the three pillars of sustainability. Therefore, this is an important aspect to consider in the market success of PHA. Although the biodegradability of PHA already creates a unique

[20] Monomer is a molecule that can react with other molecules to form very large molecules, or polymers (https://www.britannica.com/science/monomer).

niche for it in the market, the associated high costs of production, which results in a relatively high market price is still a major disadvantage [12,89]. Moreover, the personal interests of investors in the unsustainable plastic market has been noted as a barrier to a smooth market penetration of sustainable alternatives [28]. The power wielded by these investors in safeguarding their investments in the low-priced and booming fossil-based plastic market creates an obstacle for new sustainable investors to break in. Although PHAs do not pose the same environmental risks as these traditional plastics, the fact that they cannot be produced as cheaply puts them in a difficult economic situation as far as pricing is concerned [5]. However, this study shows that a strategic tactic for the early market success of PHA from wastewater would be to focus on niche applications that demand their exceptional properties and put them in a unique class of their own regarding the products and services they can deliver. The availability of such niche markets and the present demand from those markets are strong economic advantages for the polymer. For example, the European agricultural mulch film market is estimated to be about 80,000 tonnes per year and 95% of this are from fossil and non-biodegradable materials [90]. The Agriculture Plastics Environment in Europe calculated that over 30% of the fossil-based mulch films remain in the soil [81,90]. These alarming figures show the need for a sustainable transition; hence, the regulation in favour of biodegradable plastics for this application [91]. This implies a big market for PHA as it is one of the few polymers that can effectively serve this purpose.

However, another hurdle is meeting this market demand. Until PHA from wastewater is developed on a full scale to produce adequate quantities of commercial worth that meet the demand, a reliable market cannot be established for it [5]. Unfortunately, the findings of this study show that PHA from WWTPs is somewhat in a valley of death[21] at the moment (figure 12). Although work is now actively being done to bridge this gap (specifically, building a demonstration plant to produce sufficient quantities for testing), it will definitely take a while. This study further shows that funding, especially subsidies, is the biggest driver of this product as it is highly needed in moving from the left side of the valley to the commercial end.

[21] Valley of death is the resource gap between breakthrough invention and product commercialisation [92].

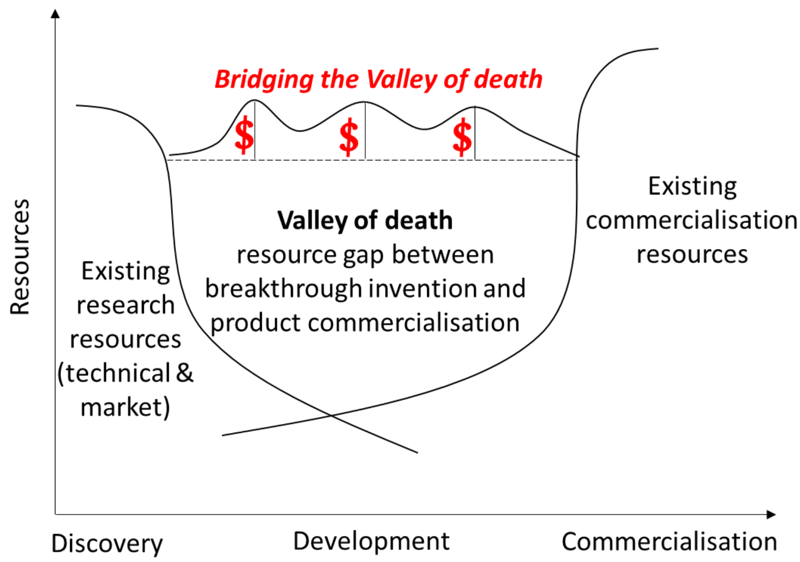

Figure 12: A representation of the valley of death between breakthrough invention and product commercialisation [92].

5.7 Interrelationship between the PESTLE categories

Figure 13 presents the major drivers and barriers highlighted in this research. A number of these have influences on one another. For example, the government, as a stakeholder, is one of the key players in PHA commercialisation as they hold the *legal*, as well as *political* power, to effectively address major *economic* barriers, such as lack of adequate funds for PHA upscaling. Additionally, the enactment of (un)favourable legislation (*legal*) has a crucial impact on the market demand or market penetration of PHA (*economic*). In the same vein, the biodegradability property of PHA, which is a strong *environmental* advantage also plays a key role in consumer acceptance (*social*), as well as in niche market penetration (*economic*). On the other hand, the inconsistency in the quality of crude PHA (*technological*) might lead to low acceptance from downstream producers and a long-term limitation in its applications (*economic*).

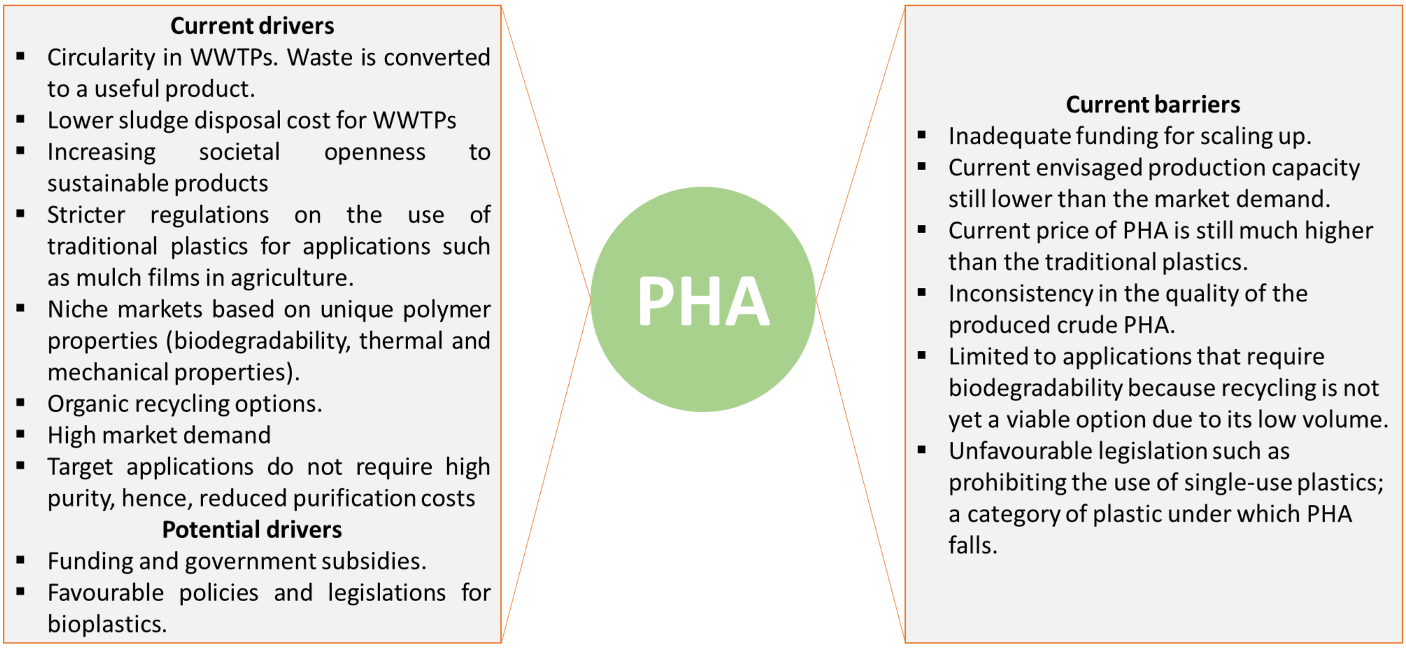

Figure 13: The major drivers and barriers to PHA commercialisation as found in the study

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This thesis examined the drivers and barriers to the commercialisation of the biobased and biodegradable plastic, PHA, produced in WWTPs. The PESTLE framework was used to categorise these factors into political/legal, environmental, social, technological and economic aspects. This framework helped to provide a broader overview of the areas to address as regards further upscaling of the product into the market. The research method adopted was based on qualitative interviews with key players across the PESTLE categories. A qualitative content analysis of the data obtained was carried out to analyse the most significant trends in the drivers and barriers to PHA commercialisation. The research findings showed that even though there are specific drivers and barriers that are central to each of the categories, most of the overall trends are highly interrelated across the different aspects. For instance, the economic barrier of inadequate funds can be compensated for by the potential political driver of subsidy provision by the government.

In the context of circularity in WWTPs, this study shows that PHA production is more sustainable and fitting than the current method of carbon valorisation, which is biogas (methane) production. For instance, the case of Wetterskip Fryslan revealed that PHA production could reduce the CO_2 footprint of the plant by 21% annually. Hence, the urgent need for process evaluation in all sectors of the economy to join in the global quest for sustainability and circularity makes it imperative for WWTPs to revisit their status quo and prioritize valuable resource recovery over energy recovery. However, this study further shows that WWTPs can still achieve both PHA production and energy generation based on a more efficient use of the organics in wastewater.

From the economic viewpoint, this innovative product is somewhat struggling in the 'valley of death' between the pilot phase and the commercialisation phase. Getting it across this valley is the greatest barrier to its commercialisation. This upscaling issue creates a dilemma whereby downstream PHA producers are not able to get enough quantity of crude PHA for application tests, while the upstream producers, which are the WWTPs and technology providers, find it difficult to meet the market demand without adequate funding. This leads to the greatest driver of the product, which is funding, especially governmental subsidies. The government has a major role to play in the upscaling of this product through the provision of financial aids, as well as enacting policies that will encourage the use of sustainable and environmentally-friendly plastics such as PHA.

Furthermore, this study clearly reveals biodegradability as the most important property and an environmental driver of this polymer that sets it apart from other biobased polymers counterparts (such as polylactic acid) because of its relatively shorter degradation time. Therefore, the targeted applications are those where this property is required and where opting for this product will be the most sustainable decision. Additionally, despite the fact that the consistency and purity of most products are technical considerations crucial to market acceptance, PHA at the early stages can successfully get past this by not focusing on applications that require these factors at their highest level. However, research is ongoing to achieve consistent PHA quality with high purity. As such, PHA from wastewater is not being considered for food packaging, for example, but the targeted niche applications are in agriculture as mulch films and as coatings for controlled-release fertilizers, as well as in buildings as self-healing concrete.

In the quest for PHA commercialisation, this research found that competition among producers should be strongly discouraged. Rather, a cooperative approach between biobased polymer producers is highly recommended to achieve a common goal, which is the production of robust products that can play indispensable roles in a circular economy. Regarding the societal perception of this product and bias against its source, it was shown that the increasing openness of the society as a result of the growing awareness about sustainability makes this social barrier easily surmountable.

Finally, the relatively high price of this product, just like most biobased products, seems to also be a barrier to its commercialisation. However, there is a need for the society to be fair in their estimation and comparison of sustainable products with unsustainable products because the cheaper fossil-based products fail to factor in the negative environmental impacts and costs of their processes in their pricing. Therefore, increased and better societal education will inform more sustainable purchase decision-making by the consumers.

6.2 Recommendations

This study reveals that the commercialisation of PHA is linked to a number of interrelated factors. Hence, there are a few recommendations for the various stakeholders involved in either driving or impeding the upscaling of the product.

First, the Dutch government needs to look into their financial incentives for valuable resources like PHA. Prioritising government aids to resources that have a stronger place in a circular economy is recommended. Subsidy allocation might be considered in two ways: the first towards PHA production from wastewater, to help move the process beyond the 'valley of death' and the second towards the end-users. For example, since agricultural application is currently the most promising market for PHA, the end-users will be farmers, who might find the relatively high price of the product discouraging. Therefore, subsidising the market price to reduce purchase costs will be extremely helpful. Moreover, imposing taxes on unsustainable plastic products is an effective mechanism to encourage investments and consumer purchase preferences for sustainable alternatives like PHA. This is therefore also recommended to the government.

Second, increased industrial symbiosis is recommended for the WWTPs. As revealed in this study, municipal WWTPs were not established for profit-making or business. The push for resource recovery will only be successful through the active involvement of industries, such as the technology providers, the industries that will co-produce PHA with the WWTPs, and other potential suppliers of volatile fatty acids (the PHA platform chemicals). Furthermore, it is important for bioplastic-producing industries to collaborate to achieve a common sustainability goal since the market is too vast for one bioplastic type or producer.

Third, more research is recommended in the field of recycling, both by the producers and the recycling industries. Even though PHA is not yet focused on applications that need recycling, the market is expected to rise and PHA recycling will become imperative.

6.3 Limitations and recommendations for further research

Due to time limitation and the COVID-19 restrictions, this study could not consider all the possible factors under the different aspects, such as the perception and willingness of the end-users, especially farmers. Hence, it is recommended that further research be carried out along this line. Moreover, to provide a more objective perspective of the national government, it is important to interview representatives from the relevant ministries such as the Dutch Water Authorities and the Ministry of Economic Affairs and Climate. This could not be achieved for the same reasons highlighted above. Likewise, conducting interviews with stakeholders from the pure culture PHA industries (the PHA currently in the market) will give deeper insights into the market issues like price elasticity, among others. Furthermore, the number of interviews conducted could be more across all categories. This would help in gaining more perspectives and wider insights into the research topic

Regarding the choice of analytical method adopted, time constraints could not allow for more methods like surveys or focus groups. These would have been more appropriate to elicit the opinions of end-users, for instance farmers, as well as general societal acceptance. This is therefore recommended in further research.

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APPENDIX A

CONSENT FORM A

CONSENT FORM TO TAKE PART IN A RESEARCH INTERVIEW

Research Topic: Circular economy in wastewater treatment plants (WWTPs): an assessment of the drivers and barriers to the commercialisation of bioplastics (polyhydroxyalkanoates) from WWTPs.

Taking part in the study

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

I understand that taking part in the study involves answering questions from a semi-structured questionnaire, note-taking by the researcher, audio recording of interview session which will be transcribed as text for effective data analysis (this will be destroyed once the research is completed)

I understand that in any report on the results of the research, my identity will remain anonymous if preferred to be so.

I understand that I am entitled to access the information I have provided after the interview and I have the right to request for modification, clarification, or changes where applicable.

I understand that I am free to contact the researcher for further clarification and information.

Use of the information in the study

I understand that the information I provide will be treated confidentially and used strictly for research purpose/master thesis report writing.

Consent to be Audio Recorded

I agree to be audio recorded.

Signatures

______________________	______________________	______________
The Participant	Signature	Date
Bukola M. Ajao ______________________	______________________	______________
Researcher	Signature	Date

b.m.ajao@student.utwente.nl

Laura Franco-Garcia

Study Supervisor

CONSENT FORM B

PARTICIPANT CONSENT FORM TO TAKE PART IN A RESEARCH INTERVIEW

Research Topic: Circular economy in wastewater treatment plants (WWTPs): an assessment of the drivers and barriers to the commercialisation of bioplastics (polyhydroxyalkanoates) from WWTPs.

I, THE PARTICIPANT, taking part in a study for THE RESEARCHER and RESEARCHER'S SUPERVISOR at the University of Twente, The Netherlands:

- consent voluntarily to be a participant in this study and understand that I can refuse to answer any question and I can withdraw from the study at any time, without having to give a reason.
- understand that taking part in the study involves answering questions from a semi-structured questionnaire and note-taking by the researcher.
- understand that in any report on the results of the research, my identity will remain anonymous if preferred to be so.
- understand that I am entitled to access the information I have provided at any time after the interview and I have the right to request for modification, clarification, or changes where applicable.
- understand that I will be provided with a copy of the report prior to submission (at least 1 week).
- understand that the interview will not be audio or video recorded for replay.
- understand that the information I provide will be treated confidentially and used strictly for research purpose/master thesis report writing.
- understand that I will be provided with information on where and to whom the report is submitted, and for what course.
- understand that I am free to contact the researcher for further clarification and information.

Signatures

____________________ ____________________ ________

The Participant Signature Date

Bukola M. Ajao ____________________ ____________

Researcher Signature Date

b.m.ajao@student.utwente.nl

0686472180

Laura Franco-Garcia ____________________ ________

Researcher's Supervisor Signature Date

APPENDIX B

Semi-structured interview questions for the participants

Researcher

1. How feasible do you think it is for WWTPs to produce VFAs without depending on external industries e.g. candy-producing industry as VFA source, as it was for the PHARIO project? Is it an issue of technology or appropriate wastewater content?
2. In your opinion, how important is PHA consistency and purity in its commercialisation? Is it possible to produce a consistent quality? To what extent does the level of purity affect potential applications?
3. Why was the PHA produced in the PHARIO project recovered in Sweden? Why could the pilot facility not be built here in the Netherlands? Could that also be the case at the planned full or demo-scale production level? How can this logistics problem be tackled, considering sustainability?
4. From the PHARIO business case, it was shown that wastewater PHA could compete with other PHAs in the market, how much progress has been made in the upscaling of PHA from WWTPs process to reduce price as at now, 2020? Do you think the €3 - €3.50 market price goal is still achievable by 2025?
5. In your opinion, in what niche markets can the uniqueness of PHA be best explored and how can the penetration into such markets be realised? What role does the government play here?
6. Considering the already existent bioplastics in the market e.g. PLA, what likely strategies do you think can be adopted to promote a successful competition with these other types of bioplastics?
7. The recycling setback facing PLA, which is the most common commercial bioplastic at the moment, is still a major barrier to its sustainability claim. How do you think PHA can circumvent the same problem?
8. Do you know if there are recycling options and technologies currently being researched for PHA?
9. How are the solid waste management companies involved in the researches going into PHA commercialisation?
10. The PHARIO project reports an LCA conducted for PHA, but that seemed more for the process of production and not for the product life cycle (from cradle to grave). Has the latter being conducted? How does it compete with other bioplastics and traditional plastics?
11. According to a spokesman of the Dutch Waste Management in a newsletter on sustainable business, "biodegradable is not equal to sustainable and therefore should not be the major selling point of biobased products", what is your opinion on this?

Industrial Expert (Upstream producer/Technology provider)

1. How feasible is it to source for VFA solely from WWTPs without the need to depend on external industries e.g. wastewater from a candy-producing industry as VFA source? Is it an issue of technology or appropriate municipal wastewater content?
2. In your opinion, how important is PHA's consistency and purity in its commercialisation? Is it possible to produce a consistent quality? How does purity affect applications?
3. In what niche markets can the uniqueness of PHA be best explored and how can the penetration into such markets be realised? What role does the government play here?

4. Which do you think will work out better: Centralised (e.g. provincial) or decentralised PHA production? For a centralised system, will it be necessary to consider WWTPs with similar treatment processes?
5. Considering the already existent bioplastics in the market e.g. PLA, what likely strategies can be adopted to promote a successful competition with these other types of bioplastics?
6. In your opinion, how important are government policies and subsidies in the commercialisation of PHA?
7. During a class excursion to Wetterskip Fryslan, I learnt the government recently turned down a subsidy application made for PHA from WWTPs, why do you think the subsidy was not granted?
8. Why is the extraction cost of PHA so high? What is the major technical difficulty involved?
9. The recycling setback facing PLA, which is the most common commercial bioplastic at the moment, is still a major barrier to its sustainability claims. How can PHA circumvent the same problem?
10. Are there currently recycling options and technologies being researched for PHA? What could be the market implication of lack of practical recycling options for PHA?
11. How are the solid waste management companies involved in the researches going into PHA commercialisation?
12. Do you think consumers will be willing to purchase bioplastics from PHA without bias against its source e.g. for packaging?
13. According to a spokesman of the Dutch Waste Management in a newsletter on sustainable business, biodegradable is not equal to sustainable and therefore should not be the major selling point of biobased products, what is your opinion on this?

Representative from a WWTP

1. In your opinion, what are the trade-offs between PHA production and biogas production?
2. With the subsidy on biogas from the government, do you think PHA production can really successfully outcompete biogas production? Do you think that a subsidy on PHA production, as it is with biogas, might boost or motivate other stakeholders to develop the business case?
3. During my class excursion to the WWTP Leeuwarden, I learnt that the government recently turned down a subsidy application made for bioplastic from WWTPs. In your opinion, why was the subsidy not granted?
4. With respect to the existing process, to what extent does PHA production benefit the WWTP in the light of sustainability e.g. CO_2 emission reduction, waste sludge reduction?
5. Which do you think will work out better: Centralised (e.g. provincial) or decentralised PHA production? For a centralised system, will it be necessary to consider WWTPs with similar treatment processes?
6. In which applications do you think PHA may receive the most acceptance by consumers without bias against its source?
7. Considering the already existent bioplastics in the market e.g. PLA, what likely strategies do you think can be adopted to promote a successful competition with these other types of bioplastics?
8. Do you think the Dutch government find PHA innovative enough to be worth giving adequate attention to, in its transition to a circular economy? If yes, what steps do you think are being taken to stimulate its commercialisation.

9. Do you have an idea if some other types of bioplastic are already been subsidized by the Dutch government? Is the Dutch government likely to subsidize PHA production from WWTPs for a competitive market price in its transition to a circular economy?
10. How do EU regulations influence or impact the bioplastics policies adopted in the Netherlands? How may EU policies likely affect the decision or preference of the Dutch government for PHA from WWTPs?
11. Due to its source, can PHA likely be legally prohibited for some applications, even in its highest purity level?
12. How do you think the government is involved in the post-consumption management of bioplastics? How do they intend dealing with the solid wastes produced in the re-collection phase e.g. social campaign for consumers?

Representative from solid waste management company

1. Do you have an idea if recycling is currently being achieved for bioplastics generally in the Netherlands, and how much?
2. Currently, are biobased plastics disposed-off separately from traditional plastics by consumers or the separation is done in the waste management sites?
3. How easy is it to separate biobased plastics from traditional plastics at the plant? Do you think biobased plastics somewhat contaminate your traditional plastics recycling streams?
4. To what extent do the different types of traditional plastics interfere with each other in the recycling processes and how is this managed?
5. Are there some traditional plastics that cannot be recycled and why? What is the implication of that?
6. Do you think PHA recycling is feasible in your current recycling scheme? Are there currently recycling options and technologies being explored for PHA?
7. How are the solid waste management companies in any way involved in the researches related to PHA?
8. Which policy instruments (perhaps legislation) do you think could help facilitate the sustainable disposal/management of these kinds of materials post-consumption?
9. Generally, how do you see the place of bioplastics, especially the biodegradable ones, in the transition to a circular economy?

Industrial Expert (Downstream producer)

1. From the PHARIO project report, I read that you produced business card holders from the recovered PHA. What other products do you think can be produced from it?
2. How was your experience working with PHA to produce the business card holders? How do you see the business case?
3. What drawbacks did you experience during production and do you think there are available technologies to tackle this?
4. In your opinion, how important are PHA's consistency and purity in its commercialisation? To what extent do you think the level of purity will affect potential applications?
5. What other properties of the material do you think may limit its application range?
6. As an end user of the crude PHA, what would convince you to invest in it as raw material for final bioplastic product and not PLA, for instance, or other competing bioplastic types.

7. In what niche markets do you think the uniqueness of PHA can be best explored and how do you think the penetration into such markets can be realised? What role do you think the government plays here?
8. How likely will sustainability consciousness impact your preference for this product? How do you think this will impact end-users' (consumers) purchasing decision too?
9. In your opinion, how do you see the public perception of bioplastics generally? How does/may fear of green washing impact their acceptance?
10. Do you think consumers will be receptive of PHA bioplastics and not be biased against its source?
11. What likely challenges do you foresee in the future of PHA in the market? Do you think the product is innovative enough to receive adequate attention in the Dutch transition to a circular economy?
12. According to a spokesman of the Dutch Waste Management in a newsletter on sustainable business, "biodegradable is not equal to sustainable and therefore should not be the major selling point of biobased products", what is your opinion on this?