Paving the way for biobased materials

A roadmap for the market introduction of PHAs

Karin Molenveld and Wouter Post - Wageningen Food & Biobased Research
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PO box 17, 6700 AA Wageningen, The Netherlands, T + 31 (0)317 48 00 84, E info.wfbr@wur.nl, www.wur.eu/wfbr.

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Summary

The family of PHA polymers has been a key player in the biobased and biodegradable plastics research and development sphere for the past couple of decades. However, till this date, large scale production facilities and volumes have not yet become available to the plastic products market. Aside from the limited production volumes, the specific production process and feedstocks, the performance properties of PHA polymers substantially differ from the current state of the art materials in the plastics industry (PE, PP and PET). To accelerate the market uptake in the upcoming decades (going through the S-curve), it is crucial to identify which markets could function as early adopters of these relatively new type of plastics, given the specific beneficial properties of PHAs. Therefore Invest-NL and Wageningen Food & Biobased Research (WFBR) have performed this market study on PHA materials.

The aim of this study is to pinpoint the market opportunities for PHAs. These opportunities are identified by analyzing the production technology, types of feedstocks used, the current production volumes and the environmental footprint of PHA materials. Specific focus is given to the material properties of a selection of industrially produced PHAs, which are compared with the most crucial properties for 17 applications of plastic products. Based on this assessment a roadmap is constructed that sequentially addresses the most promising applications for PHAs in the different stages of its market development.

The current PHA market and its position within the biobased and biodegradable plastics sector is described. From here it is concluded that the family of PHA materials differs from both fossil- and other biobased materials in many ways. As a result it is very complex to map the market potential of the whole family of PHA materials in general. The approach of this study was therefore to select five grades of PHAs that are all substantially different in composition and thereby represent a wide range of obtainable material properties. In this way a comprehensive overview of the market potential of PHA materials is given. In this approach the unique selling point of PHAs, i.e., their biodegradability in a wide range of environments, has been given a central position. The study describes the communalities and differences in the production of these PHA materials (Chapter 2) and how these impact their properties, production volume, price and CO_2 emissions (Chapter 3). This information is then coupled to a number of application markets that are subdivided in 4 different phases, based on their need for biodegradable solutions and how strongly the market relies on a specific set of mechanical, thermal and barrier) properties (Chapter 4). This information is summarized in an application roadmap that is depicted in Figure 0-2.

As becomes clear from the figure, PHA materials initially have the best fit with markets that are highly dependent on biodegradation and are less demanding with respect to mechanical performance. Paper coatings and blend components are marked as interesting application areas for all PHAs investigated in this study while for paper adhesives and fertilizer coatings other biodegradable polymers might be more relevant. For applications that more heavily rely on their mechanical performance (phase 2) and require biodegradation there are substantially fewer ‘perfect matches’ with the investigated types of PHA. Nevertheless, a number of investigated compounds have properties that offer opportunities to enter the markets of plant plugs, coffee/tea packaging and artificial reefs. In phase 3, clear options appear for tableware based on the performed analysis, but this category of products is currently heavily affected by new European legislation and hence it is highly unclear if this market is worth entering. Applications that do not need biodegradation but will need to transition towards biobased alternatives (phase 4) show limited logical entry options for PHA materials. In most of these cases other biobased plastics will be a more feasible option but specific rigid plastic product markets might be accessed by certain PHA materials based on their most crucial mechanical properties.

It must to be noted that the market potential that arises from this analysis is mainly based on the technical applicability of five representative PHA grades and that other important factors (e.g. production costs and feedstock use) are not covered in Figure 0-1. It is expected that new grades with improved properties will be developed and introduced into the market in the upcoming decade which

will have their own unique and potentially more favourable position in the roadmap developed in this study. Nevertheless, together with the information reported in Chapter 2 and 3 this study will assist the assessment of non-reported and to-be-developed PHA types and applications within the respective economic and global context. It is concluded that there is a substantial market potential for the family of PHAs, and for new grades that will enrich this family in the near future. The authors expect that the application of this roadmap can accelerate the introduction of such grades and may consequently deliver a substantial ecological improvement in the respective application markets.

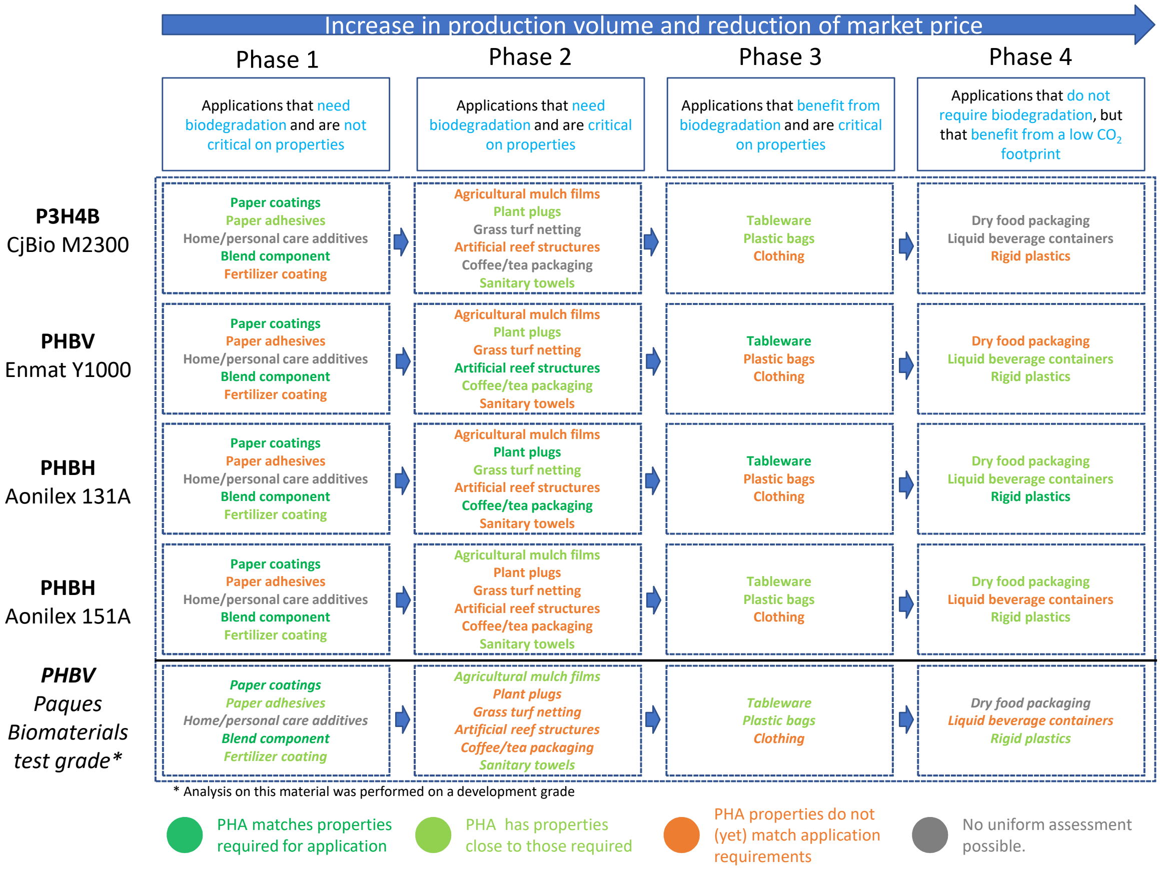


Figure 0-1 Application roadmap for the 5 PHA grades investigated in this study

Preface

Invest-NL is committed to developing a circular economy in The Netherlands by 2050, in line with Dutch government objectives. It thereby aims for a livable planet in which the balance between feeding and using the world's resources is restored. They stimulate innovations and enable financing for business and projects that support this objective and accelerate the transition to a circular economy. In practice this circular economy implies that certain materials and applications need to be replaced by environment-friendly alternatives. The Dutch target (Actieplan biobased kunststoffen) for biobased plastic is set at 15% of the plastics volume in 2030, while this is currently less than 1%.

In the materials space people have been investigating the replacement of fossil plastics with biobased and biodegradable materials. So far, this has resulted in the development and commercial availability of several bio-based drop-ins (e.g. biobased PE and PET) or bio-based substitutes such as cellulose and starch-based plastics, polylactic acid (PLA), polyesterfuranoate (PEF) and polyhydroxyalkanoates (PHA).

Notably the polymer family of PHAs are interesting because of their very wide variety of properties, and the multiple orders of magnitude faster biodegradation in nature, even in marine environments, compared to their fossil counterparts. PHAs have been offered to the market since the eighties, and very substantial investments were done both in R&D and in production capacity. Despite their potential to reduce littering and the use of fossil resources, PHA only reached small niche markets due to, among others, their difficulty of production and high price.

In recent years the context has considerably changed. Fossil based plastics are regarded more and more as an issue, rather than a solution. As there is a strong drive towards reduction of plastics use, we perceive more openness to using alternative materials. While strict regulation is not yet implemented, the European Commission is developing strategies on how biobased materials can replace fossil materials. This is a positive development, however, bringing new materials to an industrial scale remains capital and time intensive. The same journey can be expected for scaling the PHA market.

The Netherlands, with its strong chemical, plastics, agricultural and logistics sectors, provides an excellent base for the development of a bioplastics industry. To create this biobased industry, we need to understand how biobased plastics contribute to our circular ambitions and fit our material standards. Also, we need to distinguish the opportunities to accelerate large-scale market adoption of these biobased plastics. Based on initial desk research and several expert interviews, Invest-NL has discovered six value drivers that determine the impact potential of these materials: law & regulation; learning curve; marketing; (true) price; partnerships; financing. These drivers co-exist and reinforce each other. Important to note is that the relative importance of these value drivers might change over time due to developments in technology, policies and financial markets.

To validate these drivers, Invest-NL has set up a course of actions. By having a continuous dialogue with leading organizations, researchers, investors and entrepreneurs, Invest-NL aims to provide an up-to-date representation of these value drivers in practice. The value drivers below are not ranked according to importance and are presented in a random order.

1. **Law & Regulation**
   The role of the government in supporting and regulating a biobased economy is seen as the most important driver of a biobased market at this stage. Invest-NL has commissioned and published a comprehensive study by Ecomatters on all regulation that should be considered by companies producing biobased plastics: from the waste streams used as feedstock until the final applications brought to the EU market. This report helps companies to gain a better understanding of the legislative landscape, and how to do business accordingly. Moreover, knowledge on relevant legislation helps to consolidate the lobbying efforts for the bio-based materials industry. Aside from assisting innovative entrepreneurs, this study also forms the

basis for Invest-NLs discussion with government bodies on policies concerning biobased materials.

2. **Learning curve**
Creating PHA materials that can be used in a variety of products (applications) under a variety of circumstances is essential for market growth and requires a solid learning curve. Progressing through this learning curve of biobased materials requires substantial (patient) capital and determines success. This process entails applying these materials in products, opening new markets, increasing production volume, reaching scale, and reducing cost. We took a first attempt at accelerating this learning curve by understanding applications opportunities for PHAs We asked Wageningen University and Research (WUR) to develop a roadmap for several PHA materials, considering their specific properties. In addition, we gained a brief understanding on the importance of patents, to understand potential roadblocks for newcomers on the PHA market. This report is the result of this specific value driver and corresponding study.

3. **Marketing**
In the development of biobased materials, technology is key and requires a lot of attention. The marketing and positioning of these materials and their products is often neglected but important, nevertheless. Clear and effective marketing leads to an increase of interest in these materials from consumers, investors and government institutions. This is especially important when it concerns a considerably new and complex material. For this reason we cooperated with two marketing agencies, Keyfinders and Globrands. To improve PHA marketing a Dutch PHBV consortium was brought together under one name, whilst making strong choices about their identity and marketing proposition. This has become a firm basis for the positioning of these PHA companies in global markets and demonstrated how a valuable proposition goes beyond solely presenting the product.

4. **(True) Price**
Currently, the price of biobased plastic, PHA in particular, is higher than the price of fossil-based plastics. At least, this is the case when solely considering the financial costs of making these materials and neglecting the social and environmental costs of producing a product. At the moment, comparing the impact of fossil and biobased plastics has shown to be a difficult challenge. The current LCA analyses lack transparency of data and miss crucial elements essential for a comparative assessment, often in favour of fossil plastics. However, comparing the impact of biobased plastics and fossil plastics on wide range of topics is important to get an actual and complete valuation of the two material-families. This is especially important for brand owners who aim to replace fossil plastics by biobased plastics. The objective is to find a valuation that reflects the concerns of a healthy and liveable planet, offering a compelling narrative for all stakeholders, and are properly supported by data. In order to reach this objective, we have asked the Impact Institute to define the true price of three biobased materials (PLA, PHA, PEF) compared to their fossil plastic counterparts.

5. **Partnerships**
Companies that launch biobased materials need strong partnerships across the value chain, initially in the R&D phase, followed by the commercial phases. These partnerships are important enhance confidence between producers and users of PHA materials. We have connected with the recently initiated interest group Go!PHA that links PHA producers and users. Go!PHA can be seen as the first entry for companies, to become anchored in the industry. Transparent partnerships are even more important in a circular economy, where the dependency of partners in the chain is even bigger. Currently, recycling parties play an important role in most value chains. For PHA however, with its specific biodegradable properties, recycling could take place through nature. In turn, this would replace the recycling partner in the fossil world. A next step would be to explore the consequences of this situation for (circular) value chains.

6. **Financing**
   An increase of financing and investors in the biobased industry is essential to further develop the market and to become a serious competitor for fossil-based plastics. The abovementioned projects provide valuable insights and a better understanding of the barriers and opportunities in this market and eventually leads to more comfort in investing in biobased companies. This is not only valuable for our role as impact investor, but also for other investors that aim to be active in this industry. The participation of Invest-NL in the upscaling of Avantium and the expected learnings from this case will form the basis for further investments that are proposed in the biobased area.

This report explores value driver two, the learning curve of biobased materials and more specifically PHAs, in depth. Wageningen University & Research (WUR) and more specifically the applied research institute Wageningen Food & Biobased Research (WFBR) thereof has over 30 years of experience and expertise within the biobased and biodegradable plastics domain. In the past decades WUR has developed useful and extensive expertise on both the development and application of biobased and biodegradable plastics. In this respect WUR was the most suitable partner to execute this extensive research.

In this work the aim was to pinpoint the market opportunities for PHA by analyzing the material properties of a set of PHAs and compare these against the key properties for 18 plastics applications. This allowed WFBR to construct a roadmap describing what applications PHA producers should target first and what applications should follow. Hence, this report indicates what promising starting points there are for those setting foot on the PHA learning curve and it provides an overview of the opportunities of polyhydroxyalkanoates (PHAs) to enter the biobased plastics market. Invest-NL believes the biobased market is essential in realizing a 100% circular Europe. By executing the activities above and setting up collaborations with key institutions like WUR, they are committed to the development of this innovative and high-risk market.

1 Introduction

This report provides an overview of the opportunities of polyhydroxyalkonaotes (PHAs) to enter the biobased plastics market. The family of PHA polymers has been a key factor in the biobased and biodegradable plastics research and development sphere for the past couple of decades. However, till this date, large scale production facilities and volumes have not yet become available to the plastic products market. Initiatives to produce PHA on an industrial scale (>50kt/year) have been announced or set in motion a couple of times, but have not yet granted PHA polymers a stable position in the market.

The example of Metabolix is symbolic as they build and operated a 50kt/year production plant for a number of years (2010-2012), but had to file for bankruptcy as they couldn’t find substantial offset for their product to cover their expenses [1]. It is often noted that at that point in time the demand from the market was not strong enough as plastic converters and retail industries did not see the need to transition their products from fossil based towards typically more expensive biobased and biodegradable plastics.

In the past decade the market demand for sustainable materials and products has been on the rise. This is largely accelerated by a global consumer awareness on plastic pollution and climate change and associated governmental regulations. As a result, most small scale (<10kt/year) production facilities of PHA type polymers worldwide are typically sold out and PHA polymers start appearing in a wide range of plastic applications within the fields of agriculture, food packaging and durable plastic products.

Even though industrial parties worldwide have collectively announced to exponentially increase the global PHA production capacity, it is unrealistic to assume that these polymers will take over the current plastics market as whole. Aside from the limited production volumes, the performance properties of PHA polymers substantially differ from the current state of the art materials in the plastics industry (PE, PP and PET). To allow for a suitable market uptake in the upcoming decades (going through the S-curve), it is crucial to identify what markets could function as early adapters of these relatively new type of plastics. It is for this reason that Invest-NL and Wageningen Food & Biobased Research (WFBR) have performed this market study on PHA materials.

Since PHAs are a family of polymers that all have different feedstocks, production routes and performance properties, an assessment on the market potential of PHA polymers in general is rather complex.

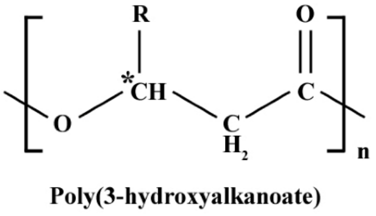
The common denominator in all PHA polymers is the polymer backbone as is depicted in Figure 1, but based on the quantity and length of the polymer side chains the mechanical properties can be directed from soft and rubbery materials (e.g. elastomers, natural rubbers) towards strong and rigid materials (e.g. PP and PET). One property that does connect all PHAs is the fact that they will biodegrade in virtually any (natural) environment within a timeframe that is multiple orders of magnitude faster than that of conventional fossil-based plastics.

The focus of the study is on PHA polymers, but also information is provided on other materials and developments that influence the opportunities of the PHA market. This ranges from feedstock use, where PHAs compete with biofuels, chemicals and other biobased plastics to specific applications where PHAs compete with fossil based plastics and other biobased plastics and non-plastic materials (e.g. paper, cardboard and wood).

1.1 Selected PHA reference materials

In order to handle the complexity of assessing the market potential of a whole range of polymers with different production and performance parameters while still providing qualitive output, this study has selected 4 representative grades of commercially available PHA polymers. These grades are CjBio M2300 PH3B4, Enmat Y1000 PHBV, Kaneka Aonilex X131A PHBH and Kaneka Aonilex X151A PHBH. As these grades are all produced from pure microbial cultures, the study will also include a mixed culture PHBV from the start-up company Paques Biomaterials that is not yet commercially available. Since analysis on this last material was performed on a non-optimized raw test grade without processing additives (e.g. nucleating agents and stabilizers), an objective comparison between this material and the other commercially available grades cannot be made based on this study.

Ultimately, these 5 grades were selected as they represent a wide range of PHA types which results in a large variety in performance properties. A second selection parameter for these specific PHA materials is the fact that detailed information on material performance was either available within the public domain or could be assessed within the laboratory facilities of WFBR. Other PHA materials that are gradually becoming available to the market (e.g. from RWDC and Danimer Scientific) could not be taken into account as data is both not available in the public domain and no material could be obtained for inclusion in this study. The two grades produced by Kaneka that are included in this study are currently no longer being sold as the company recently launched modified versions of these materials. Nevertheless, the selected grades are anticipated to give a good representation of the opportunities and challenges for the PHBH grades produced by Kaneka.



R group	Carbon no.	PHA polymer
methyl	C_4	Poly(3-hydroxybutyrate)
ethyl	C_5	Poly(3-hydroxyvalerate)
propyl	C_6	Poly(3-hydroxyhexanoate)
butyl	C_7	Poly(3-hydroxyheptanoate)
pentyl	C_8	Poly(3-hydroxyoctanoate)
hexyl	C_9	Poly(3-hydroxynonanoate)
heptyl	C_{10}	Poly(3-hydroxydecanoate)
octyl	C_{11}	Poly(3-hydroxyundecanoate)
nonyl	C_{12}	Poly(3-hydroxydodecanoate)
decyl	C_{13}	Poly(3-hydroxytridecanoate)
undecyl	C_{14}	Poly(3-hydroxytetradecanoate)
dodecyl	C_{15}	Poly(3-hydroxypentadecanoate)
tridecyl	C_{16}	Poly(3-hydroxyhexadecanoate)

Figure 1-1 List of PHAs based on side chain length [2]

1.2 Report outline

While focusing on these specific PHA polymers the study will first outline the internal factors that are important for the market implementation of PHAs. These are firstly the boundary conditions (Chapter 2) of the PHA production process such as the feedstock, fermentation and extraction processes and the capacity to upscale. Next come the performance indicators (Chapter 3) of the resulting PHAs, being the material properties, environmental footprint, potential and current production volumes and the associated product costs and environmental impacts.

The next step of the study focuses on how these internal factors affect the market potential in different (plastic) market segments (Chapter 4). An assessment is made on how well the specific PHA grades compare with the product requirements and state of the art materials for each market segment. In addition, an overview of the other biobased polymers relevant for a specific market segment is given.

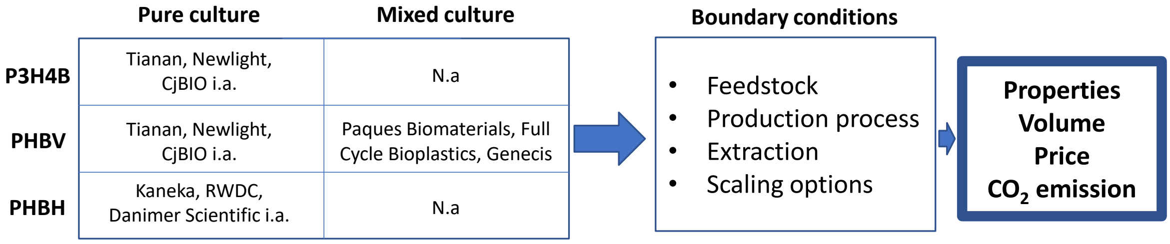
The patent and financial landscape describing the hurdles that need to be met prior market integration of PHA materials are described in Chapter 5 and 6 respectively.

With the information gathered in these chapters, a roadmap is drafted that clearly shows which markets could be accessed by PHA polymers within the short term, long term and what markets could better be left unexplored due to a mismatch in functionality or the existence of more suitable alternatives.

2 PHA production process

2.1 Introduction

This section describes the boundary conditions and performance indicators that determine the market opportunities of PHAs (see Figure 2-1). First, the boundary conditions are reviewed from a broader perspective in comparison with other (biobased and biodegradable) plastics. Second, they are discussed for the PHA family, and finally in detail, comparing different PHA types and production processes. This same structure is used to review the performance indicators.



	Pure culture	Mixed culture
P3H4B	Tianan, Newlight, CjBIO i.a.	N.a
PHBV	Tianan, Newlight, CjBIO i.a.	Paques Biomaterials, Full Cycle Bioplastics, Genecis
PHBH	Kaneka, RWDC, Danimer Scientific i.a.	N.a

Figure 2-1 Schematic overview of the internal factors

2.2 Biobased Feedstock

2.2.1 General introduction on biobased feedstocks

The source and type of biobased feedstock that is used to produce specific chemicals and materials is an important topic. Not only are feedstock costs a considerable part of the production costs of biobased materials, they also influence environmental impacts (e.g. related to agricultural practice and land-use). Moreover, new uses of biobased feedstock compete with current and alternative uses of this feedstock, and expanding feedstock production is not always an option. The viability to use a specific feedstock is determined by the following factors:

- Scarcity; competition with other uses like food, feed and fuel
- Composition; what percentage of the feedstock can be converted into target products
- Conversion factors; how efficiently is the feedstock converted into target products

Scarcity influences not only the potential availability for a new application but also the feedstock price. The composition and conversion factors determine the amount of feedstock that is needed to produce products (and thus price). Additionally, there is pressure to move away from virgin (food grade) feedstock and to use waste streams and agricultural byproducts and residues.

The global biomass (biobased feedstock) demand by different sectors is provided in Figure 2-1 [3, 4]. The data presented in this figure compares data from 2011 and 2020 to illustrate the (limited) effect of policies that promote the use of biomass for the production of biofuels. Most biobased feedstock (around 60%) is used for (animal) feed. The use for energy mainly relates to the use of wood and other types of biomass for heating and energy production and is almost a factor 4 lower. The use of biomass for plant-based food and materials is slightly lower that energy use. The use of biomass to produce biofuels is limited but has doubled since 2011. The current (2020) use of biomass for biobased plastics is negligible and estimated at 0.04% [4].

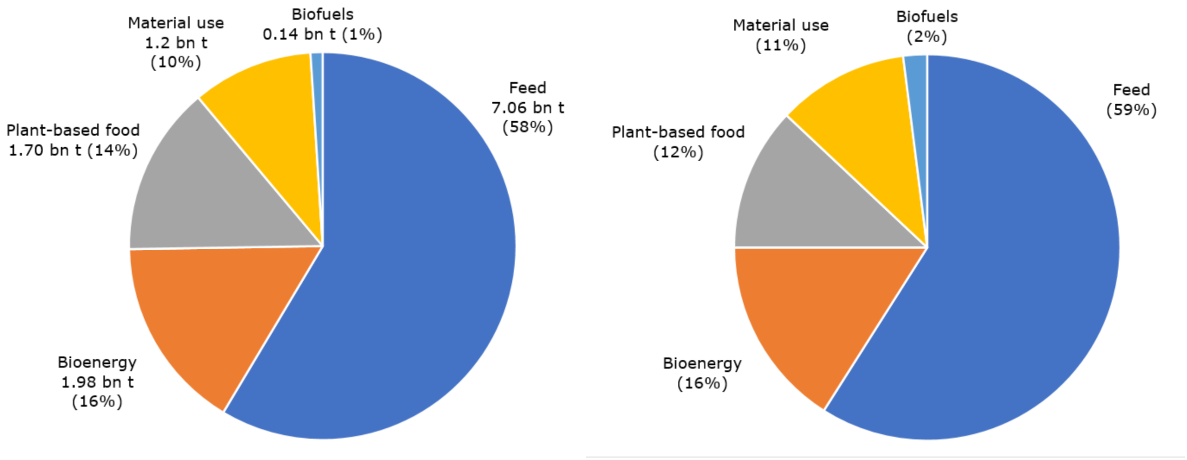


Figure 2-2 Global biomass demand in by sectors 2011 (left) and 2020 (right) *(Feed = animal feed, Bioenergy = energy produced from biomass, biofuels = liquid fuels produced from biomass like bioethanol and biodiesel, material use includes wood for building but also chemicals from biobased origin and plant based products likes adhesives, paper and board, textiles etc.)*

Biobased feedstock can be divided into three main categories of material types: carbohydrates (e.g. sugars, cellulose, starch), oleaginous feedstocks (e.g. vegetable oil, fats) and proteins. The main developments with respect to non-food use of biomass (fuels and materials) focus on carbohydrates and oleaginous feedstocks. As compared to carbohydrates the availability of oleaginous feedstock is more restricted and this is illustrated by Figure 2-2. The EFO (Edible Fats and Oils Collaboration) reports an even lower availability of edible oils and fats and estimates a maximum availability of about 0.25 bn t annually [5].

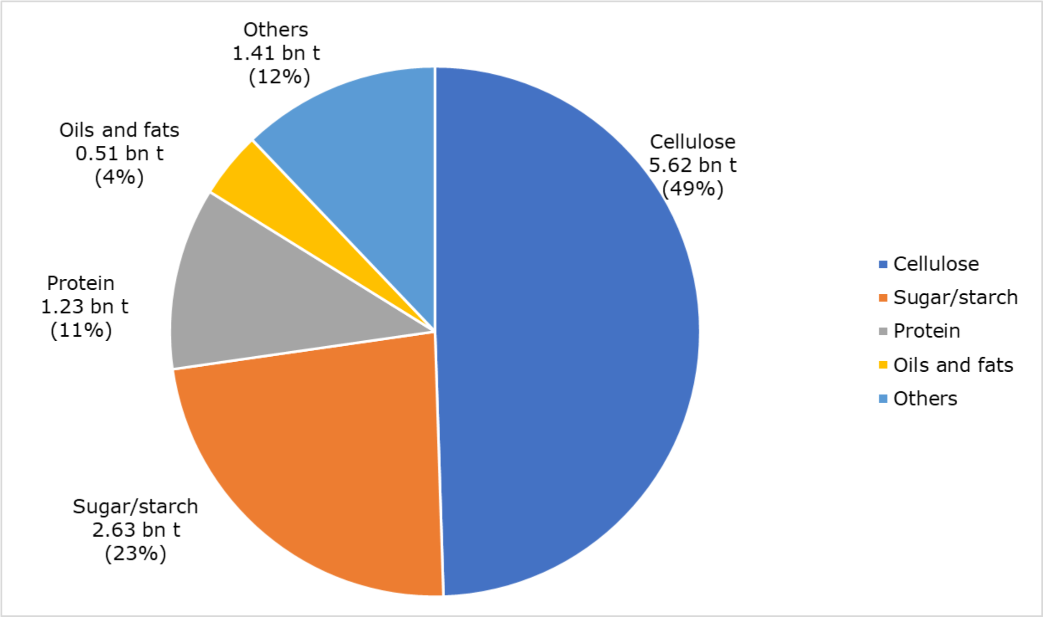


Figure 2-3 Global biomass supply in 2011 by biomass constituents [3]

The more favourable (low) C/O ratio explains the preference for oleaginous feedstock for use in biofuels and renewable naphtha. Vegetable oils (and/or animal fats) are converted via a hydrotreatment into HVO (hydrotreated vegetable oil) with a theoretical mass yield of about 90% HVO and 10% light gases. Most of the HVO is used as renewable diesel for transport or used as jet fuel. Renewable naphtha and propane are formed as co-products. Renewable naphtha can be co-fed in current naphtha crackers to produce building blocks for chemicals and plastics. A mass balance approach is used to attribute the renewable naphtha to specific products like "certified biobased" PE and PP. Polymers produced via this route not necessarily contain a measurable amount of biobased carbon and are not considered biobased plastics according to EN17228:2019 (Plastics -Biobased polymers, plastics, and plastic products- Terminology, characteristics and communication.

At present only 0.3% of the naphtha is of renewable origin, but there are many new initiatives for the production of renewable naphtha [4]. In Europe, renewable naphtha is produced by Neste (based on waste vegetable oils and animal fats) and UPM (based on tall oil, a by-product of wood pulp production). The volumes of these waste streams and side products are limited and specifically for tall oil a shortage is expected in the near future (see Table 2-1). This shortage is caused by the increased use of tall oil (and waste oils and fats) for the production of biofuels resulting from the strong policy support [6]. This strong policy support for biofuels negatively influences industries related to the production of biobased materials and chemicals. These industries indicate that there is a non-level playing field as there are no incentives for the use of biomass for the production of materials and chemicals. The EFO reports that biodiesel incentives shifted the division food/non-food use of vegetable oils and fats from 75% food/25% non-food in 1995 to 50/50 in 2010.

Table 2-1 Examples of non-food sources of oleaginous feedstocks and their estimated volumes.

Feedstock	Type	Estimated production volume [million ton in 2015-2020]	
		Europe	Worldwide
Tall oil	by-product	0.65 [6]	1.8 [6]
Waste cooking oil	Waste stream	~1 +1.4 imported [7]	5.1 [7]
Waste fats	by-product	4.5 [8]	7.5 (tallow) [9, 10]
Castor oil	Non-food crop	0 (only import)	0.74 [11]

Figure 2-3 shows that carbohydrates (sugars, starch, cellulose) are more abundantly available and scarcity issues are less likely to occur. They are already used in a wide range of non-food applications without a negative effect on their availability for food production [12]. This is illustrated in Figure 2-4 showing the uses of starch in the European Union in 2012.

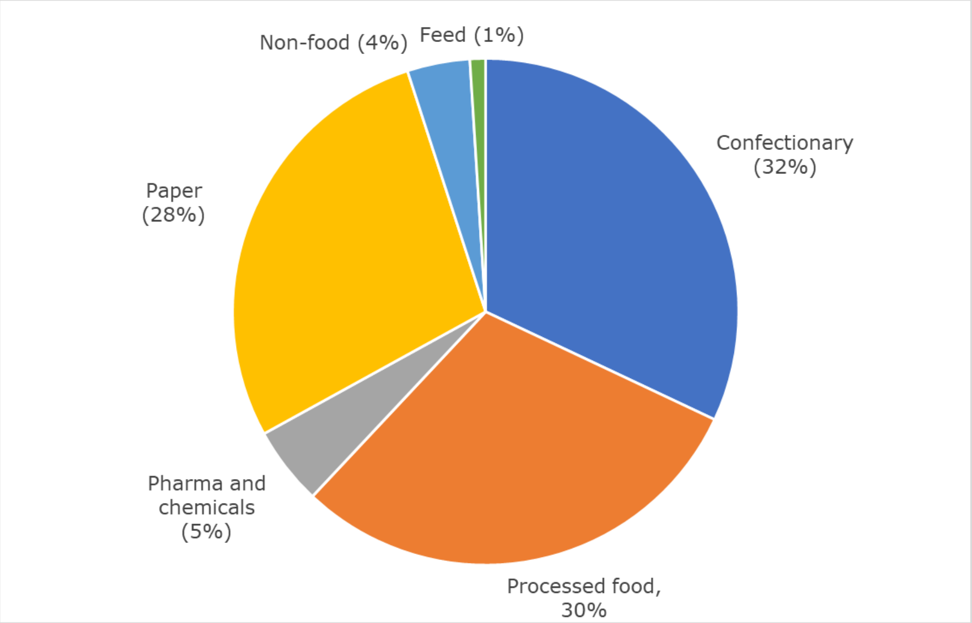


Figure 2-4 The use of starch in the European Union, total volume in 2012 is about 10 million tons [12]

4.8 million ton biomass is used to produce 4 million tons of biobased plastics [4]. Over 50% of the biobased plastics are produced from sugars and starches originating from highly productive crops like sugar cane, sugar beet, wheat and corn. The arguments for using these raw materials is the availability of existing biorefinery infrastructures (to extract the functional components from these crops) and the opportunity to produce affordable, functional building blocks (see

Table 2-2) [4]. Attributed biobased plastics produced from renewable naphtha are not included in these figures.

Table 2-2 Main feedstocks for the production of biobased plastics.

Raw material	Feedstock	Biobased plastic	Share of the specific feedstock (%)
Starch	Corn, wheat, potato, tapioca	PLA, PTT, starch blends	38
Sugar	Sugar cane,	PE, PLA, PHA	25
Ricinus	Castor oil	PA	19
Cellulose	Wood, cotton	CA	14
Edible oil	Palm, soy, rapeseed, sunflower	PHA	3

2.2.2 Feedstock use for PHAs

PHAs are a family of biobased polyesters that can be produced by various microorganisms using a variety of feedstocks from both categories (carbohydrates and oleaginous biomass). The bacteria that produce PHAs use glucose or fatty acids as energy source. The production of PHAs from organic waste streams is an opportunity that receives a lot of attention as it gives rise to cost and environmental footprint reductions. An example is the production of PHAs in wastewater treatment systems. In this case organic substances formed in the wastewater treatment facility, like propionic- and butyric acid, are used as energy source. A more recent development is the production of PHAs from greenhouse gasses like carbon dioxide (CO_2) and methane (CH_4). In principle, the combination of feedstock, the bacteria culture (and the production strategy) determines the PHA type(s) that are produced. An overview (examples) of feedstock, bacteria and produced PHA is shown in Table 2-2.

Table 2-3 Some typical examples of combinations of feedstock, micro-organisms and PHA types produced [13, 14].

Feedstock	Micro-organism	PHA type
Glucose	*Bacillus cereus UW85, Bacillus spp. 87I, Caulobacter crescentus DSM 4727,*	PHB
Methane	*Methylocystis sp. GB 25 DSM 7674*	PHB
Carbon dioxide	Cyanobacteria like *Nostoc muscorum Agardh,*	PHB
Glucose	*Burkholderia sacchari sp. IPT101, Ralstonia eutropha, Natrinema ajinwuensis*	PBHV
Organic acids like acetate, propionate and butyrate in waste treatment facilities	Mixed cultures	PHBV
Glycerol	*Cupriavidusnecator DSM 545*	Short chain length PHA e.g. PHB
Lauric acid, oleic acid	*Aeromonas hydrophila 4AK4 mutant*	Medium chain length PHA e.g. PHBH
Agro-industrial oily wastes	*Pseudomonas aeruginosa NCIB 40045*	Medium chain length PHA e.g. PHBH
Dairy whey	*Pseudomonas hydrogenovora DSM 1749*	Medium chain length PHA e.g. PHBH

The table shows that feedstocks like glucose can be used to produce different types of PHA (PHB and PBHV). It also shows that different feedstocks can be used to produce a specific PHA type. A last scenario is when different feedstocks are fed to the same bacteria. Some micro-organisms are very specific for the feedstock they can utilize, others not. Sometimes feeding different feedstock would lead to production of a different PHA type. Still, there are also bacteria that first convert the feedstock into other molecules and in that case. they could produce the same PHA type. The complex synthesis pathway of producing PHAs is shown in Figure 2-5 and explained by Akinmulewo [15].

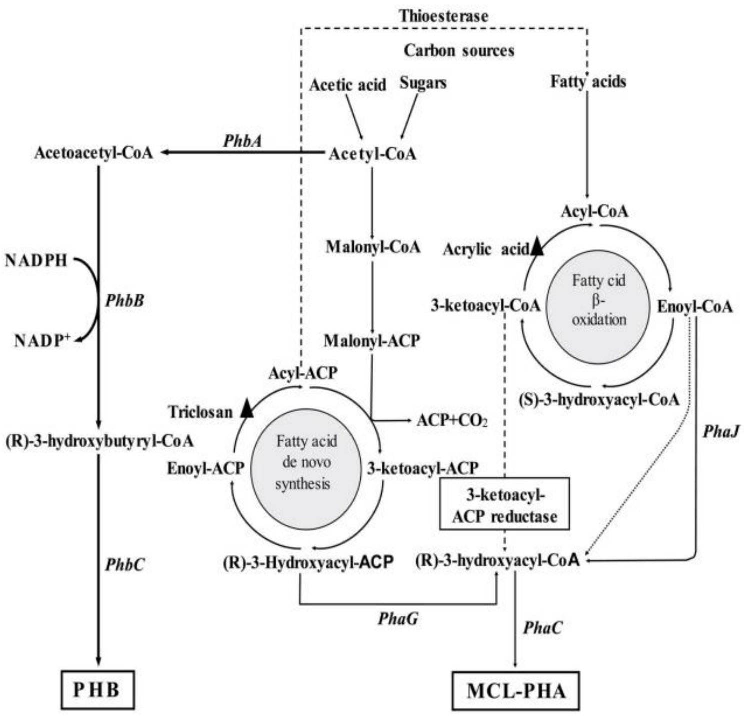


Figure 2-5 Synthesis pathway of producing PHAs [15]

2.2.2.1 Sugars like glucose and fructose

Glucose is the most frequently used and traditional feedstock for PHA production. It can be derived from highly productive crops like corn (hydrolysis of starch) and sugar cane. The advantage of using glucose is its availability and the main disadvantage is its high price as compared to other feedstocks. This price issue is specifically relevant since not all glucose is converted to PHA (conversion factors are discussed in paragraph 2.3).

2.2.2.2 Vegetable oils

Specifically for the production of mcl (medium chain length) PHAs, like PHBH, vegetable oils are used. At present these vegetable oils are derived from virgin feedstocks like palm oil or canola oil. These oils can be certified for sustainable sourcing and production via RSPO (Roundtable on Sustainable Palm Oil), ISCC (International Sustainability Standard), Rainforest Alliance, ISPO (Indonesian Sustainable Palm Oil) or MSPO (Malaysian Sustainable Palm Oil). Still, the use of vegetable oils is associated with direct and indirect land use change issues.

2.2.2.3 CO_2 and methane

Production of PHAs from gasses like methane and CO_2 is receiving a lot of attention. Most advanced is the use of methane [16]. Methane is preferably retrieved from landfills or anaerobic digester (biogas production). Typically. PHB is produced, but by adding feed supplements it is possible to produce PHBV. The main technical challenge is the low gas-liquid mass transfer rate that results in low cell densities and low synthesis rates. Although the use of methane aims to reduce costs at present it is estimated that production cost are in the range of 4.1 $/kg due to high costs for e.g. reactor cooling and air compression [17].

The production of PHAs from CO_2 is feasible by using cyanobacteria (blue-green algae). The process is described as reverse respiration (oxygenic photosynthesis) converting CO_2 and water into sugars and is at a research stage. Often the feed is supplemented with sugars or acids, and this allows for the production of PHB and PHBV.

2.2.2.4 Hydrocarbons

Certain micro-organisms (e.g. various *Pseudomonas* strains) can grow on hydrocarbons like octane and accumulate mcl-PHAs. The main drawback is the limited PHA productivity when these hydrocarbons are used as a feedstock. Still, this route is proposed as an option to produce PHA from plastic waste (polyolefins, polystyrene or PET). Via pyrolysis plastic waste can be converted to small hydrocarbons that can be utilized to produce PHAs [18].

2.2.2.5 Heterogeneous biomass waste streams and organic residues

Although most PHAs are produced from virgin feedstocks, the use of heterogeneous waste streams and residues is highly feasible. The main reason for using waste streams and residues is cost reduction as feedstock costs comprise about 50% of the total production costs of PHAs. Whether cost savings are actually realized using specific waste streams depends on additional costs. Examples of these additional costs would be transportation of feedstocks (with a high-water content), removal of impurities, unfavorable feedstock conversions or additional costs for down-stream processing. Complex logistics of scattered feedstock sources can also hinder the use of waste streams. On the other hand, single culture production of PHA requires a sterile feedstock and sterilization increases (the costs of) energy usage.

The use of waste streams and residues is demonstrated in both in single culture PHA production as in mixed culture PHA production (see Table 2-3). Waste streams used in mixed cultures typically have a high-water content, limited other uses and need to processed anyway. Most waste streams and residues described for PHA production in single cultures can also be used for other biobased plastics and biofuels and this can limit their availability.

Table 2-4 Examples of waste streams and residues described for the production of PHAs [19].

Single culture	Mixed culture
Molasses, whey, lignocellulosic feedstock, glycerol, waste cooking oils	Molasses, lignocelulosic feedstock, vegetable, fruit and garden waste, biodiesel wastewater, food processing waste effluents, brewery waste effluents, kraft mill wastewater, sugar industry wastewater.

The composition of the waste stream determines how efficiently it can be converted into PHAs. This is commonly based on the amount of recalcitrant components and the water content. The composition of common lignocellulosic feedstocks (their convertible components) is listed in Table 2-4 and of residues of the food industry in Table 2-5 [20, 21]. Typically, the cellulose and hemicellulose fraction is available for conversion into PHA (and other bioplastics and chemicals) whereas the lignin fraction is not utilized.

Table 2-5 Composition of lignocellulosic feedstocks [21].

Feedstock	Cellulose (%w/w of dry feedstock)	Hemicellulose (%w/w of dry feedstock)
Woody biomass	41.3	27.7
Corn stover	36.9	21.3
Sugar cane straw	33.0	26.0
Bagasse	39.1	22.5
Beet pulp	22.0	53.0

Table 2-6 Water and carbohydrate content of various waste streams from the food industry [20].

Type of food waste	Water content [%]	Carbohydrate content [%]
Molasses, beet	23	65.1
Spent grains from breweries	80-83	9-11.6
Whey	92.7	4.9
Potato peel	85	*69.7* (dry basis)

2.2.3 Feedstock use for the target PHAs

The feedstock used to produce the target PHAs as defined in this project are listed in Table 2-6. Since CjBio uses Metabolix technology it is assumed that glucose is used as a feedstock. Glucose can be derived from a wide variety of crops like sugar cane, cassava or tapioca depending on local availability.

Table 2-7 Feedstock use for the target PHAs

PHA type	Company/Grade	Feedstock	Comments
P3H4B	CjBio PHA M2300	Glucose from sugarcane or corn	Metabolix technology
PHBV	Tianan Enmat Y1000	Glucose from corn [22]	
PHBH	Kaneka Aonilex X131A and X151A	Palm oil	Looking into waste streams
PHBV	Paques Biomaterials test grade	Heterogeneous waste streams	Multiple options

From Table 2-6 it can be concluded that at present virgin feedstock is used for the production of commercially available PHAs. Heterogeneous biomass waste streams (sources of organic carbon) used by Paques Biomaterials include effluents from industries. Feedstock use of some other PHA producers (of whom the PHA is not taken as an example in this study) is listed in Table 2-7.

Table 2-8 Feedstock use by various companies other than producers of target PHAs.

Company	Feedstock	PHA type
Danimer	Vegetable oil (soy, palm canola)	PHBH, PHBO, PHBD
RWDC	Waste cooking oil	PHBH
Bleupha	Heterogeneous waste streams	PHBH, P3HB4HB
Full Cycle Bioplastics	Heterogeneous waste streams	PHB, PHBV
Newlight technologies	Methane	PHB, PHBV

2.2.4 Concluding remarks on feedstock

At present the PHAs are produced from virgin feedstocks. Virgin organic feedstock is readily available and allows scale-up to large facilities. The use of organic waste streams and residues is feasible but for specific waste streams competition with the use for biofuels and bioenergy can be expected (e.g. waste cooking oils). Of specific interest for the production of PHAs are heterogeneous waste streams with a high-water content and negative value. Use of these waste streams is most feasible in smaller operations due to logistic challenges. The use of greenhouse gasses is and interesting development but can be costly due to technological challenges.

2.3 Production and isolation process

2.3.1 General

Three different routes can be distinguished for the production of biobased plastics (see Table 2-9). The oldest route uses naturally occurring polymers like cellulose and converts them into plastic by chemical or physical modification. In a second route, monomers are produced from biobased feedstock (for example via fermentation) and these biobased monomers are converted into polymers using methods similar to the production of fossil based polymers. A third route is the production of plastics by microorganisms and plants.

Table 2-9 Routes for the production of biobased plastics.

Route	Examples
Modification of natural polymers	Thermoplastic starch, Cellulose acetates, cellophane, casein plastics
Biomass conversion	PLA, PEF, bioPE, PBS
Production in microorganisms or plants	PHA, natural rubber, microbial cellulose

All three routes have their own advantages and challenges. Cellulose acetate production requires very pure cellulose (dissolving pulp) and is energy and chemical intensive. Biomass conversion routes are a two-step approach, but a broad range of biobased plastics can be produced. Moreover, the biobased monomers can be integrated into existing polymer production infrastructure (e.g. biobased ethylene, biobased ethylene glycol, biobased succinic acid and biobased butanediol). Microorganism and plants have lower conversion factors but can produce polymers with very high molar masses and stereo chemical purity, that cannot easily be achieved via chemical routes. Commercially available PHAs are produced by bacteria that accumulate PHA within their cells. The molar mass of these PHAs is high. Synthetic routes to produce PHA are reported in literature but until now of limited commercial value [18]. The most promising synthetic PHA is Poly(3-hydroxypropionate) (P3HP) from carbon monoxide and ethylene oxide. The technology developed by Novomer has recently been acquired by Danimer [23].

2.3.2 Industrial production of PHAs

PHAs are produced in nature by a wide range of microorganisms that use PHA as carbon and energy storage. Most common is the accumulation in bacteria through conversion (fermentation) of sugars or fatty acids. Production of PHA involves the multiplication of microorganism, and by changing nutrients making the microorganisms produce and accumulate PHA. Bacteria can accumulate up to 80% PHA based on their dry weight within their cells.

PHA production on an industrial scale involves various production steps including fermentation, separation of biomass from the broth, biomass drying, PHA extraction and PHA drying (see Figure 2-5). Typically, production of PHA is a batch process.

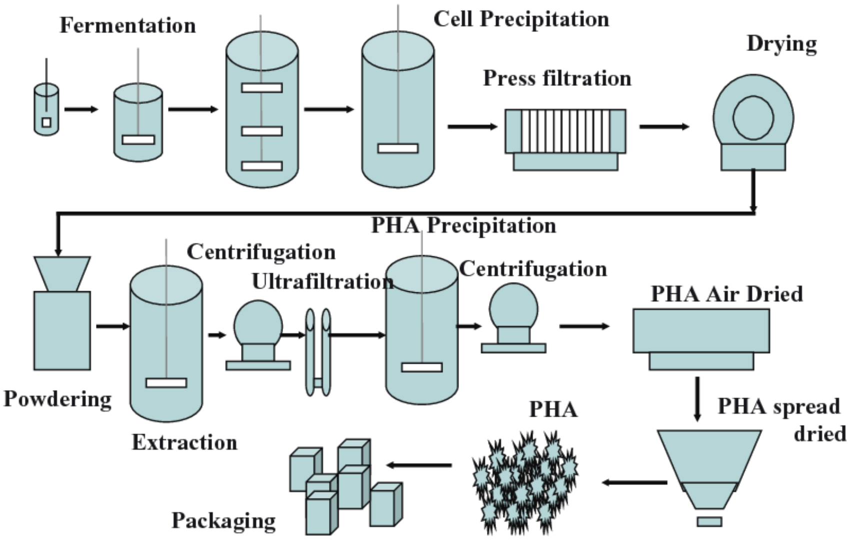


Figure 2-6 General industrial production scheme for PHA [24]

In the 1980’s PHAs were first produced on an industrial scale by ICI. Operation was subsequently taken over by Monsanto and Metabolix. In a joint venture with ADM, PHA production was scaled up to

50 kton annually in 2010. To date, this remains the largest scale at which PHAs have been produced. The operation stopped in 2012 when ADM stepped out of the joint venture. At present the technology is owned by the Korean company CJBio.

Although industrial production and commercialization of PHA started over 30 years ago, research to improve the market opportunities of PHA by optimizing PHA production are still ongoing. Most research and development aims at reducing the costs of PHA production. In this respect most focus is on the fermentation process (PHA accumulation by microorganisms) but also on the PHA extraction process. Together with novel improved industrial production routes the costs of PHA production can be reduced and the quality of PHAs can be improved.

Improving fermentation involves engineering bacteria strains that grow more rapidly, accumulate higher amounts of PHA and have a more favorable conversion factor (kg feedstock needed for the production 1 kg PHA). In this respect the use of vegetable oils has a more favourable conversion factor (0.6-0.8 g/g) than sugar substrates (0.3-0.4 g/g) [25] .

Other targets of the engineering of microorganisms for PHA production include: [24, 26]

- Species that can use simple carbon sources for scl and mcl production
- Enhancing the production of larger PHA granules to facilitate extraction
- Weakening cell walls to facilitate the disruption of cells needed for extraction
- Controlling PHA molar mass
- Development of strains for continuous production processes
- Development of novel PHAs with unique properties

At present most commercially available PHAs are produced using single culture fermentation processes. Typical differences between companies are target PHA, bacteria strains, feedstocks and downstream processing. Alternative routes, currently in the academic or early start-up phase, include the use of mixed cultures but also continuous PHA production. Companies targeting mixed culture PHA production are Paques Biomaterials, Full Cycle Bioplastics and Genecis. The main characteristics of PHA production via single or mixed cultures are listed in Table 2-10, and an example of PHA production using mixed cultures is presented in Figure 2-7. An essential step is the acidogenic fermentation which serves as a pretreatment of the waste feedstock. In this pretreatment step organic feedstock is converted into short chain organic acids like acetic acid, propionic acids and butyric acid, often referred to as volatile fatty acids (VFA). These VFAs can then be readily converted into PHA.

Table 2-10 Characteristics of single culture and mixed culture PHA production [19].

Single culture	Mixed culture
Expensive aseptic operation, requiring sterilization of feedstock and installation	Aseptic operation is not necessary
Aerobic fermentation (need air flow through the reactor)	Anaerobic conversions of feedstock to organic acids (VFA) used as feed for PHA accumulation
Expensive substrates	Organic substances from (cheap) waste streams
High productivity and yields via engineered bacteria	Lower volumetric productivity

The aim of using mixed cultures is to reduce costs via the use of waste streams but also by avoiding cost intensive sterilization processes.

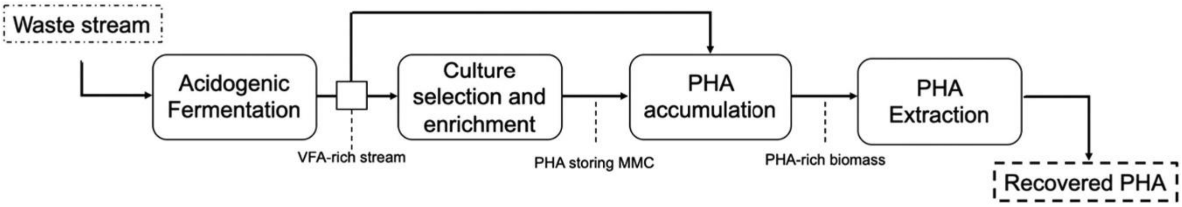


Figure 2-7 Schematic representation of industrial PHA production using mixed cultures[27]

Preventing contaminations is also an issue in (open) continuous processes. These could be feasible using microorganisms that grow under extreme conditions (high or low pH, high osmotic pressure, high or low temperature). Halophilic bacteria that can adapt to high osmotic pressure, high pH and elevated temperature are a promising species. Moreover, these halophilic bacteria can grow in mixed substrates like kitchen waste or low-quality agricultural waste streams [28]. The development of continuous production processes is still in the academic research stage.

2.3.2.1 Production of the target PHAs

Pure culture **P3H4B** can be produced using *R. eutropha* and recombinant *E.coli* feeding 1.4-butandediol to control the copolymer composition. Typically, the 4-hydroxyburtyrate content varies from 5 to 40 mol%. Processes for the production of P3H4B were developed by Metabolix [29].
The typical production route as operated by Tianan for the production of **PHBV** is shown in Figure 2-8 [22]. Typically *R. eutropha* is used to convert sugarcane molasses into PHBV [30].

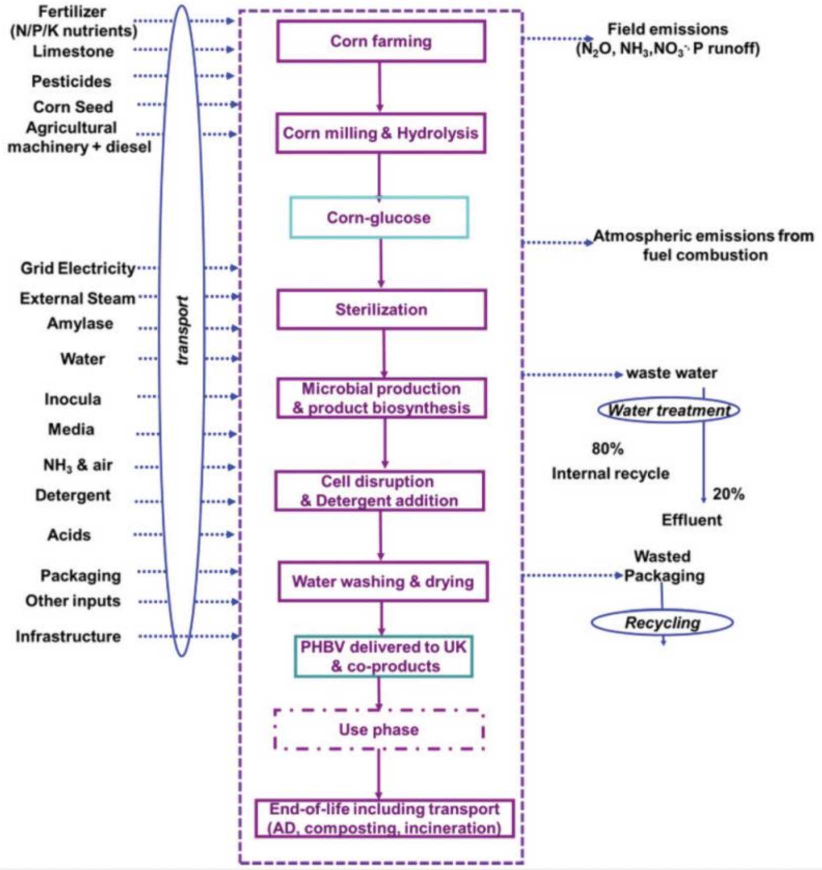


Figure 2-8 ***PHBV production system based on data provided by Tianan Biologic Materials Co. (copied from [22])***

PHBH is produced by Kaneka using *P. putida* [30]. Whereas sugars are used to produce P3H4B and PHBV, PHBH is produces from vegetable oil.

Paques Biomaterials aims to produce **PHBV** using mixed cultures in a wastewater treatment system. A schematic representation of this process is shown in Figure 2-9. Organic carbon containing waste streams are added to enhance PHA production. By controlling the propionic acid/butyric acid ratio the valerate (V) content can be steered.

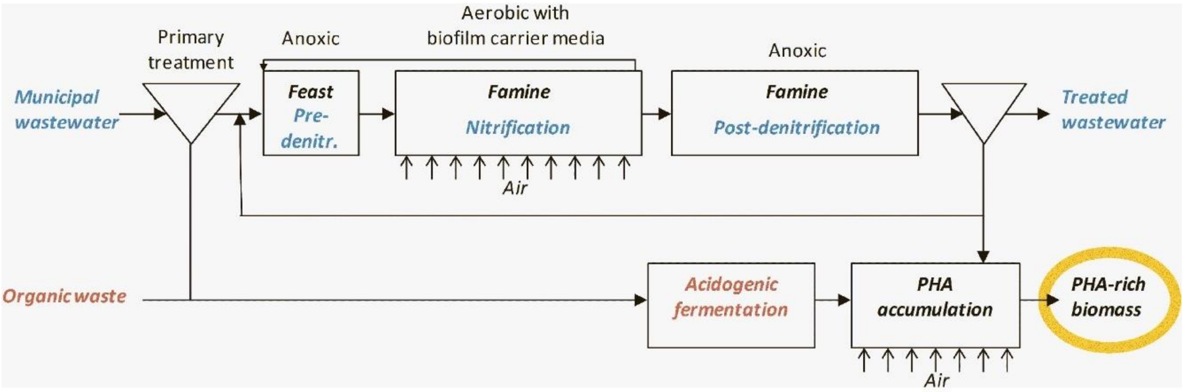


Figure 2-9 PHA production in a municipal waste water treatment facility [31]

2.3.3 Extraction

As PHAs need to be harvested from biomass strategies are needed to recover and purify PHA. Commonly the downstream processing of PHA starts with precipitation, filtering and drying processes to obtain concentrated PHA containing biomass. As the PHAs produced by bacteria are located within the cell wall of the microbes, extraction is in general challenging. Initially organic solvents were used to extract PHA. Using chlorinated solvents, high extraction yields, and high polymer quality (purity) was obtained. A typical solvent extraction process is shown in Figure 2-9 [32].

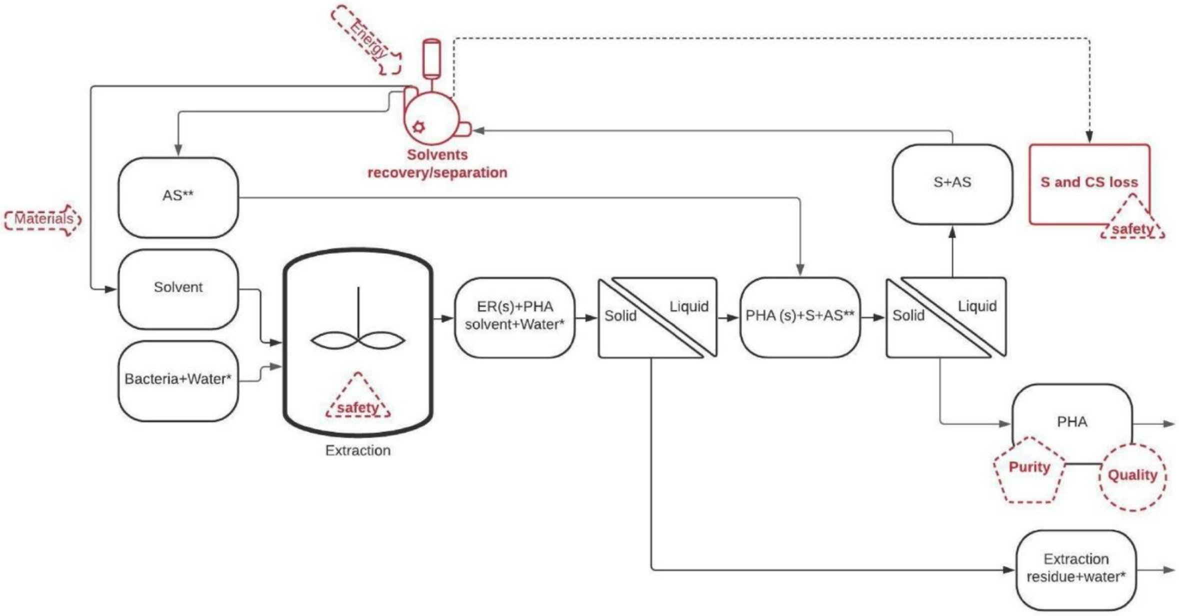


Figure 2-10 General scheme representing the solvent-based approach for recovering PHA from PHA rich bacteria. AS, anti-solvent; S, solvent; PHA, polyhydroxyalkanoate; PHA (s), polyhydroxyalkanoate in suspended solid form; ER (s), extraction residue as suspended solids. Copied from [32]

High costs (high quantities of solvents and energy use for solvent recovery) and environmental concerns has led to development of various alternative extraction routes. A recent review by Pagliano provides an overview over PHA extraction routes [32]. Two main recovery methods can be distinguished; recovery with solvents, and recovery by cellular lysis (disruption of the cell membranes). A typical cellular lysis process is shown in Figure 2-10 [32].

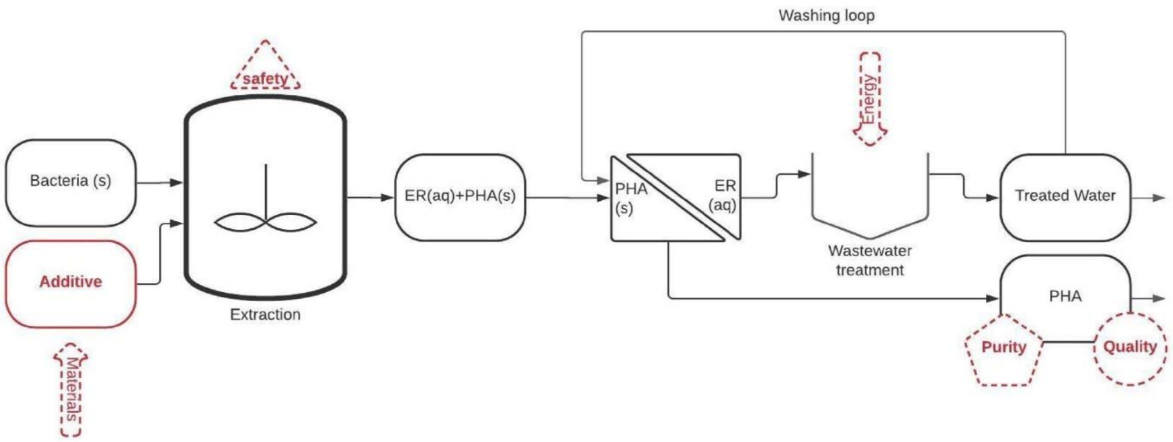


Figure 2-11 ***General scheme representing the cellular lysis approach for recovering PHA form PHA rich bacteria. ER (aq), extraction residue dissolved in water; PHA, polyhydroxyalkanoate; PHA (s), polyhydroxyalkanoate in suspended solid form. Copied from [32]***

A comparison of the two extraction approaches including advantages and drawbacks is presented in Table 2-11.

Table 2-11 ***Classifying PHA extraction methods [32].***

	Extraction with solvent	Cellular Lysis
Chemicals and additives used	Halogenated solvents, alkanes, alcohols, esters, carbonates, ketones	Oxidants, acid compounds, alkaline compounds, surfactants, enzymes
Advantages	High quality PHA Solvent recovery	Drying of biomass not needed Low cost method Better environmental performance
Drawbacks	Expensive Not environmental friendly	Lower quality PHA Less suitable for mixed culture PHAs Recovery of additives difficult

An advantage of cellular lysis is that drying of the biomass is not needed. The main drawback is that PHA degradation can occur and that the additives for cellular lysis can often not be recycled. Moreover, cellular lysis is less effective for PHAs produced in mixed cultures were cell walls seem to be more resistant to hydrolysis. Importantly solvent processes are more suitable to produce high quality PHAs.

The main technical parameters that determine the suitability of an extraction method are extraction yield and the purity and molecular mass of the extracted PHA. Typical impurities include proteins, lipids and cell wall components. Overviews of the reported extraction results of various methods are listed in Table 2-12 and Table 2-13. It should be noted that depending on the method used there are very large differences in number of studies and there is a large variation between the reported results.

Table 2-12 ***Comparing different solvent extraction methods [32].***

	Recovery (%)		Purity (%)		Molecular weight (MDa)	
	Single culture	Mixed culture	Single culture	Mixed culture	Single culture	Mixed culture
Halogenated solvents	48	45	97	97	0.8	0.88
Alcohols	75	83	94	97	0.3	0.65
Ketones	79	50	97	99	0.4	0.4
Carbonates	90	63	92	92	0.88	0,65

Table 2-13 ***Comparing different cellular lysis methods. Singe cultures and mixed cultures between brackets [32].***

	Recovery (%)		Purity (%)		Molecular weight (MDa)	
	Single culture	Mixed culture	Single culture	Mixed culture	Single culture	Mixed culture
Surfactants	89	75	92	77	0.6	0.1
Alkali	88	84	92	82	0.9	0.3
Acids	92	--	90	--	0.2	--
Oxidants	83	82	95	85	0.45	0.32

From the tables it can be concluded that solvent extraction methods (specifically with halogenated solvents and carbonates are most suitable for producing high quality PHAs (high purity and high molar mass). The high extraction yield of cellular lysis methods can be explained by the measurement method/used definition. The main issues of these methods are a lower quality of PHA (purity and molar mass).

Commonly extraction of PHA from mixed cultures results in lower recovery yields and lower purity products when cellulose lysis is used as a recovery method. A comparison is presented in Table 2-14

Table 2-14 ***Extraction of PHA from single and mixed cultures [32].***

Single culture	Mixed culture
Targeted processes optimized for specific PH types	Versatile processes needed to cope with the copolymer range
Higher accumulation levels facilitate extraction	Often operated as smaller scale and thus more costly
	Cellular lysis is less effective resulting in lower recovery yields and purities and often lower molar masses

2.3.3.1 Extraction of target PHAs

Not all PHA producers publicly share the extraction technology they use. It is assumed that Metabolix used a solvent based extraction process and this is in-line with the patents filed by Metabolix. Most likely a shift has been made from halogenated to non-halogenated solvents. Based on literature it is expected that Tianan uses a solvent free process [22].

Kaneka claims solvent free extraction of PHBH. An 18 year old patent (EP1609868) describes extraction with alkali at low temperatures and then treating the PHA with enzymes or surfactants. Moreover they indicate that by suspending the PHA in a hydrophilic solvent or water and stirring at elevated temperatures the PHAs can be agglomerated. The extraction process for PHBVs produced by Paques Biomaterials is under development. Based on literature, solvent based processes seem most effective for PHAs produced in mixed culture processes.

Table 2-15 ***Overview of extraction processes for the target PHAs in this study.***

PHA type	Company/Grade	Extraction process
P3H4B	CjBio PHA M2300	Non-halogenated solvents
PHBV	Tianan Enmat Y1000	Solvent free
PHBH	Kaneka Aonilex X131A and X151A	Solvent free, alkali base
Mixed culture PHBV	Paques Biomaterials test grade	Non-halogenated solvents

2.3.4 Scaling

The largest plant for PHA production had a scale of 50 kton annually and was operated by Telles (Metabolix/ADM JV). Current production facilities have typical sizes up to 5 kton per annum.
Large scale production is only demonstrated and reported in literature for 4 types of PHA; PHB, PHBV, P3H4B and PHBH [24]. Important characteristics needed for upscaling are sufficient polymer accumulation, productivity and conversion factors. Table 2-15 lists production characteristics that are representative for large scale production of PHA

Table 2-16 ***Characteristics of PHA production representative for large scale production [24, 33].***

	PHB	PHBV (8-10%V)	P3H4B	PHBH (5 mol% HHx)
Species	*Bhurkolderia sp.*	*Ralstonia. eutropha*	*Ralstonia. eutropha*	*Wautersia eutropha strain*.
Feedstock	Sucrose	Glucose + propionate	Glucose +1,4 butanediol	Soybean oil
Polymer accumulation	120–150 g/l CDW (cell dry weight) containing 65–70% PHB	160 g/l CDW containing 80% PHBV	>100 g/l CDW containing > 70% P3H4B	100-150 g/l >80% PHBH
Productivity	1.44 kg/m^{3}h PHB	2.5 kg/m^{3}h PHBV		
Conversion factor	3.1 kg sucrose per kilogram polymer			1.4 kg soybeen oil per kg polymer
Facility	Pilot-scale run by Copersucar	Pilot plant run by Tianan	Metabolix	Japan Science and Technology Corporation

The challenges of scaling-up PHA production from waste streams are reviewed by Rodriguez-Perez [34]. He concludes that economic viability is the main obstacle for using waste streams in commercial PHA production. Selection of an adequate waste stream is critical to ensure sufficient and constant supply. Most promising are wastewater, glycerol from biodiesel production and whey. Combining two or more waste streams can avoid dependency on additional virgin feedstocks. Moreover, integration of PHA production into processes like wastewater treatment plants and biodiesel factories is suggested to facilitate implementation.

Estevez-Alonso discusses the current status and challenges of scaling-up mixed culture PHA production [35]. Pilot scale productions show promising results but not all result are consistent and more understanding is needed on the evolution of polymer properties in the PHA accumulation process. Recommendations listed in this publication include:

- Develop a downstream processing method with a focus on applications and product requirements
- Organize and secure feedstock supply that matches with production needs and potential applications
- Build a sound business case

2.3.5 Concluding remarks on PHA production and isolation

The production of PHAs is markedly different from the production of conventional plastics. PHAs are produced via fermentation in batch operations. Typically concentrations of PHA in the fermentation broth are 100 g/l at maximum whereas production of synthetic polymers can reach up to 500 g/l [36]. Substrate utilization rates are around 33% and for synthetic polymers values ranging from 90-100% are common. Recovery of PHA from the fermentation broth is very specific and adds to the production complexity. Typically process improvements target at using low cost (waste) substrates, higher PHA accumulation levels and improved down-stream processing.

3 PHA performance indicators

3.1 Properties

3.1.1 Properties of bioplastics as compared to fossil based plastics

Biobased plastics are developed and used because of their biobased origin and associated lower carbon footprint but also because of specific beneficial properties, and biodegradability can be one of these beneficial properties. The properties of plastics do not depend on the carbon source implying that the properties of biobased PE are identical to fossil based PE. The origin of the carbon does not determine potential biodegradability and various fossil based plastics are biodegradable in the natural environment. Attributed (or certified) biobased plastics are excluded from this figure (Attributed biobased indicates that the biobased content is attributed a mass balance method. It represents the extent to which fossil fuel-derived feedstocks have been substituted by renewable or biobased feedstocks).

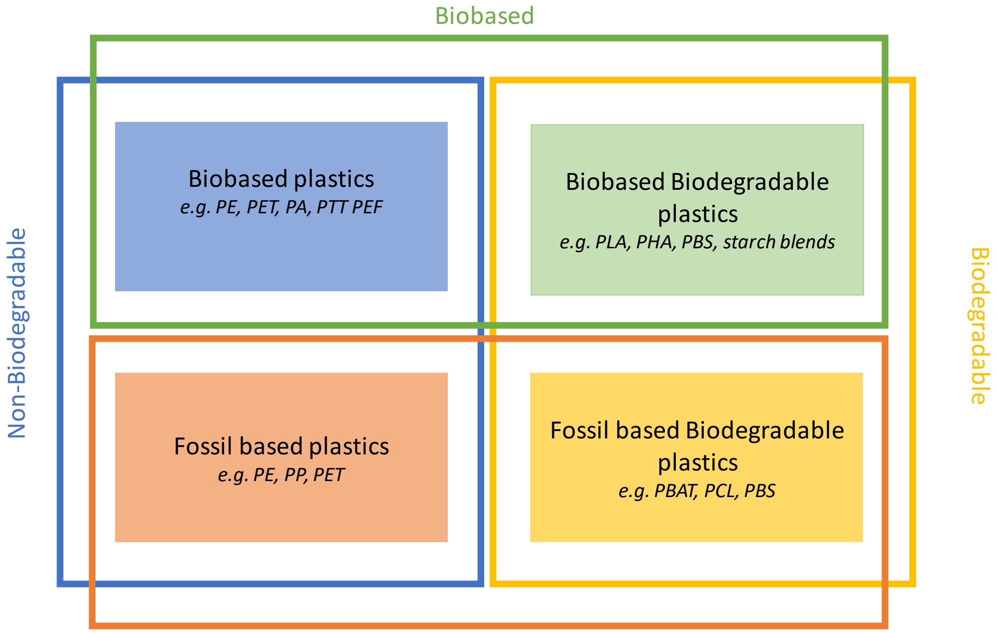


Figure 3-1 Classification of plastics

A typical classification of biobased and biodegradable plastics is presented in Figure 3-1. Biobased, non-biodegradable plastics (blue square) include drop in biobased plastics like bioPE and (partly biobased) bioPET. Moreover, it includes newly developed biobased plastics like PTT (improved properties in carpet and textile applications) a range of polyamides (PA) and Polyethylene furanoate (PEF). PEF is not commercially available yet and has outstanding barrier properties compared to PET. It is not marketed as biodegradable or compostable but studies indicate that it is less persistent than PET in industrial composting conditions [37].

Fossil based biodegradable plastics (yellow square) are predominantly aliphatic polyesters and most commonly used materials are PBAT (Ecoflex), PBS(A) and PCl. Developments are ongoing to include biobased content (monomers) in these biodegradable plastics. PHAs belong to the biobased biodegradable plastics. In this category PLA and starch based plastics are most commonly used.

Over 50% of the biobased plastics on the market is biodegradable. Biodegradability is a system property, resulting from the interaction between the material properties of the plastic and the biotic and abiotic conditions of the environment in which it biodegrades. Whereas, most biodegradable plastics are degradable in industrial composting facilities large differences in biodegradability are found in natural environments. Table 3-4 provides an overview of the biodegradability of most commonly used bioplastics in various environments. This table considers biodegradability in the listed environments in acceptable time frames that prevent accumulation and that are used in certification schemes. Please note that home compostable or marine degradable materials not necessarily degrade faster during industrial composting as compared to materials that are only certified industrial compostable. In fact, among commercially available biobased plastics, PLA is the fastest degrading material under industrial composting conditions which is reflected by the fact that PLA products up to a thickness of 3 mm can be certified industrial compostable.

Table 3-1 Potential biodegradability of biobased plastics in various environments [38].

Plastic type	**Industrial composting (EN13432)**	**Home composting**	**Soil (EN 17033)**	**Marine**
Maximum Time Frame biodegradatio	6 months	12 months	24 months	6 months
Cellulose acetate	Some grades	Some grades	Some grades	Some grades
PLA	Yes	No	No	No
PBS	Yes	No	No	No
PHB	Yes	Yes	Yes	Yes
PBAT	Yes	Yes	Yes	No
Starch based plastics	Yes	Specific grades	Specific grades	Specific grades
Starch	Yes	Yes	Yes	Yes
Cellophane	Yes	Yes	Yes	Yes

Comparing biobased plastics with fossil based plastics based on properties is difficult. There are various grades of one material and depending on the application a wide range of properties can be relevant. Direct replacements are discouraged and redesign is promoted to make optimal use of the specific properties of a material. Table 3-1, Table 3-2 and Table 3-3 give some comparisons on relevant properties in focussing on materials with a high flexibility, moderate stiffness and high stiffness.

Table 3-2 Typical properties of biobased and biodegradable plastics in film applications as compared to HDPE and LDPE. Properties are indicative and can vary between grades.

Property	**HDPE**	**LDPE**	**Starch blends**	**PBAT**	**PBSA**	**PHBH (H=10%)**
Tm [°C]	129	110	118	115	84	126
Tensile Strength [MPa]	30	40	28	25	30	20
E-Modulus [MPa]	1200	200	180	110	300	800
Elongation at Break [%]	700	300	450	700	600	12
Density [g/cm^3]	0.95	0.92	1.3	1.26	1.24	1.2

Most frequently used in film applications (like mulching films and biowaste collection bags) are PBAT and starch based blends. This is due to maturity, availability but also the outstanding properties of PBAT in film application (tear strength). Apart from their biobased nature the strength of PHAs (as a component) in film applications is their biodegradability in the natural environment. This is specifically relevant for mulching films but also for film applications in market were home compostability is required or demanded.

Table 3-3 Typical properties of biobased and biodegradable plastics with moderate stiffness as compared to PP and HDPE. Properties are indicative and can vary between grades.

Property	PP	HDPE	PBS	Starch blend	PHBH (H=10%)
Tg [°C]	-10	-110	-32	--	0
Tm [°C]	163	129	114	135	126
HDT-B [°C]	110	82	97	55	66
Tensile Strength [MPa]	33	30	34	31	20
E-Modulus [MPa]	~1500	1200	700	2000	800
Elongation at Break [%]	415	700	560	7	12
Density [g/cm^3]	0.90	0.95	1.24	1.3	1.2

Biobased plastics with moderate stiffness are typically used in injection moulded products that are used in agricultural applications (plant pots, tree protectors, binding clips) and small articles like coffee capsules. PBS is known for its excellent behaviour in injection moulding (short cycle times). Starch based plastics are also frequently used in these applications because they are more affordable than PBS and PHAs. By using newly developed additives (nucleating agents to enhance crystallisation) PHAs also show the required processing behaviour in injection moulding. Specific benefits of PHAs in these applications (apart from being biobased) are biodegradability in the natural environment but also their relatively high heat deflection temperature and good oxygen barrier as compared to polyolefins.

Table 3-4 Typical properties of biobased and biodegradable plastics with a high stiffness as compared to PET and PS. Properties are indicative and can vary between grades.

	PET	PS	PLA	PHBV (V=2%)	Starch blend	Cellulose acetate
Tg [°C]	75	90	55	2	--	210
Tm [°C]	260	--	150-180	175	135	
HDT-B [°C]	100	90	55	142	55	100
Tensile Strength [MPa]	70	46	60	40	31	40
E-Modulus [MPa]	3000	3250	3600	3500	2000	1600
Elongation at Break [%]	40	3	4	2	7	2.5
Density [g/cm^3]	1.35	1.05	1.24	1.2	1.3	1.3

In applications were a high stiffness is required (thermoformed products) PLA is the most commonly used biobased plastic because of availability and price. Specific PLA grades are available for products that need a high temperature resistance. Typically, cellulose acetates and PHAs are more expensive and are more difficult to process. Another drawback of PHAs is that they are not transparent which limits the use in specific bottles, trays and cups (PET and PS reference materials are transparent) are and that PHA types with a high stiffness are in general relatively brittle.

With the exception of PET, most fossil based plastics have a lower density as compared to bioplastics. This can be a disadvantage in applications were weight is important but can also contribute to higher costs.

3.1.2 Properties of PHAs

The properties of PHAs depend on the specific type. PHAs can be highly crystalline and brittle with a melting temperature up to 177°C for PHB (polyhydroxy butyrate). Depending on sidechain length and copolymer composition both the melting temperature and the crystallinity will drop until the material becomes completely amorphous. More details of the range of properties of PHAs can be found in paragraph 3.1.3 were the properties of target PHA;s are discussed. General properties that are often discussed and could limit the applicability of PHAs are their low melt viscosity and low melt strength as well as their limited thermal stability. Sufficient melt strength (and viscosity) is needed for processes like film blowing, fibre spinning and extrusion foaming. It is advised not to process PHA above 180°C as molecular chain scission typically occurs at this temperature. This implies that generally PHAs have a more narrow processing window then other polyesters and polyolefins.

3.1.3 Properties of target PHAs

Mechanical, thermal and barrier properties of Enmat Y1000, Aonilex X131A, Aonilex X151A and the representative grade supplied by Paques Biomaterials (PB test grade) are measured by WFBR. CjBio PHA M2300 data is based on available technical data sheets. Table 3-8 contains a number of non-measured properties that are being estimated based on in-house WFBR knowledge and general literature that is available for these materials.

Table 3-5 Mechanical properties of the target PHA materials.

PHA type	Representative compound	Tensile strength (MPa)	Young's Modulus (MPa)	Strain at break (%)	Unnotched Impact resistance (kj/m2)
P3H4B	CjBio PHA M2300	36	800	n.a.	5
PHBV	Enmat Y1000	40.1 (±0.2)	3469 (±59)	1.6 (±0.7)	6.6 (±0.3)
PHBH	Aonilex X131A	31.3 (±0.2)	1546 (±12)	14.6 (±5.3)	37.4 (±6.0)
PHBH	Aonilex X151A	19.8 (±0.3)	796 (±30)	12.2 (±2.7)	67.7 (±13.8)
PHBV	*PB test grade*	*16.9 (±0.2)*	*665 (±13)*	*359.6 (±79.2)*	*Did not break*

Table 3-6 Thermal properties of the target PHA materials.

PHA type	Representative compound	Melting temp. (°C)	Glass temp. (°C)	HDT (°C)	MFI (g/10min)	Melt Strength (mN)
P3H4B	CjBio PHA M2300	119	-10	n.a.	10	n.a.
PHBV	Enmat Y1000	170-176	2	141 (±0.2)	10.7 (±0.4) (@180°C)	Too low to measure
PHBH	Aonilex X131A	145	2	97.4 (±1.9)	2.0 (±0.3) (@170°C)	20.6 (±6.5)
PHBH	Aonilex X151A	126	0	65.8 (±2.5)	3.3 (±0.3) (@170°C)	4.5 (±1.2)
PHBV	*PB test grade*	*165 (trajectory peak)*	*-3*	*54.0 (±0.3)*	*0,36 (±0.0) (@170°C)*	*278.0 (±8.9)*

Table 3-7 Barrier properties of the target PHA materials.

PHA type	Representative compound	Oxygen transmission rate (cm3*100 µm /m2*bar*day) 23C, 85% RH)	Water vapour transmission rate (g*100 µm/m2/day) 23C, 85% RH
P3H4B	CjBio PHA M2300	N.a.	N.a.
PHBV	Enmat Y1000	5.5 (±0.3)	22.4 (±1.2)
PHBH	Aonilex X131A	11.6 (±0.0)	70.6 (±0.6)
PHBH	Aonilex X151A	7.9 (±0.8)	127.4 (±127.4)
PHBV	*PB test grade*	*Test in progress*	*Test in progress*

Table 3-8 Non qualitative or non-measured properties of the target PHA materials.

PHA type	Representative compound	UV resistance	Hydrophobicity	Tack	Abrasion resistance (shore D hardness)	Tear strength
P3H4B	CjBio PHA M2300	Good	Medium	Good	N.a.	Medium
PHBV	Enmat Y1000	Good	Medium	Low	79.5 (0.4)	Very low
PHBH	Aonilex X131A	Good	Good	Low	66.7 (0.4)	Low
PHBH	Aonilex X151A	Good	Good	Medium	54.3 (1.0)	Medium
PHBV	*PB test grade*	*Good*	*Good*	*Good*	*54.0 (0.3)*	*Medium*

3.1.4 Concluding remarks

The PHA family offers a broad range of properties that are beneficial in specific applications. Materials range from stiff and brittle to flexible and tough. Well known is the excellent biodegradability of PHAs in the natural environment that can be beneficial in applications where leakage into the environment cannot be prevented. Other specific benefits include a high HDT (maximum usage temperature) and good moisture and gas barrier properties as compared to most other biobased and biodegradable plastics.

3.2 Production volume

3.2.1 Production volume of biobased plastics as compared to fossil based plastics

Figure 3-2 shows the increase in plastic production over the past decades comparing world-wide plastic production against production in Europe and the share of biobased plastics based on data provided by Plastics Europe and European Bioplastics. From this graph it can be seen that production volumes of biobased plastics are very small (~ 1%)[1]. From the graph it can be seen that world-wide plastic production increases rapidly whereas in Europe plastic production is fairly constant.

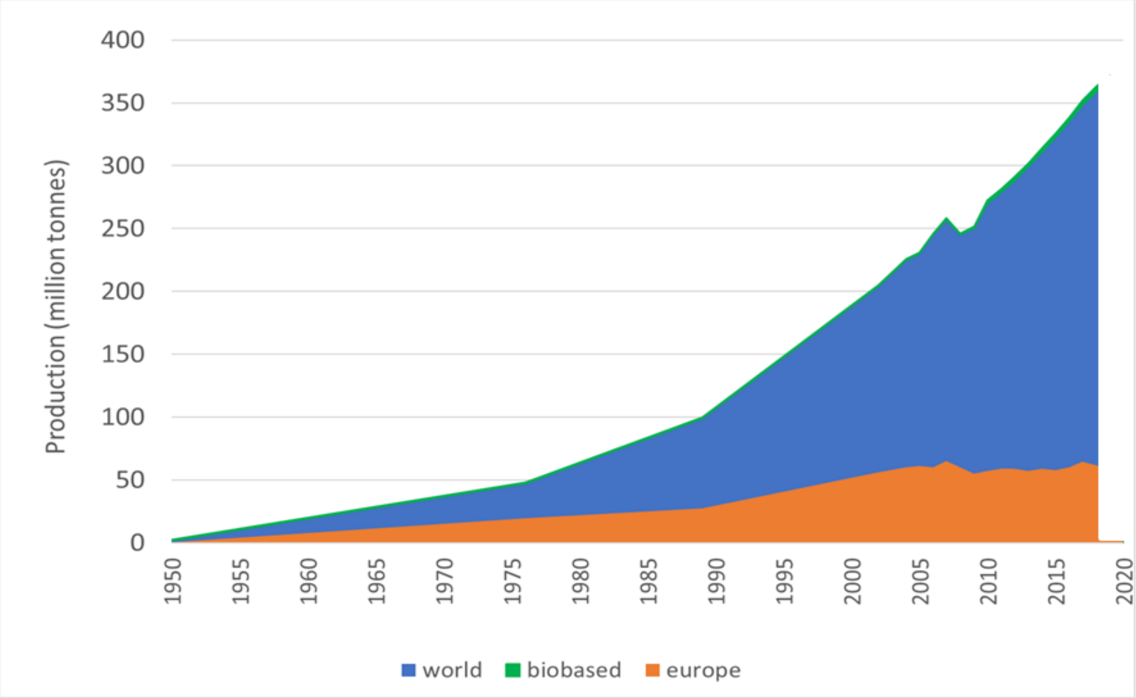


Figure 3-2 Plastics production from 1950 to 2018

Significant (8%) growth in production capacity (actual production data is not available) is expected for biobased plastics and this can be seen in Figure 3-3. Moreover from this figure it can be seen that most growth is expected for biodegradable plastics and limited growth for biobased non-biodegradable plastics including drop-in biobased plastics. A possible explanation is that due to price competition, the market does not accept a higher price for biobased content (e.g. biobased PE vs fossil based PE). In applications were biodegradability is required bioplastics do not have to compete with fossil based plastics.

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[1] Excluded are biobased resins like polyurethanes and epoxies (1.3 million tons), as well as natural rubber (14.1 million tons) and biobased manmade fibres (7 million tons), because of the focus on (thermo)plastic materials

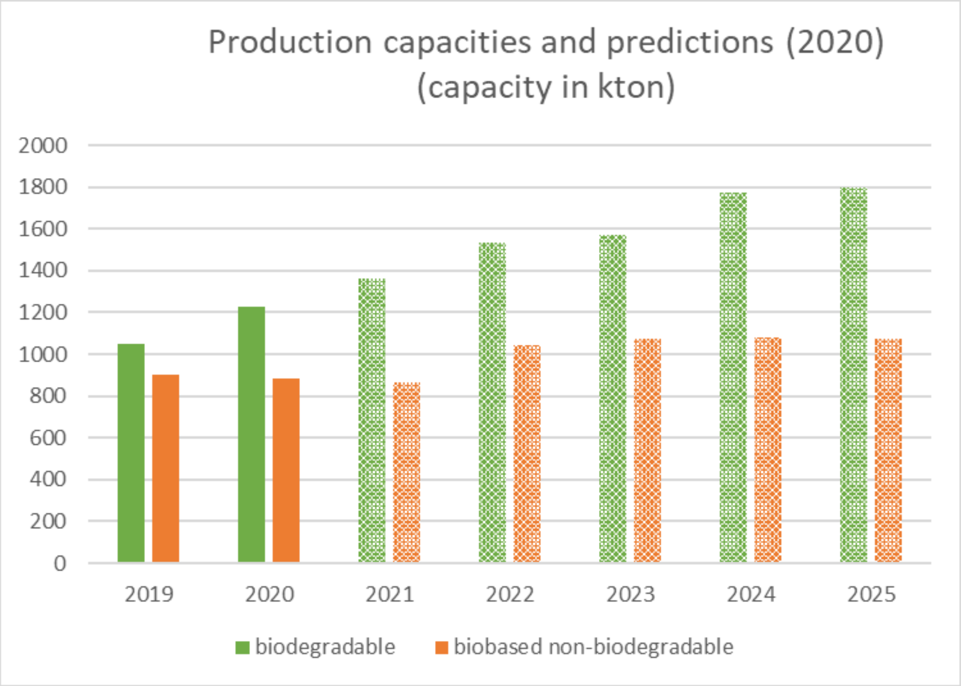


Figure 3-3 ***Production capacities and predictions as listed in the recent market update of European bioplastics***

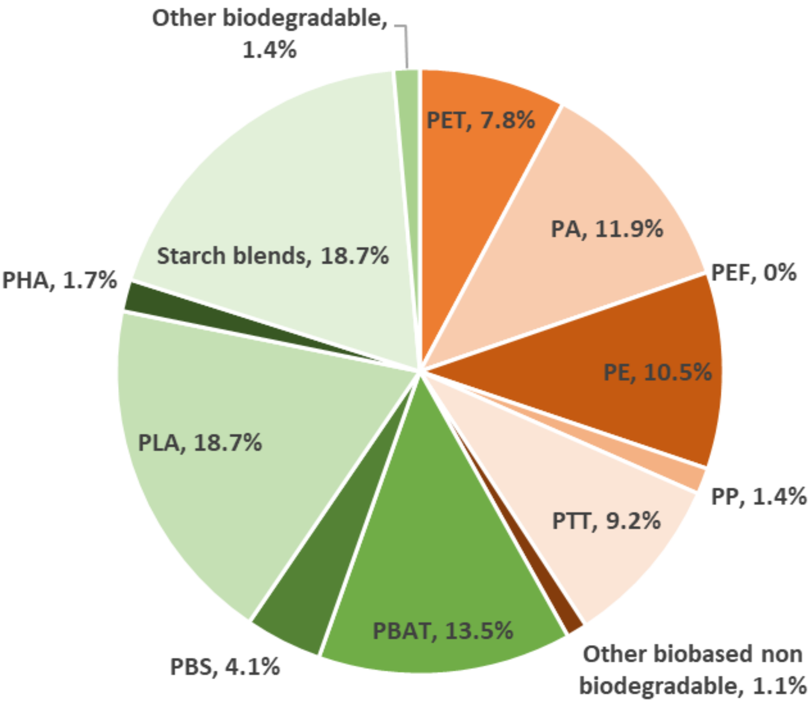


Figure 3-4 ***Relative market shares of different biobased and biodegradable plastic types in 2020. Total volume 2.11 million ton.***

The development of production capacities of specific biobased plastics types over the past years is shown in Figure 3-4 and Table 3-8. The most obvious changes are the relative and absolute decrease of the production capacity of bioPET and the relative and absolute increase in the production capacity of PBAT and PLA.

The largest capacity growth is expected for PHAs, PLA, bioPE and bioPP. This growth is based on expansion plans of various producers. Three new PLA production facilities were announced (Total-Corbion in France, Natureworks LCC in Thailand and LG Chem/ADM in the U.S.) and this will lead to an increase of PLA production capacity of 225 kton in 2025. PHAs have been a very promising material for a long time. Until now large scale market introduction failed and the closure of the 50 kton PHA factory of Telles (joint venture of ADM and Metabolix) was a big set-back. The current focus on biodegradable plastics and introduction of new feedstock may support large scale market introduction and a factor 10 capacity expansion is expected in the next 5 years (see section 3.2.2).

The use of biobased plastics over different market segments is shown in Table 3-9. From this table it can be seen that flexible and rigid packaging are the most important market segments but the use of biobased/biodegradable plastics in these applications is decreasing. Other important market segments are textiles, consumer good and agri- and horticulture.

Table 3-9 Global production capacity in 2018 and 2020 by market segment.

Market segment	Share of biobased plastic production capacity (%) 2018	2020	Main biobased polymers used in segment
Flexible packaging	31	26	Starch blends, bioPE, PBAT
Rigid packaging	23	21	bioPET, bioPE, PLA
Textiles	11	11	PTT, PLA (cellulose acetate not included)
Consumer goods	8	12	Starch blends, PLA
Agri- and horticulture	8	8	Starch blends, PBAT
Automotive	7	6	Biobased PA
Coatings and adhesives	6	4	Starch blends, PBAT, PLA
Building and construction	4	4	Biobased PA
Electronics	2	3	Biobased PA, PLA
Others	1	5	PLA

3.2.2 Production volume of PHAs

Although a large increase in production volumes is predicted (quadrupled within the coming years) production volumes are low. According to the market reports of European Bioplastic and NOVA institute the current production volume is ~30 kton/year, but this figure could be an overestimation looking at commercial availability of PHAs. Main producers at present are Kaneka, TianAn, Newlight, RWDC and Danimer Scientific. The largest production facilities of PHAs including expansion plans are presented in Table 3-10. In this table companies are ranked on the largest current production scale.

Table 3-10 Largest production facilities of PHAs including expansion plans [4].

Company	PHA type	Current Capacity (tons in 2020)	Expansion plans Expected capacity (tons in 2025)
Danimer Scientific	PHBH	8.000 + 2.000	20.000 + 2.000
Kaneka Corporation	PHBH	5.000	5.000 +20.000
Newlight	PHB	5.000	23.000
RWDC	PHBH	5.000	105.000
TianAn	PHBV, P3H4B	2.000	10.000

Additionally various “new” PHA producers have announced commercial production of PHAs (see Table 3-11).

Table 3-11 Announced PHA production of significant scale [4].

Company	PHA type	Current Capacity (tons in 2020)	Expansion plans Expected capacity (tons in in 2025)
Bluepha	PHBH P3H4B	1.000	5.000
PHABuilder	unknown	1.000	10.000
Full Cycle Bioplastics	PHBV	2.5	2.500
CJ Bio	P3H4B, PHBV	0	6.000
Paques biomaterials	PHBV	0	5.000

Full Cycle Bioplastics aims at mixed culture PHA production. Other announced production facilities include those announced by Cristal Union Group together with Bio-On, TAIF group with Bio-On and SECI based on Bio-On technology. The status of these plans is unknown as the Bio-On company has gone bankrupt. Moreover the Spanish start-up company Venvirotech aims to produce PHAs from waste streams and is planning a 20 kt production facility in 2024.

3.2.3 Production volume of the specific (target) PHA types

Based on the data presented in Table 3-10 and Table 3-11 and the summary, it can be concluded that most focus is on PHBH production.

Table 3-12 Production capacities of target PHAs.

PHA type	Current Capacity (tons in 2020)	Expansion plans Expected capacity in 2025
P3H4B +PHB(V)	9.000	54.000
PHBH	20.000	152.000
Mixed culture PHBV	2.5	7.500

3.2.4 Concluding remarks on production volumes

The market share of biobased and biodegradable plastics is limited to about 1% of the total plastic market. Within this category the production volume of PHAs is less than 2%. The specific attention and growing market for biodegradable plastics stimulates the development and production of PHAs and fast growth numbers are predicted. Still it needs to be emphasized that figures are based on installed capacities (not on production) and expansion plans that still need to materialize.

3.3 Market price and production costs

3.3.1 Market price and costs of biobased plastics as compared to fossil based plastics

Public data on the market prices of biobased plastics is not available. Price estimates were presented by WFBR in 2017 [39]. This data was used in the report “ Actieplan Biobased Kunststoffen” to make price comparison with conventional plastics [40]. An overview is presented in Table 3-13.

Table 3-13 Price estimates of various commercially available biopolymers [39, 40].

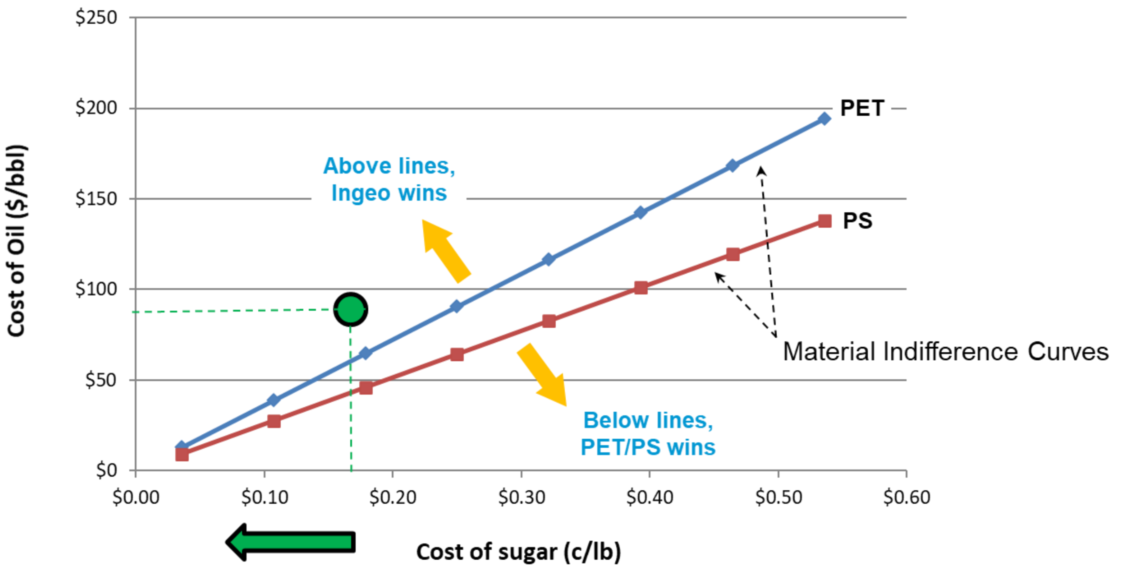
Polymer	Price estimate (range) (€/kg)	Price alternative (€/kg)	Relative difference
BioPE	1.7-1.8	1.35 (PE)	1.3
Certified Biobased PP	2.0	1.1 (PP)	1.9
PBAT	3.5 - 4.5	1.35 (PE)	3.0
BioPBS	4 – 5	1.1 (PP)	3.6
PLA	2 – 3	1.35 (PS)	1.5
PHA	4 – 6	1.1 (PP)	1.5
Starch blends	2 – 5	1.35 (PE)	2.5
Cellulose acetates	5 – 6	1.35 (PS)	3.7

From this table it can be observed that:

- Drop-in biobased plastics (bioPE) are sold at a premium price of about 30%.
- PLA and starch blends belong to the most affordable biobased/biodegradable plastics.
- PBAT, bioPBS, PHAs and Cellulose acetates are significantly more expensive than conventional plastics.

Moreover the higher density of biobased plastics as compared to most fossil based plastics contribute to the costs of products prepared from these materials.

It is believed that a significant part of the price difference is cost by scaling, but also the price of building blocks (raw materials) is important as well as investment costs.
Most data is available on the prices (and costs) of PLA production. According to Natureworks LCC, PLA becomes more affordable than PS (polystyrene) at an oil price of $90/barrel and a sugar price of 16-17 ct/lb (see Figure 3-5) [41]. The current (November 2021) market price of oil is $68/barrel and the sugar price is 19ct/lb.



PET and PS Analysis from McKinsey margin models, CMAI,February 2006

Figure 3-5 ***PET:PS Ingeo Feedstock Cost Comparison***

A recent study by HWWI (Hamburg Institute of International Economics proposes the cost structure for PLA production from corn grain and corn stover [42] . They report minimum costs of 1 $/kg and maximum costs of 1.37 $/kg for PLA production from corn grain and minimum costs of 1.13 $/kg and maximum costs of 1.97 $/kg for PLA production from corn stover. The main difference is in the fixed costs that are significantly higher for production from corn stover.

Table 3-14 ***Distribution of costs for PLA production [42].***

Cost type	Corn grain ($/kg PLA)	Corn stover ($/kg PLA)
Feedstock	0.27	0.10
Pre-treatment	0.01	0.08
Fermentation	0.38	0.50
Polymerization	0.08	0.08
Variable unit costs	0.74	0.77
Fixed unit costs	0.44	0.63
Total unit costs	**1.18**	**1.40**

3.3.2 Market prices and production costs of PHAs

The market prices of PHAs are high and estimated at 4-6 euro/kg. Still, actual data on market prices is not publicly available as well as insights in the relationship between market price and productions costs. In an article published in 2007 Jacquel listed prices (see Table 3-15), but since then many changes in producers and facilities are reported [43]. From this table it can be concluded that current prices are still highly similar to prices reported in 2010.

Table 3-15 PHA prices as found in literature [43].

Company (and brand)	PHA type	Price (€/kg)
Biotechnology Co., (Biomer)	PHB	20 (2003) and 3-5 (2010)
Metabolix (Mirel)	PHB, PBHV	2.2 (2010) 10-12 (2003) and 3-5 (2010)
P&G (Nodax)	PHBH	2.5 (2010)

In literature the productions costs of PHAs are frequently discussed. A graph of the most important factors contributing in PHA production cast is presented in Figure 3-6 [36].

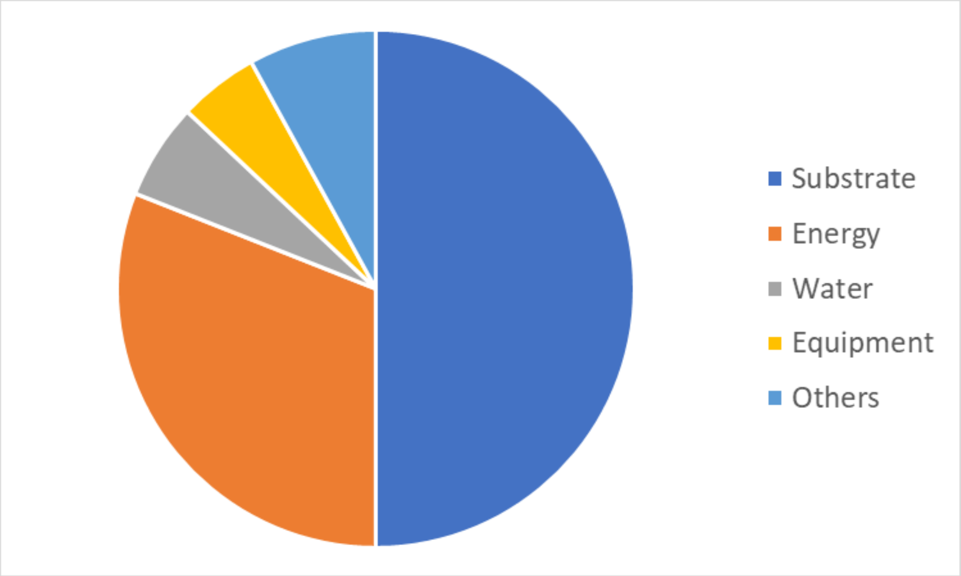


Figure 3-6 Important factors contributing in PHA production costs [36].

According to literature 40 to 50% of the cost are related to feedstock. Moreover, high production cost of PHA have been related to high energy demand for high temperature sterilization using super-hot steam and intensive aeration under pressure, slow growth of microorganisms, discontinuous production processes and complicated downstream processing [26].

Table 3-16 PHA production costs [32].

Cost type	Costs (€/kg)	Remark
Feedstock	0.8-1	0.4 €/kg glucose with a 30-40% yield
Fermentation costs	0.8-1.8	Single strain fermentation
Extraction costs	0.7-1.3	
Total costs	**2.3-4.3**	

Various strategies to reduce production costs are already described in chapter 2 and are summarized in Table 3-16

Table 3-17 Strategies for sustainable and cost-effective production of PHAs [44].

Topic	Strategy
Process optimization	Engineered bacterial strains toward higher productivity and lower costs Mixed culture production High cell density cultivation Mathematical modeling
Renewable substrates	Agro industrial by-products
Downstream recovery	Recyclable non-toxic solvents Low cost recovery strategies

Downstream processing costs including extraction (see Figure 2-9 and Figure 2-10 for typical processing schemes) are estimated to be about 50% of the costs of PHA production [43]. Solvent based recovery processes yield the highest costs (1.95 €/kg) and environmental impacts whereas alkali treatments are more economic (1.4 €/kg) [45]. Pagliano compares solvent extraction (chloroform) with cellular lysis (hypochlorite) and also concludes that solvent based recovery processes yield the highest costs; about 1.2 €/kg for chloroform extraction at 1000 kg/hour and about 0.7 €/kg for cellulose lysis with hypochlorite at the same scale [32].

Fernández-Dacosta has prepared a detailed overview on the production costs as a function of feedstock, microorganisms and downstream processing method [45].

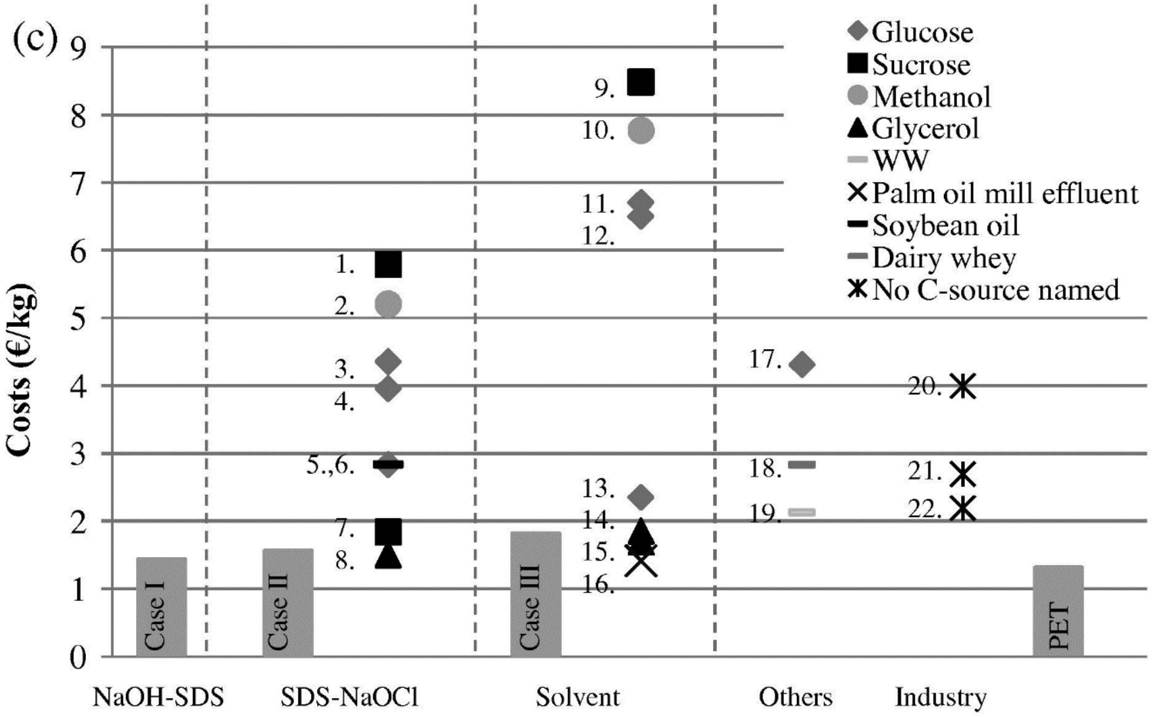


Figure 3-7 ***Economic evaluation of PHA production based on various literature sources. 1-19 single culture fermentation and 20-22 mixed culture fermentation [45]***

In this figure it can be seen that reported production costs range from 1.5 €/kg to over 8 €/kg. The costs of industrial processes range from 2 to 4 €/kg.

A technoeconomic analysis of PHA production using different waste streams is provided in Table 3-18 [46] .

Table 3-18 ***Technoeconomic analysis of PHA production using different waste streams and extraction processes [46].***

Waste stream	Production scale (ton PHA/year)	Extraction method	PHA production costs €/kg	Reference
Oil palm frond	9900	Solvent	3.44	[47]
Soybean oil	5000	Chemical extraction	3.5- 4.5	[33]
Crude glycerol	9000	Aqueous 2 phase	5.77	[48]
Wheypol waste	Small pilot	Solvent	2.82-10.5	[49]
Slaughterhouse waste	10000	Chemical extraction	1.39	[50]
Citric molasses	2000	Various methods	4.36-4.72	[51]

Most favourable was the production of PHAs using slaughterhouse waste. Other waste streams do not seem to provide economic advantages.

An economic evaluation of the production of PHAs in municipal wastewater treatment plants is published by Crutchik [52]. In this case PHA production from sludges is an alternative for methane production. It is concluded in this study that retrofitting of waste water treatment plants to produce PHAs is economically viable. PHA production (excluding extraction) in a large facility that already had installed anaerobic digesters could be as low as 1.11 €/kg. Extraction would add (at least) 25% to the production costs and minimum total costs are estimated at 1.40 €/kg. These values are comparable to other literature sources [45].

3.3.3 Costs of target PHAs

A cost comparison of PHBH productions from vegetable oils with PHB production from glucose is presented by Chen [24]. Although in case of vegetable oils the feedstock conversion factor is more favorable, production costs are highly similar. Annual production costs (5 kton scale) of PHBH is estimated at 3.1-4.0 €/kg and PHB from glucose is estimated at 3.4-3.7 €/kg.
The cost price for the production of mixed culture PHBV is estimated at 3.4 €/kg, this includes 2.1 €/kg operational costs and 1.3 €/kg capital costs [53].

3.3.4 Concluding remarks on prices and costs

Due to unfavourable feedstock conversion factors and the markedly more complex production process it can be expected that PHAs will stay substantially more expensive than fossil-based plastics. Specifically when they are produced from virgin feedstock in single culture processes. This implies that the higher price is not only due to a lower production scale and literature does not provide insights in possible price reductions at higher schales. Production in mixed cultures in waste water treatment facilities could offer prices reductions provided that efficient extraction processes can be used. It is advices to retrofit larger installations that already have installed anearobic digesters.

3.4 Carbon footprint and CO_2 emission

3.4.1 Biobased plastics as compared to fossil based plastics

The main objective and benefits of biobased plastics are decoupling from fossil fuels and reduction of GHG emissions. Biobased plastics are produced from renewable carbon and at end of life these do not cause additional CO_2 emissions. Various peer reviewed articles and reports list LCA data on biobased plastics and large variations are found depending on biobased plastic type, type of feedstock used and the manufacturing process. As there is a lack of harmonized standards and approaches the comparability of studies is limited within the biobased plastics family (and occasionally for the same biobased plastic) but also in comparison to their fossil-based counterparts.

Biobased PE, PLA and PHA are the most frequently studied biobased plastics. These LCA studies are mainly cradle to factory gate studies that include biogenic carbon uptake. This to demonstrate the difference with fossil based plastics that are completely based on fossil based carbon. A rather complete overview is presented by CE Delft [54]. Some data on bioPE, PLA and starch based plastics is summarized in the next tables.

Table 3-19 Climate change LCA results for 1 kg bioPE in cradle-to-gate system [54].

	Fossil	Corn	Sugar cane
Climate change (kg CO_2-eq per kg PE)	2.0	-0.34	-2.05

Table 3-20 Climate change LCA results for 1 kg PLA in cradle-to-gate system as compared to PET [54].

	PET	PLA from Corn (US)	PLA from Sugar cane (Thailand)	PLA from corn stover (US- Europe)
Climate change (kg CO_2-eq per kg polymer)	3.2	-0.3	1.0	0.5-1.5

Table 3-21 Climate change LCA results for 1 kg Starch based plastic in cradle-to-gate system as compared to PE [54].

	PE	Starch based plastics
Climate change (kg CO_2-eq per kg polymer)	2.0	1.0-2.15

The environmental footprint of starch based plastics is highly dependent on the specific blend type and starch source, resulting in a range of 50% reduction in environmental footprint to a higher footprint as compared to PE.

3.4.2 PHAs

According to the Ecoinvent database the footprint of PHAs is lower than the footprint of fossil based PE.

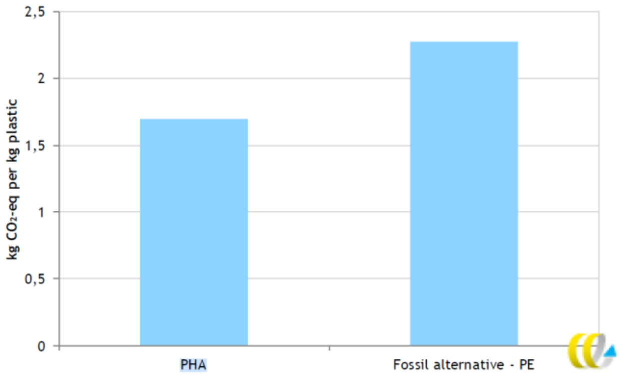


Figure 3-8 The cradle to gate environmental footprint of PHA as compared to PE (Ecoinvent database v3.3) [54]

CE Delft presents LCA data showing the influence of feedstock use (Table 3-22). Depending on the feedstock used the environmental footprint of PHAs can be higher or lower than the footprint of common fossil based polymers.

Table 3-22 Climate change LCA results for 1 kg PHA based plastic in cradle-to-gate system [54].

	Corn (US)	Sugar cane (Brasil)	Lignocellulose waste (US)	Soybean (US)	Rapeseed (Europe)
Climate change (kg CO_2-eq per kg PHA)	-2.3	1.1	1.3	0.26	5-6.9

In most cases PHA would offer a lower footprint than common fossil-based plastics like PE, PP and PET.

There are various publications on the environmental footprint of PHAs that show similar large differences. The factors clarifying these differences are summarized in Table 3-23 [55].

Table 3-23 Differences found in LCAs of PHAs [55].

Type	Examples
LCA Methodology differences	Problem oriented: Global Warming Potential or acidification potential Based on Carbon Footprint/Water Footprint Using a combination of indicators Applying a weighing method; Emergy or Sustainable Process Index
Differences in data	Functional units Energy sources
Process differences	Different biopolymer type Feedstock Downstream processing

Important LCA studies and outcomes are highlighted by Narodaslawsky (Table 3-24). From this table it is clear that contradictory information is found in literature.

Table 3-24 Some highlights from important LCA studies [55].

Publication	Main Findings
Patel (2002) [56]	Energy consumption and CO2 emissions range from 10% better to 8 times worse compared to HDPE PHA less advantageous than other biopolymers Maturing of production and use of renewable energy can dramatically improve the footprint.
Essel (2012) [57]	PHA production will emit between -2 to +2 kg CO2,equ/kg of PHA and will consume from 2 to 70 MJ/kg PHA of fossil resource Fossil based competitors will range between 2 and 8 kg CO2,equ/kg of PHA and between 75 and 110 MJ/kg PHA PHA is more advantageous than PLA
Tabone (2010) [58]	Positive with respect to GWP, CO_2 emission Negative with respect to ozone depletion, acidification etc. related to agricultural practice

LCA studies can be used to pinpoint the factors that contribute most to the environmental impacts and improve the production process. The electrical energy use to produce PHAs is high (sterilization), but using clean energy the environmental footprint can be lowered. Furthermore, unfavourable logistic parameters of raw materials should be avoided (transportation of wet biomass). Selecting the most beneficial raw material is important and production in a biorefinery concept is beneficial. Moreover, it should be noted that most processes are in an early stage and are not fully optimized. Both costs and environmental impacts are likely to be lower for a developed process.

An example of the impact of process optimisation is provided by Koller, focussing on pilot production of PHA from whey [59]. Without any optimisations the impact (SPI method) is 10.433 m^2/kg and implementing all optimisations this can be reduced to 1.455 m^2/kg (using this SPI method the impact of PP is 1.726 m^2/kg). The impact of energy use is stressed in this article and authors found that 88% of the fermentation impact and 79% of the cradle to grave impact is related to energy use (see Table 3-24 . Also concentrating whey at the dairy plant significantly reduced the impacts of transportation.

Table 3-25 Share (percentage distribution) of the ecological footprint of PHA according to the origin [59].

Origin	Fermentation (%)	Whole PHA process (%)
Electricity	88	79
Heating energy	6	7
Transport	0	8
Chemicals	5	5
Emissions	1	1

Efficient conversion of feedstock influences price but also environmental impact. Production of PHBH has a lower energy use (50 MJ/kgPHA) and carbon footprint (0.26 kg CO_2/kg PHA) as compared to PHB production from glucose (59 MJ/kgPHA and 0.26 kg CO_2/kg PHA respectively).

The environmental impact of different downstream processing routs was reviewed by Saavedra del Oso [60]. An overview is presented in Table 3-26.

Table 3-26 GWP of different PHA production processes.

PHA type	Feedstock	System	Recovery	GWP (kgCO2 eq.)
P4HB	Glucose	Single culture	Acetone	9.3
P3HB	Food waste	Single culture	Surfactants	0.8
P3HBco4HB	Oleic acid	Single culture	Alkali	2.4
PHBH	Glucose +soybean oil	Single culture	Ethyl acetate	13.0
P3Hbco4HB	Methane	Single culture	Acetone	3.9
P3HB	Indust Food waste	Halophilic	Osmotic + surfactants	4.2
P3HB	Waste water	Mixed culture	Hypochlorite + surfactents	1.2
P3HB	Sugar molasses	Single culture	Fusel alcholol	10.2

Downstream processes are highly energy intensive, specifically those based on solvent extraction. The use of surfactants and alkali are good alternatives but surfactant recovery can reduce the environmental performance. This is in line with the findings of Pagliano that methods based on cellular lysis have better environmental performance (0.81–4.16 kg CO_2eq) than those based on solvent extraction (3.93–12.96 kg CO_2eq) [32].

Various studies report on the environmental impact of PHA production in mixed culture systems [45, 61-64]. Again energy use is a hot spot and, more specifically, the more difficult extraction of PHA from mixed cultures is considered an important factor. Reported carbon footprints depend on the downstream processing method and are lowest for hypochlorite (2.06 CO_2-eq/kg) and highest for solvent based methods (4.3 CO_2-eq/kg).

3.4.3 Environmental impacts of target PHAs

CJBio does not report on the LCA data of their PHA. In literature a reference can be found to the PHBs produced by Metabolix and in this study and environmental impact of -2.3 CO_2-eq/kg is reported [65].

Tianan does also not report on the LCA data of their PHA. Again scientific literature can be found and this presents insights in the PHA production process (see Figure 2-8). It is concluded that the environmental impact of PHA production is lower than of fossil based plastics. It is also concluded that there is room for optimization and that at a larger production scale environmental impacts can be reduced significantly.

Kaneka does not present LCA data on their PHAs. From literature it can be seen that PHBH production from vegetable oils is beneficial with respect to the global warming potential. Still, the use of vegetable oils is associated with land use change issues.

An LCA study was performed for mixed culture PHA production. A 70% lower environmental impact as compared to PHA produced via single cultures is claimed [53].

3.4.4 Concluding remarks on the environmental impact of PHAs

Large differences in environmental impact of PHAs are reported depending on the feedstock used, but also on the extraction process. Moreover energy use contributes to the environmental impact. Still it is concluded that PHAs have a more favourable environmental footprint than fossil-based plastics. Using renewable energy and avoiding solvent extraction methods is suggested. Moreover, mixed culture PHA production in waste water treatment can result in PHAs with a low environmental impact. Producers of the target PHAs do not list data on the environmental footprint of their materials.

4 Position of PHA in the chemicals and plastics landscape

Aside from the internal factors (volume, price, properties and CO_2 emission), the potential market share of PHAs will be determined by the overall chemicals and plastics landscape in which PHAs will be integrated. In order to achieve this market share it needs to be clear which already existing markets can benefit, and what potential new markets could sprout based on the identified characteristics of PHA materials. Compared to the current fossil-based state of the art for chemicals and plastics, PHA materials are expensive and production volumes are small. In order to gain market share, PHA materials should therefore initially target markets in which they introduce advantages based on their unique properties or leave a substantial positive impact on the CO_2 footprint compared to the current materials that are used for this applications, i.e. the current state of the art (SOTA). With respect to material properties, the one characteristic that is unique for all types of PHA is the excellent biodegradability in natural environments compared to both fossil based and other biobased plastics. Therefore, the market implementation strategy of PHAs should revolve around the necessity of this biodegradable characteristic. The application markets that are depending on this characteristic to such an extent that they want to pay the excess costs of PHA for this property need to be identified. These markets will therefore not compete with non-biodegradable plastics. In addition, these markets will allow for scale-up of the overall PHA production which is then expected to reduce the cost price. Consequently, this will spark the interest of other (more demanding) application areas. Based on this insight, four different phases for PHA market implementation are identified:

1. Applications that need biodegradation and are not critical on other material properties
2. Applications that need biodegradation and are also critical on other material properties
3. Applications that could benefit from biodegradation and are also critical on material properties
4. Applications that do not require biodegradation, but that are preferably produced biobased (and therefore have a lower CO_2 impact).

These phases are schematically shown in Figure 1 and could be seen as a rough timeline for PHA market implementation. The time to move from one phase to the other will be co-dependent on the available production volume and the reduction of the market price for this application.

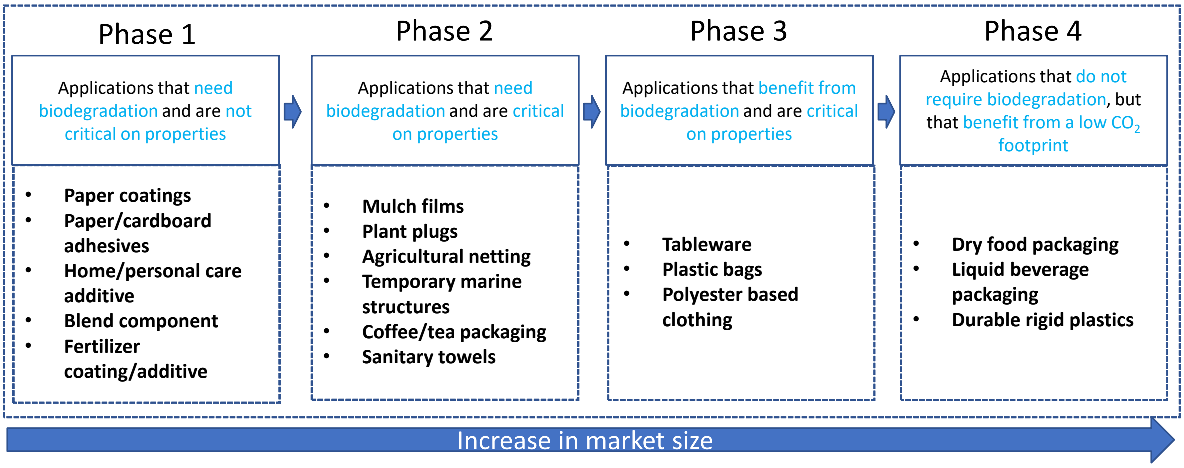


Figure 4-1 ***Overview of the four phases that are defined for the market implementation of PHA materials***

This chapter describes the general landscape of each of the four phases and shows detailed representative examples of relevant product (groups) and how the different types of PHA compare to the current state of the art.

In order to make this comparison tangible and not over-extensive, the comparison is only performed on the most characteristic key properties (both functional and blocking properties) that are required for a specific product category. Furthermore, the ability to process the selected PHA polymers via the relevant product processing routes are compared and used as an assessment parameter. The characteristic key properties and the required processing operations are selected based on the insights and experience of the WFBR research team and thereby intrinsically arbitrary. Nevertheless, they are expected to assist the identification of the most suitable target markets of PHA materials in a comprehensive and effective manner.

Based on the output of this assessment it will be clear what markets have a high potential to be targeted by PHA plastics and which markets are better left unapproached. In addition, a comparison is made with those biobased and/or biodegradable plastics that will compete with PHAs in obtaining the biobased plastic market share in a specific category. For this comparison, the biobased and/or biodegradable plastics with the highest current market volume and a matching end-of-life potential are included.

Table 4-1 Overview of characteristic key properties and desired processing operations of the selected applications in this study.

Material category	Characteristic Key Properties	Processing operations
Phase 1		
Water resistant paper coating	*Hydrophobicity, Glass transition temperature*	*Extrusion coating, dispersion coating*
Paper cardboard adhesives	*Tack, Glass transition temperature*	*Hotmelt application*
Home/personal care additives	*Case specific*	*Case specific*
Biodegradable blend component	*Case specific*	*Polymer extrusion*
Fertilizer coating/additive	*Melting point, hydrophobicity, melt flow index*	*Mixing, dispersion coating*
Phase 2		
Mulch films	*UV resistance, Elastic modulus, Strength*	*Film blowing, film casting*
Plant plugs	*Strength, Elastic modulus, Melt strength*	*Injection moulding, fibre spinning*
Agricultural netting	*Strength, Melt strength*	*Net extrusion*
Temporary soil/marine structures	*Elastic modulus, larvae settlement*	*Injection moulding*
Coffee/tea packaging	*OTR, Elastic modulus, HDT*	*Fibre spinning, injection moulding, film casting*
Sanitary towels	*Hydrophobicity, Elastic modulus, strain at break*	*Sheet extrusion*
Phase 3		
Tableware	*Elastic modulus, impact resistance, melt flow index*	*Injection moulding*
Plastic bags	*Elastic modulus, Strength, Tear strength*	*Film blowing*
Polyester based clothing	*Strength, HDT, Abrasion resistance*	*Fibre spinning*
Phase 4		
Dry food packaging	*WVTR, OTR, Melt strength*	*Film blowing*
Liquid beverage packaging	*WVTR, Modulus, Melt strength*	*Blow moulding*
Rigid plastic products	*Elastic modulus, Strength, Impact Resistance*	*Injection moulding*

4.1 Phase 1 – biodegradation required, mechanical, thermal or optical properties not critical

A first target group for PHA based applications can be found in products that need a biodegradable component, but do not require this component to have any other critical mechanical, thermal or optical properties. This can typically be the case when the PHA polymer is used in a composite application where other materials are responsible for these properties, (coatings, binders) or when the PHA is dispersed into solid or liquid mixture as a functional additive. Products that could benefit from the addition of a PHA polymer are typically biodegradable itself but need certain plastic/polymer features to increase their performance. A clear example of such a material is paper/cardboard which is also covered in the examples below. In the case of dispersed additives, PHAs are either a logical choice because the overall mixture ends up in the natural environment (e.g., home & personal care products) or the microbial affinity (e.g., biodegradation) is crucial for the overall material performance.

Example product 4.1.1.: Water resistant paper coating (for beverage containers)
From an environmental and circular point of view, paper-based solutions are often selected over plastic alternatives in beverage containers such as coffee- and teacups. However, for an optimal performance, a plastic liner or coating is often crucial as paper itself has very poor water resistance. PE coatings are the most conventional solutions for this application, but it comes at the expense of a severely reduced recyclability as removal of the coating is difficult. By using PLA as an alternative, a full industrial compostable solution is obtained. By using PHA polymers as paper coatings, biodegradation in the natural environment (and home-composting) is added to the suitable end-of-life scenarios. In addition, it is likely that the coating will no longer be the determining factor in the accumulation of these products in the natural environment upon littering, as is the case for the current state of the art PE coatings.

<u>Governing properties</u>
The most important property for these coatings is obviously the ability to retain moisture, which can be quantified by the hydrophobicity of the materials. In addition, the glass transition temperature needs to be outside the range of temperatures that are used during the application. Finally, the processability of the polymer onto the paper product is of importance and will largely govern the applicability as well. These (indicative) parameters are reflected for both the SOTA materials as the selected PHAs in Table 3-1 to Table 3-8.

Table 4-2 Overview of state of the art (SOTA) materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Hydrophobicity	Glass transition temperature [˚C]	Extrusion coating/dispersion coating
HDPE	High	-110	Possible

Table 4-3 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Hydrophobicity	Glass transition temperature [˚C]	Extrusion coating/dispersion coating
CjBio PHA M2300	Medium	-10	Possible
Enmat Y1000	Medium	2	Possible
Aonilex X131A	Good	2	Possible
Aonilex X151A	Good	0	Possible
PB test grade	*Good*	*-3*	*Possible*

Table 4-4 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Hydrophobicity	Glass transition temperature [˚C]	Extrusion coating/dispersion coating	Producers
PLA	Medium	60	Film casting possible	Natureworks, Total Corbion
PBS	Medium	-30	Film casting possible	PTTMCC, Ecoworld
PBAT	Medium	-30	Film casting possible	BASF

<u>Application assessment: PHA plastics match the properties required for this application</u>
Based on the data in the tables above it can be stated that all PHA compounds could serve as a functional coating for paper-based beverage containers. The currently used PE has hydrophobicity that is superior to that off all PHA types. However, since other biodegradable polymers with a comparable hydrophobicity are already used for this application and the hydrophobicity of PHAs is typically higher than many other biobased polymers, this is not considered to be showstopper. The glass transition temperature of all compounds is located around 0°C which might pose a problem for cold served

beverages. For hot beverages such as coffee and tea, no problems are envisioned. However, the glass transition temperature of PBS and PBAT are located at a more favorable temperature region. The glass transition temperature of PLA is in principle unfavorable for hot beverages, but by using stereo-complex PLA morphologies an increased thermal resistance is shown. The required processing operations for these coatings are anticipated to be possible for all studied PHA compounds.

Example product 4.1.2.: Paper/cardboard adhesives
Asides to paper coatings, polymers are also used as binder material for paper and cardboard products. A typical binder combination is based on poly acrylates and polyurethanes which are not biodegradable and partially biobased at most. By using PHA materials as binding agents, the overall industrial and home compostability of these products can be enhanced and the biobased content will be increased.

Governing properties
Prerequisites for the use of PHA as paper/cardboard binders is that they possess sufficient tack and that the glass transition temperature is not located in the application temperature range. A change in Tg might be accompanied with a loss of adhesive properties.

Table 4-5 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Tack	Glass transition temperature [˚C]	Hotmelt application
EVA	Good	-25 [66]	Good
Starch based	Good	n.a.	Good

Table 4-6 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Tack	Glass transition temperature [˚C]	Hotmelt application
CjBio PHA M2300	Good	-10	Likely, not tested
Enmat Y1000	Low	2	Likely, not tested
Aonilex X131A	Low	2	Likely, not tested
Aonilex X151A	Medium	0	Likely, not tested
PB test grade	*Good*	*-3*	*Likely, not tested*

Table 4-7 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Tack	Glass transition temperature [˚C]	Hotmelt application	Producers
Starch based	Good	n.a.	Good	Multiple companies (e.g. Novamont, Rodenburg)
PLA dispersions	Medium	55	Likely not tested	Total Corbion, Natureworks

Application assessment: PHA plastics approach the properties required for this application
In the current study, it is complex to make an accurate prediction on the use of specific PHA types in hotmelt applications. This is because the qualitative data on tack of the PHAs and their applicability as hotmelts is not available. In general, it is anticipated that this set of properties is most likely to be met by PHAs with longer sidechains (mcl & lcl PHAs) and/or high co-monomer loadings as these are typically classified as tacky and tough materials. Hence, the M2300 and the Paques test grade are considered as the most likely candidates for this application type compared to the other PHA grades included in this study. The glass transition temperature of these grades is also relatively low (sub-

zero), but for some cardboard applications (e.g., food containers for the freezer) this might still pose a problem. The current SOTA solutions, but also PLA dispersions will allow for a larger temperature usage window. Therefore, they might be the more favorable solutions, as long as biodegradation is not the desired EOL scenario for these products.

Example product 4.1.3.: Home/personal care additive

Polymers and plastics are present as dispersed additives in many home & personal care products. The most often used plastic type in this application is polyethylene [67]. Visible examples can be found in for example peeling, encapsulated fragrances and scrubbing products. Most often they are dispersed in microplastic form in order to introduce a certain absorption function into the product. After use of these products the additives will end up either in the wastewater treatment or in the natural environment.

Governing properties

In any case, it will be highly beneficial if these waste products will biodegrade after disposal and PHA polymers can introduce this property in these products. Currently the Nafigate Corporation is highly active in the development of PHB for cosmetic applications (www.nafigate.com).

Application assessment: potential for PHA plastics, but should be assessed case by case.

As the desired functions of the additives will greatly vary for each application, applicability must be assessed case by case, as no PHA type will be explicitly suitable for this type of application. However, the fact that PHA is biobased, made by microbial processes and biodegrades in nature might be perceived as a unique selling point and hence might be used for explicit marketing of these products.

Example product 4.1.4.: Home-compostable blend component

One of the most impactful properties of plastics in general is that they can be melt processed together with other plastics and/or additives with relative ease compared to other material classes such as ceramics and metals. This melt blending allows for tuning of the thermal, chemical and mechanical properties of plastics. This concept can and is also be applied for biobased and biodegradable polymers (e.g. for improving the toughness of certain PHA grades). For biodegradable polymers it can even be used to promote the disintegration of a plastic compound in a specific environment. In general, the quality of a polymer blend is determined by the miscibility of the individual components. Typically, polymers with similar chemical linkages and sidechains blend better than combinations that have a very different chemical nature. As an example, polyolefins tend to mix very poorly with polyesters.

Governing properties and application assessment: high potential for PHA plastics

Different types of PHA, showing similar chemical nature, will typically yield good blends upon mixing with each other. A promising development route that is currently explored in industry (e.g. by Helian Polymers) is the blending of highly crystalline PHAs with highly amorphous PHAs which leads to compounds with very balanced properties negating many of the negative properties of the individual components. All PHA types investigated in this study might be suitable to be used as blend component. Further research and development needs to be performed in order to find the most suitable combinations and determine whether these combined materials are favorable compared to homogeneous polymer alternatives. The latter is important as homogeneous systems will pose a clear advantage if collection, separation and recycling into new products is a required EOL route.

Example product 4.1.5.: Fertilizer coating

Fertilizer coatings are used to facilitate the controlled release of fertilizer into agricultural soils, which enables the fertilizer to become more effective and efficient over a longer period. As fertilizers tend to be highly water soluble by nature, polymer resins that have high water retention and can be applied at low temperatures in order sustain the fertilizer functionality, are most often used. Examples can be polyurethane and acrylic thermoset resins. A clear disadvantage of these materials is that they will persist in the soil as microplastic after use. Therefore, the European Union has announced legislation that will restrict the use of such persistent fertilizer coatings by means of regulation 2019/1009 [68]. This regulation states that per 2026 all fertilizer coatings will need to fulfill a specific set of biodegradation criteria (which will be defined in 2024). Although the exact criteria remain unclear it is thereby certain that the current SOTA will no longer be allowed and therefore this market segment needs a biodegradable alternative. PHA materials are a logical candidate to be considered due to their high biodegradable nature.

Governing properties

As the primary function of the fertilizer coating is to protect the product from moisture, a certain hydrophobicity is required. In addition, the application temperature of the coating should be low enough to not diminish the functionality of the coating. Compared to low temperature (<80 °C) curable thermoset resins, this poses a disadvantage for thermoplastic polymers which most often are processed at temperatures higher than 100°C. The permanent crosslinks of thermoset resins are in general not biodegradable, so it seems likely that a certain optimum between functionality and processability needs to be found for this product category. When this product category switches from thermoset to thermoplastic polymers this will automatically impact the current production processes in place. Hence it becomes difficult to make a comparison on this aspect. Nevertheless, it is anticipated that a low viscosity during application/melt processing will be a favorable characteristic and therefore the melt flow index is included in this analysis as well.

Table 4-8 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Hydrophobicity	Melting temperature temperature [˚C]	Melt flow index (g/10min)
PUR	High	Not applicable	Not applicable
Acrylate resin	High	Not applicable	Not applicable

Table 4-9 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Hydrophobicity	Melting temperature temperature [˚C]	Melt flow index (g/10min)
CjBio PHA M2300	Medium	119	10
Enmat Y1000	Medium	176	10.7 (±0.4) (@180°C)
Aonilex X131A	Good	145	2.0 (±0.3) (@170°C)
Aonilex X151A	Good	126	3.3 (±0.3) (@170°C)
PB test grade	*Good*	*165 (trajectory peak)*	*0,36 (±0.0) (@170°C)*

Table 4-10 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Hydrophobicity	Melting temperature temperature [˚C]	Melt flow index (g/10min)	Producers
PCL	Good	60	15	Perstorp/Ingevity
PBSA	Good	115	5	PTTMCC, Ecoworld

Application assessment: potential for PHA plastics, but other biodegradable polymers show a better match

Aside from the biodegradation characteristics of the investigated PHA materials, their hydrophobic nature compared to other polyesters makes them interesting candidates for this application type. In that respect those PHAs with longer sidechains (PHBH types) and high co-monomer content (Paques Biomaterials test grade) pose interesting candidates. However, these materials are also characterized by a low melt flow index which might make mixing procedures more complex. Finally, the melt temperature of all the investigated PHAs is above 100°C degrees. This temperature is substantially higher than conventional thermoset curing conditions so functionality of the fertilizer might be diminished, but this should be further studied per specific application. In this respect polycaprolactone

(PCL) and polybutylene succinate adipate (PBSA) might be more favorable thermoplastic polyester alternatives as their melting temperature is typically lower than that of PHAs.

4.2 Phase 2 – biodegradation required, critical properties

A second target group of PHA based applications are those that require biodegradation in order to improve their performance, but also require properties of non-biodegradable plastics to fulfill their primary function. This will be the case for applications that are intentionally placed in a natural environment in which they fulfill a certain function for a certain period, but can no longer (or with great difficultly) be removed once this function has been fulfilled. Example products can be agricultural plastics or ocean reef structures. Another type of application that falls in this category are food containers or sanitary products that, during use, are contaminated to such an extent that the product can no longer effectively be recycled. This makes (industrial) composting the preferred end-of-life option. Several example products and the potential of the selected PHA grades in these applications are described below.

Example product 4.2.1.: Agricultural mulch films

Plastic mulch films are a commonly used in open field agriculture crop growth processes as they are able to alter and optimize the microclimate of the soil in which specific crops are embedded. Especially low-density polyethylene (LDPE) films have a long-standing history of being an effective material for mulch films and it is currently still considered to be the state of the art for this application [69, 70]. However, the largest disadvantage of LDPE mulch films is the relatively high amount of both macro and micro plastic leakage into the environment due to inadequate cleaning, disposal and recycling. Since LDPE is not biodegradable these plastics will accumulate in the soil and remain in the environment for multiple decades or even centuries. An initial solution was sought in the development of oxo-degradable PE. However, these types of plastics are highly suspected to only disintegrate into smaller (non-visible) fractions while remaining in the environment in the form of microplastics. As a result, the use of oxo-degradable plastics has been forbidden in all applications within the European Union per July 2021 [71]. Soil biodegradable plastics such as PHAs could serve as an actual sustainable alternative material for this application as they are converted into water, carbon dioxide and minerals upon exposure to soil environments.

Governing application properties

In order to compete with the current state of the art PHA polymers will have to show a performance that is competitive with PE. The most important property of a mulch film is to create a physical barrier between the soil and the external environment. In order to maintain this barrier for the required amount of time for crop growth, sufficient strength and UV resistance is required. Furthermore, mulch films need to have a certain flexibility (elastic modulus) to be effectively applied and film casting or, more preferred, film blowing should be possible for production. A biodegradable plastic that is currently already commercially offered as a mulch film alternative is PBAT. The tables below outline these properties for the current mulch films SOTA, the selected PHA compounds and the most relevant biobased and biodegradable alternatives.

Table 4-11 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Tensile strength (MPa)	UV resistance	Young's Modulus (MPa)	Film blowing/casting
LDPE	40	Medium	200	Possible
PBAT	20	Poor	80	Possible

Table 4-12 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Tensile strength (MPa)	UV resistance	Young's Modulus (MPa)	Film blowing/casting
CjBio PHA M2300	36	Good	800	Film casting possible Film blowing limited
Enmat Y1000	40.1 (±0.2)	Good	3469 (±59)	Film casting possible Film blowing limited
Aonilex X131A	31.3 (±0.2)	Good	1546 (±12)	Film casting possible Film blowing limited
Aonilex X151A	19.8 (±0.3)	Good	796 (±30)	Film casting possible Film blowing limited
PB test grade	*16.9 (±0.2)*	*Good*	*665 (±13)*	*Film casting and film blowing unexplored*

Table 4-13 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Tensile strength (MPa)	UV resistance	Young's Modulus (MPa)	Film blowing/casting	Producers
PBS(A)	30-40	Good	300-600	Film casting possible Film blowing limited	PTTMCC, Ecoworld
PCL	30	Good	450	Film casting casting possible, film blowing limited	Perstorp/Ingevity
PBAT	20	Good	80	Possible	BASF
Starch compounds	Depends on specific compound	Depends on specific compound	Depends on specific compound	Depends on specific compound	Multiple companies (e.g. Novamont, Rodenburg)

Application assessment: potential for PHA plastics

Comparing the SOTA properties with the selected PHA materials, it appears that all materials might be too stiff for the given application. However, the Paques Biomaterials test grade and the Aonilex 151A might still be considered as mulch films as their properties are relatively close to that of the SOTA materials. Still, for the Paques Biomaterials test grade the processability into sheets and or film materials needs to be proven. This might be complex due to the anticipated broad melting trajectory that is typically accompanied with mixed culture PHA materials. However, with PBAT there is already a soil-biodegradable material film material on the market that is considered to be the state of the art. Therefore, for PHA materials to enter this market the added value needs to come from the biobased nature and possible faster biodegradation rates of PHA compared to PBAT.

Example product 4.2.2.: Plant plugs

Plant plugs are used as substrates in which plant seedlings are placed in order to assist and support them during their early phase growth. They can come in different forms such as small injection moulded containers or netting. In order to remain comprehensive, the focus in this chapter is put on container-based products. After the initial growth phase, the root structure of the plant takes over the functionality of the plant plug. As a result the plant plug is no longer necessary. As they are typically placed in soil and in some cases have plant roots integrated in the plant plug structure, it is complex and labour intensive to fully remove the plugs at this point in time. Consequently, these products often remain in the soil environment. As this contributes to soil plastic pollution, biodegradable alternatives could pose an effective alternative both from an economical and environmental point of view.

Governing application properties

The current state of the art for these products is based on polypropylene plastics which are typically processed via injection moulding (containers). As their primary function is to create support, mechanical properties such as stiffness (modulus) and strength are anticipated to be most crucial. For processing of the net structures sufficient melt flow is required. The tables below outline these properties for the current plant plug SOTA, the selected PHA compounds and the most relevant biobased and biodegradable alternatives.

Table 4-14 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Strength (MPa)	Elastic modulus (MPa)	Melt Flow Index (g/10 min)	Injection Moulding
PP	25-35	1500-1800	35	Possible

Table 4-15 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Strength (MPa)	Elastic modulus (MPa)	Melt Flow Index (g/10 min)	Injection Moulding
CjBio PHA M2300	36	800	10	Possible
Enmat Y1000	40.1 (±0.2)	3469 (±59)	10.7 (±0.4) (@180°C)	Possible
Aonilex X131A	31.3 (±0.2)	1546 (±12)	2.0 (±0.3) (@170°C)	Possible
Aonilex X151A	19.8 (±0.3)	796 (±30)	3.3 (±0.3) (@170°C)	Possible
PB test grade	*16.9 (±0.2)*	*665 (±13)*	*0,36 (±0.0) (@170°C)*	*Potential limitations for large and thin products*

Table 4-16 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Strength (MPa)	Elastic modulus (MPa)	Melt Flow Index (g/10 min)	Injection Moulding	Producers
PBS/PBSA	30-40	300-600	4	Possible	PTTMCC, Ecoworld
Starch compounds	Depends on specific compound	Depends on specific compound	Depends on specific compound	Depends on specific compound	Multiple companies (e.g. Novamont, Rodenburg)

Application assessment: potential for PHA materials with adequate flow properties

When comparing the properties of the selected PHA materials with the SOTA materials, the Aonilex X131A grade seems to be a good biobased and biodegradable alternative for polypropylene based plant plug containers. A limiting factor for this material might be the low melt flow properties, but it is anticipated that this can be modified using additives to an extent that is suitable for this application. Enmat Y1000 and CjBio M2300 might be considered as well as their melt flow index is an order of magnitude higher, but in this case a compromise on the stiffness of the product needs to be made. In the case of CjBio M2300 the lack of stiffness could be solved by the addition of reinforcing filler material. The other PHA materials (X151A and Paques Biomaterials test grade) seem to be less relevant candidates for this application.

Example product 4.2.3.: Agricultural netting

Agricultural and horticultural netting is widely used to improve crop quality, increase yield and reduce labour during harvesting. In line with the mulch films and plant plugs, a major drawback of the plastic netting is their disposal; currently used non-biodegradable plastics, like (oxo-degradable) polyethylene and polypropylene, can accumulate in soil as visible and invisible plastic waste. Recycling of the plastic netting is labour intensive and difficult because nets are highly contaminated with or even fully grown into soil and organic materials. In recent years, biobased and biodegradable nets have been developed on a commercial level with main applications in food packaging. These nets do not, however, satisfy performance requirements for horti- and agriculture applications such as grass turf growing.

Governing application properties

Due to their versality PHAs could potentially serve as a suitable alternative for the currently employed non-biodegradable plastics. Asides from a certain strength that the nets should possess the processing of the polymer is considered to be the most crucial design parameter. As such, sufficiently high melt strength is crucial. In addition, the plastics need to be processed via net extrusion, which is a complicated processing operation that involves multiple different high-demanding steps.

Table 4-17 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Strength (MPa)	Melt Strength (mN)	Net extrusion
PP	25-35	>50	Possible

Table 4-18 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

PHA type	Strength (MPa)	Melt strength (mN)	Processing options
CjBio PHA M2300	36	n.a.	N.a.
Enmat Y1000	40.1 (±0.2)	Too low to measure	Unexplored
Aonilex X131A	31.3 (±0.2)	20.6 (±6.5)	Unexplored
Aonilex X151A	19.8 (±0.3)	4.5 (±1.2)	Unexplored
PB test grade	*16.9 (±0.2)*	*278.0 (±8.9)*	*Unexplored*

Table 4-19 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

Identified biobased and/or biodegradable plastic alternatives	Strength (MPa)	Melt strength (mN)	Processing options	Producers
PBS/PBSA	30-40	>50	Net extrusion possible	PTTMCC, Ecoworld
PBAT	20	>25	Net extrusion possible	BASF
PLA	80	>30	Net extrusion possible	Total Corbion, Natureworks

Application assessment: PHA plastics do not match application requirements

Based on the identified PHA properties the Aonilex X131A matches the required strength and has a decent melt strength for a PHA material. The latter is nevertheless expected to be insufficient for the net extrusion process. The Paques Biomaterials test grade has a high melt strength that meets the initial requirements for net extrusion. But for this material, the tensile strength is too low to match the current SOTA. The characteristics of the M2300 grade by CjBio that are relevant for this application are not known and no recommendation can therefore be made. In general, the feasibility of net extrusion for PHAs is a currently non-investigated topic and therefore it is difficult to draw conclusions on this specific parameter. When other biodegradable polymers are considered for this application, it becomes apparent that PBS/PBSA based compounds are most likely a more logical fit for this application.

Example product 4.2.4.: Artificial reef structures

Artificial reef structures are designed to support and assist the growth of marine animals such as mussels and oysters or coral polyps in regions where the natural environment of these animals needs to be restored. A recently emerging example can be found in off-shore wind farms where the marine surface in between the wind turbines allows for relatively sheltered growth options for these creatures. This was not possible in the past decades due to extensive fishery or heavy sea transport. In general, the restoration of coral reefs requires worldwide attention as it one of the most important protection mechanisms of coastal areas against heavy floods and tsunamis. In order for these natural reef structures to grow effectively a substrate is necessary on which the first larvae can settle and grow. Once the growth process is in progress, the marine fauna will produce their own natural structures and the artificial reef structure loses its functionality. At this point in time, it would be highly beneficial if the artificial reef biodegrades in the marine environment as removal of the structure would destroy the newly created ecosystem. However, currently these structures are made from concrete which will persist many decades after serving its functional life. Marine biodegradable materials such as PHAs could serve as potential alternative provided the degradation time can be matched with the required lifetime of the structures. Since marine biodegradability is one of the unique selling points of PHAs there are few plastics that could serve as an alternative.

Governing application properties

Asides from (tuned) biodegradability, the main assessment parameters would be material stiffness and the affinity of the larvae to settle on the material. Injection moulding seems the most obvious processing operation for production of these type of products.

Table 4-20 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Elastic modulus (MPa)	Larvae settlement	Injection moulding
Concrete	30000-50000	Good	Not possible

Table 4-21 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Elastic modulus (MPa)	Larvae settlement	Injection moulding
CjBio PHA M2300	800	Unknown	Possible
Enmat Y1000	3469 (±59)	Unknown	Possible
Aonilex X131A	1546 (±12)	Unknown	Possible
Aonilex X151A	796 (±30)	Unknown	Possible
PB test grade	*665 (±13)*	*Unknown*	*Potential limitations for large and thin products*

Table 4-22 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Identified marine biodegradable plastic alternatives	Elastic modulus (MPa)	Larvae settlement	Injection moulding	Producers
PGA	7000	Unknown	Possible	PJChem

Application assessment: potential for PHA plastics
Of the PHA materials investigated in this study, the highest theoretical fit for this application is with the Enmat Y1000 grade as it has a high elastic modulus compared to other PHA materials. The modulus is however still an order of magnitude lower than that of concrete, but this can potentially be overcome with the use of (non-toxic) filler material. Furthermore, it might very well be that a modulus of more than 30 GPa is not necessarily required for this application. Another marine biodegradable plastic that has an intrinsically high modulus and could therefore be considered for this application is polyglycolic acid (PGA). Finally, the affinity of the PHA materials and other biodegradable plastics with the specific larvae has not yet been investigated and is crucial for successful usage in this application.

Example product 4.2.5.: Coffee/tea packaging

Coffee and tea are typically are sold in powder or fibrous form and often processed into their intended liquid beverages whilst being in their packaging product. This is the case for tea bags and coffee pads and capsules. Since tea and coffee itself are preferably processed via the organic waste streams, and this form of packaging and processing restricts effective separation of package and product, it would be advantageous to enable coffee and tea to be processed via composting EOL route with their packaging. In the Netherlands this insight has, in April 2021, led to the signing of a Green Deal on the transition towards compostable tea bags and coffee pads. The ambition is to have 75% of this packaging type compostable by the end of 2021 which will then be followed by officially approving the disposal of these products with organic waste in the Netherlands [72]. As PHA polymers are both industrial and home compostable, this is a highly relevant market for PHA polymers to access. Coffee capsules have not (yet) been included within this deal, but seem to be a logical next step within this process. However, these capsules have more stringent requirements on barrier properties, but as PHA polymers typically have good oxygen barrier properties compared to other compostable plastics and polyolefins (PE, PP), this could actually pose an opportunity for the market growth of PHA materials. Even though not yet included in the Green Deal, several coffee capsule producers (e.g. Capsul'in) have started with exploring the use of PHA polymers within their capsule and first results seem promising.

Governing application properties
In addition to the barrier properties of the packaging, it is important that it can withstand the thermal process that is applied on the product during the preparation of coffee and tea. In this respect, the heat deflection temperature (HDT-B) is a good quantification value to assess the material stability during hot water exposure. Finally, the elastic modulus is a relevant parameter as sufficient stiffness is required for these application (especially for the coffee capsules).

Table 4-23 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	Elastic modulus (MPa)	HDT-B (°C)	Fibre spinning, injection moulding, film casting
PP	500	1500-1800	90	All options possible
Cellulose	>1000	n.a.	n.a.	Fibre spinning possible
PLA	150	3600	55	All options possible

Table 4-24 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	Elastic modulus (MPa)	HDT-B (°C)	Fibre spinning, injection moulding, film casting
CjBio PHA M2300	N.a.	800	n.a.	Injection moulding and film cassting possible, fibre spinning unexplored
Enmat Y1000	5.5 (±0.3)	3469 (±59)	141 (±0.2)	Injection moulding and film cassting possible, fibre spinning unexplored
Aonilex X131A	11.6 (±0.0)	1546 (±12)	97.4 (±1.9)	Injection moulding and film cassting possible, fibre spinning unexplored
Aonilex X151A	7.9 (±0.8)	796 (±30)	65.8 (±2.5)	Injection moulding and film cassting possible, fibre spinning unexplored
PB test grade	*N.a.*	*665 (±13)*	*54.0 (±0.3)*	*Injection moulding potentially limited for thin and large products. Film casting and fibre spinning unexplored*

Table 4-25 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	Elastic modulus (MPa)	HDT-B (°C)	Fibre spinning, injection moulding, film casting	Producers
PBS	150	600	85	All options possible	PTTMCC, Ecoworld
PLA	150	4000	55	All options possible	Total Corbion, Natureworks

Application assessment: potential for PHA plastics provided the processing is possible

The protection of coffee and tea from the surrounding environment (i.e. air) is one of its most important properties. Compared to the current SOTA, PHA materials have a clear advantage on this performance indicator. Their oxygen transmission rate is typically higher than the current SOTA and other biodegradable polyesters in general. In addition, the modulus and HDT values of the Enmat Y1000 and especially the Aonilex X131A match the current PP SOTA values. The other PHA materials investigated have less optimal properties and therefore seem less logical candidates for this application. This makes that these materials are particularly interesting candidates for the development of compostable coffee capsules. The potential for the development of coffee pads or tea bag fibers will be highly dependent on the ability to process these materials via fibre spinning which is currently an unexplored field.

Example product 4.2.6.: Sanitary towels

Sanitary towels, typically used for menstrual hygiene purposes, are an essential product for woman all around the world. EOL life routes range from incineration to landfill, but recycling of this class of product is highly likely due to organic contamination. A compostable solution is therefore a highly anticipated outcome, but the complex nature of the product forestalled that fully biodegradable products have not yet appeared on the market. The complexity mainly stems from the conflicting functionality of the product as it needs to be both moisture absorbent as moisture retaining. As a result multi-material solutions are most often used [73]. A similar complex design problem applies to the development of sustainable diaper products. Towards the development of a compostable sanitary towel (or diaper) starch based materials are being explored by researchers and industrial parties to serve as the superabsorbent component. PHA polymers on the other hand, could be an interesting option for the moisture retaining components in these products as they will biodegrade under composting conditions. This could even open the door to sanitary products that can be disposed via the sewage systems.

Governing application properties

Asides from a certain hydrophobicity for moisture retention and biodegradation the processability into flexible film type structures is deemed important, as these products often come in the form of flexible sheet like materials. This is assessed by the elastic modulus, which should be relatively low, and the strain at break which is a measure for the extent of bending the material can withstand prior to rupture.

Table 4-26 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Hydrophobicity	Elastic modulus (MPa)	Strain at break (%)	Sheet extrusion
PP	High	1500-1800	>100	Possible
PE	High	<1000	>100	Possible

Table 4-27 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Hydrophobicity	Elastic modulus (MPa)	Strain at break (%)	Sheet extrusion
CjBio PHA M2300	Medium	800	n.a.	Possible
Enmat Y1000	Medium	3469 (±59)	1.6 (±0.7)	Possible
Aonilex X131A	Good	1546 (±12)	14.6 (±5.3)	Possible
Aonilex X151A	Good	796 (±30)	12.2 (±2.7)	Possible
PB test grade	*Good*	*665 (±13)*	*359.6 (±79.2)*	*Unexplored*

Table 4-28 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Hydrophobicity	Elastic modulus (MPa)	Strain at break (%)	Sheet extrusion	Producers
PBS/PBSA	Good	300-600	>100	Possible	PTTMCC, Ecoworld

Application assessment: potential for PHA plastics

This application needs a high amount of flexibility and toughness which is typically a disadvantage of PHA materials. This makes that the Enmat Y1000 and Aonilex X131A grade are clearly unsuitable for this application. The CJBio M2300 and Aonilxex X151A have a matching modulus and can be processed into sheets, but their strain at break values are respectively unknown or insufficient. The Paques Biomaterials test grade is characterized with a suitable strain at break and modulus for this application. The processability into sheets of this grade is currently unexplored. Complex processing operations such as sheet extrusion might prove challenging for mixed culture PHA materials as they are expected to have a broader melting trajectory than single culture PHA compounds. However, if good processing is achieved, the Paques Biomaterials test grade could be a good candidate for this application.

4.3 Phase 3 – biodegradation beneficial, critical properties

The third category of products that could be of interest for PHA based plastics is that in which biodegradation can be an unintended, but positive side effect. This could be the case for products that are designed to be recycled (mechanically or chemically), but still have a high risk of being littered and accumulate in nature. Examples of such products are (single-use) tableware, plastic bags and clothing. When PHAs (or other biodegradable plastics) would be used in these applications they will have a positive impact on large societal issues such as soil contamination and the plastic soup. However, introduction of biodegradable polymers in this product category should not yield a net increase of littered products and therefore the recycling potential of the PHAs should be at least as high as the products that are currently used. In addition, it should be noted that use of biodegradable polymers in this product category will only give a small contribution to global waste and litter issues while the real impact is expected to be obtained from optimized design for recycling and reduction of material use in products in general. Nevertheless, it is interesting to evaluate whether the properties of specific PHA products meet the requirements of the products in this category till such an extent that biodegradation can become an asset.

Example product 4.3.1.: Tableware

Plastic tableware such as plates, forks and knifes are often developed for single-use applications due to the combination of lightweight, high strength and low costs. As a result, they became one of the main product categories that became restricted within the market upon the implementation of the EU Single-Use Plastic directive in 2019 [74]. Although this directive restricts the use of all types of plastic for these applications, including biodegradable and biobased options, the EU commission indicated they see the potential that biodegradable alternatives could pose for this type of products. They announced to review this option in 2027. As alternative solutions that are permitted (mainly paper with water resistant additives) are not expected to yield a better performance or are anticipated to be subjected to alternative regulations (e.g. PFAS restrictions), it seems likely that biobased and biodegradable plastics can play a role within this product category. This is, however, under the assumption that these type of products will not be restricted entirely, which might be an alternative outcome of the current legislative developments.

Governing application properties
From a technical point of view PHA polymers could serve as a suitable alternative for these products which are typically made from polypropylene or polystyrene. Most important properties are the elastic modulus, the impact resistance and the ability to be processed via injection moulding which is typically measured by means of the melt flow index (MFI).

Table 4-29 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Elastic modulus (MPa)	Impact resistance (kj/m2)	Melt flow index (g/10min)	Injection moulding
PP	1500-1800	90	35	Possible
PS	3250	20	5	Possible

Table 4-30 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Elastic modulus (MPa)	Impact resistance (kj/m2)	Melt flow index (g/10min)	Injection moulding
CjBio PHA M2300	800	5	10	Possible
Enmat Y1000	3469 (±59)	6.6 (±0.3)	10.7 (±0.4) (@180°C)	Possible
Aonilex X131A	1546 (±12)	37.4 (±6.0)	2.0 (±0.3) (@170°C)	Possible
Aonilex X151A	796 (±30)	67.7 (±13.8)	3.3 (±0.3) (@170°C)	Possible
PB test grade	*665 (±13)*	*>100 (did not break)*	*0,36 (±0.0) (@170°C)*	*Potential limitations for large and thin products*

Table 4-31 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Elastic modulus (MPa)	Impact resistance (kj/m2)	Melt flow index (g/10min)	Injection moulding	Producers
PBS	600	>100 (did not break)	4	Possible	PTTMCC, Ecoworld
PLA	3600	15	<30	Possible	Total Corbion, Natureworks
Starch compounds	Depends on specific compound	Depends on specific compound	Depends on specific compound	Depends on specific compound	Multiple companies (e.g. Novamont, Rodenburg)

Application assessment: properties of PHA plastics match the application, but legislation might be restrictive

This application requires a good balance between sufficient stiffness (modulus) and impact resistance. None of the PHA materials investigated in this study yield a perfect match with the current SOTA properties, but the Aonilex X131A grade comes relatively close and might meet the minimum mechanical requirements for these applications. The other PHA compounds might be suitable upon combination with specific additives to either increase the modulus or the impact resistance. The use of additives for compound optimization is standard practice for tableware applications. Therefore, all PHA materials are potentially interesting candidates to further explore if provided biodegradation actually turns out to be a desired end-of-life route. The same statements apply to other biobased and biodegradable plastics listed in Table 4-21.

Example product 4.3.2.: Plastic carrier bags

Another plastic product that contributes to the global plastic pollution and is therefore included in the EU Single-Use Plastic regulations are the plastic carrier bags. However, as opposed to tableware, plastic carrier bags are not restricted within the market but subjected to extended producer responsibility [74]. This implies that carrier bag producers will be responsible for the EOL fate and waste processing of their products. In that sense, it might be interesting for plastic bag producers to use PHA polymers to add composting as an additional EOL scenario to their products, while at the same time safeguarding the impact their products will have upon the plastic accumulation in nature upon unintended littering on land and sea.

Governing application properties

Plastic carrier bags typically are sealed blown LDPE based films with a thickness of 50 micron or less for which enough flexibility (low modulus), sufficient strength and a high tear strength are crucial.

Table 4-32 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Elastic Modulus (MPa)	Strength at break (MPa)	Tear strength	Film blowing
LDPE	200	40	High	Possible

Table 4-33 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Elastic Modulus (MPa)	Strength at break (MPa)	Tear strength	Film casting & film blowing
CjBio PHA M2300	800	36	Medium	Film casting possible Film blowing limited
Enmat Y1000	3469 (±59)	40.1 (±0.2)	Very low	Film casting possible Film blowing limited
Aonilex X131A	1546 (±12)	31.3 (±0.2)	Low	Film casting possible Film blowing limited
Aonilex X151A	796 (±30)	19.8 (±0.3)	Medium	Film casting possible Film blowing limited
PB test grade	*665 (±13)*	*16.9 (±0.2)*	*Medium*	*Film casting and film blowing unexplored*

Table 4-34 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Elastic Modulus (MPa)	Strength at break (MPa)	Tear strength	Film blowing	Producers
PBS/PBSA	300-600	30-40	Medium	Film casting possible Film blowing limited	PTTMCC, Ecoworld
Starch compounds	Depends on specific compound	Depends on specific compound	Depends on specific compound	Depends on specific compound	Multiple companies (e.g. Novamont, Rodenburg)
PBAT	80	20	Good	Possible	BASF

Application assessment: potential for certain types of PHA plastics

There is a clear analogy between the product requirements for agricultural mulch films and plastic bags. However, the mechanical requirements for plastic bags are more stringent as the product is under a higher mechanical load during use. Hence the tear strength is an important measure, and this is typically a poor performing property of PHA materials. Furthermore, the PHA grades investigated in this study are considered too stiff compared to the LDPE state of the art. Still, the CJBio M2300, Paques Biomaterials test grade and the Aonilex X151A could be further explored for this application as their properties have the best fit. In addition, the processability via sheet extrusion and film blowing needs to be further investigated before this application is further explored. Based on the current development status of biodegradable polymers, PBS/PBSA or PBAT might be the more logical candidates for more sustainable plastic bags.

Example product 4.3.3.: Clothing (polyester based)

In contrast to plastic packaging and single-use products, governmental organizations and society as a whole have given relatively little attention and awareness to the waste that is associated with textile based clothing. However, a substantial part (>50%) of the clothing available on the market is based on polyester (plastic) materials and this is especially true for so-called fast-fashion products. A serious issue with all these polyester based textiles is that upon wear during use and washing procedures, small fragments of these materials end up in the wastewater systems or the natural environment.

Governing application properties

As the most commonly used polyester fibres PET and PTT are not biodegradable in the natural environment they are likely to persist as microplastics for multiple decades or longer. From an environmental point of view PHA polymers could bring a substantial improvement to this product category. In order to realize this sustainability gain the PHA materials will need to be able to compete with PET and PTT on strength, thermal resistance (assessed via HDT-B) and abrasion resistance. The latter property can in general be correlated with the hardness of material. As comparative data on the abrasion resistance is not available as this data is not typically published and the characterization equipment for these experiments is not available at WFBR. Therefore the Shore-D hardness was used as an indicative measure instead.

Table 4-35 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Strength at break (MPa)	HDT-B (°C)	Shore-D hardness	Fibre spinning
PET	70	100	75	Possible
PTT	60	55	75	Possible

Table 4-36 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Strength at break (MPa)	HDT-B (°C)	Shore-D hardness	Fibre spinning
CjBio PHA M2300	36	n.a.	N.a.	Unexplored
Enmat Y1000	40.1 (±0.2)	141 (±0.2)	79.5 (0.4)	Unexplored
Aonilex X131A	31.3 (±0.2)	97.4 (±1.9)	66.7 (0.4)	Unexplored
Aonilex X151A	19.8 (±0.3)	65.8 (±2.5)	54.3 (1.0)	Unexplored
PB test grade	*16.9 (±0.2)*	*54.0 (±0.3)*	*54.0 (0.3)*	*Unexplored*

Table 4-37 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Strength at break (MPa)	HDT-B	Shore-D hardness	Fibre spinning	Producers
PBS	40	85	65	Possible	PTTMCC, Ecoworld
PLA	80	55	80	Possible	Total Corbion, Natureworks

Application assessment: PHA plastic properties do not match application requirements

Compared to PET and PTT all PHA materials investigated in this study show a substantially lower tensile strength. The Enmat Y1000 and the Aonilex X131A grades are in this respect the most performing materials, and this also applies for their measure of thermal resistance (HDT-B) and abrasion resistance (Shore-D hardness). The CJBio M2300 grade has no data available to be assessed on these characteristics. Although the mismatch of properties seems rather small, the spinning of fibres is currently unexplored for all these materials. It is expected that this processing operation for this class of materials will be highly complex as melt strengths are generally low. Furthermore, as both the performance (strength, toughness and thermal resistance during dry cleaning) and processing (spinning of thin fibres) parameters are stringent, and margins are small it is not foreseen that PHA polymers will set foot in this market. If the transition to biodegradable fibers is required PBS and PLA are seemingly more interesting candidates to fill this gap.

4.4 Phase 4 – biobased replacement of fossil-based plastics

The final category of applications that might be considered as a potential offset market for PHA polymers are plastic products that are not expected to gain any benefits from biodegradation. The main reason for PHA implementation lies in the reduced CO_2 emissions that are accompanied by using biobased and/or waste feedstocks. This category is comprised of products that typically have effective closed-loop recycling schemes (food and drinks packaging) or have such long product lifetime that recycling is not relevant to begin with (toys and home appliances). Within this category of products, PHA polymers will need to compete with both fossil based plastics and other biobased plastics with no or less favorable biodegradation characteristics.

Example product 4.4.1.: Dry food packaging

Dry food products such as crisps, candy, cookies or grounded coffee are typically packed in multilayer films that deliver the combination of superior gas and moisture barrier properties that is crucial to give these products the shelf life they require.

Governing application properties

The moisture barrier (WVTR) and gas (OTR) requirements are often so high that full plastic solutions based on PE and EVOH are not always sufficient. For example, aluminum layers need to be applied to create additional functionality. Separation and recycling of these multilayer structures is highly complex. As a result, they are often incinerated. Nevertheless, in the transition towards a circular economy it is foreseen that (mechanical or chemical) recycling is the most suitable EOL option for these products. Furthermore, as these packages are often thin multilayer materials, a sufficient melt strength is required for optimal processing.

Table 4-38 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	WVTR (g*100 µm/m2/day) 23C, 85% RH	Melt Strength (mN)	Film casting/laminating
PE-PET aluminium multilayer	<0.1	<0.1	N.a.	Possible
PE monolayer	1000	1	>100	Possible

Table 4-39 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	WVTR (g*100 µm/m2/day) 23C, 85% RH	Melt Strength (mN)	Film casting/laminating
CjBio PHA M2300	N.a.	N.a.	N.a.	Possible
Enmat Y1000	5.5 (±0.3)	22.4 (±1.2)	1.6 (±0.7)	Possible
Aonilex X131A	11.6 (±0.0)	70.6 (±0.6)	14.6 (±5.3)	Possible
Aonilex X151A	7.9 (±0.8)	127.4 (±127.4)	12.2 (±2.7)	Possible
PB test grade	*N.a.*	*N.a.*	*359.6 (±79.2)*	*Unexplored*

Table 4-40 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	OTR (cm3*100 µm /m2*bar*day) 23C, 85% RH)	WVTR (g*100 µm/m2/day) 23C, 85% RH	Melt strength (mN)	Film casting/laminating	Producers
Biobased PE	1000	1	>100	Possible	Braskem
PLA	180	35	>30	Possible	Total Corbion, Natureworks
PBS	100	35	>50	Possible	PTTMCC, Ecoworld
PBAT	500	25	>25	Possible	BASF

Application assessment: potential for certain types of PHA plastics

Compared to the current state of the art, PHA polymers could bring the advantage of being fully biobased, although biobased PE may be the more logical sustainable alternative as this is chemically identical to the current SOTA. The category of dry food packaging that could be a good fit for PHA polymers can be found in those products that have a high risk of ending up in the nature due to littering. An example could be single portion bread or crisp products. Compared to the current SOTA, the WVTR properties of the investigated PHAs are not at the level of PE, while their OTR is substantially higher. Compared to other biodegradable polyesters, the OTR of PHAs is typically an order of magnitude higher. However, the barrier properties of PHAs are not yet sufficient to fulfill the product requirements as a stand-alone material. Therefore, co-development of a fully biodegradable gas barrier layer is necessary before this implementation route can become a feasible alternative for the current SOTA. The PHA polymer would then replace the PE material in these products and will need to perform on the same level when it comes to the moisture barrier, elasticity and toughness of these plastics. The big unknowns in this analysis are the CjBio M2300 and the Paques Biomaterials test grade, as their barrier properties are unknown. The melt strength of the Paques Biomaterials test grade is substantially higher than that of the other investigated PHAs, so it is of high interest to investigate the barrier properties of this grade in order to assess the applicability for this specific application.

Example product 4.4.2.: Liquid beverage packaging

Plastic bottles have become the global packaging standard for non-alcoholic beverages in the past decades as they combine lightweight, mechanical strength and sufficient moisture and gas barrier performance. The SOTA material in this product category is fossil based PET. One of the main advantages of PET is that it is not as easily contaminated (specifically in refund schemes) compared to PE and PP which makes that PET bottles can be recycled at a high efficiency. In the transition towards a circular materials economy, the substitution of PET by biobased alternatives has received much attention. PET itself can only be partially produced biobased as a biobased alterative of one of its monomers (PTA) has not yet been developed on an economically feasible scale. PEF has been developed as a fully biobased alternative but is currently not yet available within the market.

Governing application properties

The barrier properties of PEF are seemingly better than PET, but the thermal and mechanical stability after multiple lifecycles still needs to be addressed. Based on material performance, costs and the already existing recycling infrastructure for PET, this market does not present itself as a logical target market for PHA polymers. The exception could, as is the case for dry food packaging, be in the specific market for single-use bottles that have a risk to be littered. Still, these products will also still be designed for recycling and their product performance. This means that PHA polymers will need to be competitive with PET on all performance indicators (stiffness, moisture barrier, melt strength and processing via blow moulding) before the biodegradable characteristics can become an additional asset.

Table 4-41 **Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.**

SOTA Material	WVTR (g*100 µm/m2/day) 23C, 85% RH	Elastic modulus (MPa)	Melt Strength (mN)	Blow moulding
PET	50	3000	>50	Possible

Table 4-42 **Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.**

PHA type	WVTR (g*100 µm/m2/day) 23C, 85% RH	Elastic modulus (MPa)	Melt Strength (mN)	Blow moulding
CjBio PHA M2300	N.a.	800	N.a.	Possible
Enmat Y1000	22.4 (±1.2)	3469 (±59)	1.6 (±0.7)	Unexplored
Aonilex X131A	70.6 (±0.6)	1546 (±12)	14.6 (±5.3)	Possible
Aonilex X151A	127.4 (±127.4)	796 (±30)	12.2 (±2.7)	Possible
PB test grade	*N.a.*	*665 (±13)*	*359.6 (±79.2)*	*Unexplored*

Table 4-43 **Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.**

Biobased and/or biodegradable plastic alternative	WVTR (g*100 µm/m2/day) 23C, 85% RH	Elastic modulus (MPa)	Melt Strength (mN)	Blow moulding	Producers
Biobased PET	50	3000	>50	Possible	Indorama
Biobased PE	1	1200	>5	Possible	Braskem
PEF	> PET	2500	N.a.	Possible	Avantium
PLA	180	3600	>30	Possible	Total Corbion, Natureworks

Application assessment: potential for certain types of PHA plastics

PHA materials have already been successfully converted into beverage bottle products and have set foot on the market. Upon comparing the target PHAs in this study with those of PET it becomes clear that the most crucial properties are in the same order of magnitude. Enmat Y1000 shows WVTR and modulus values that come most close to that of PET, but its melt strength seems insufficient. The Aonilex X131A performs better on melt strength but must settle on modulus and WVTR. Depending on the beverage that is packed and complexity of the bottle, this set of properties might still be acceptable for the market. The elastic modulus of the other target PHAs appears to be too low to be relevant for this application. Alternative biobased polymers that could be considered for this application, listed in Table 4-31, such as biobased PET and PEF have a better fit based on the properties assessed in this study, but do not bring the potential additional benefit of being biodegradable in various natural environments.

Example product 4.4.3.: Durable rigid plastics (toys and home appliances)

Most plastic product covered in this study have a relatively short lifecycle that comprises of a couple of months at a maximum. However, a lot of plastic consumer products are more durable which is a direct consequence of their mechanical rigidity. Home appliances, plastic furniture and toys are examples of products that fall within this category. In addition, these products can technically be recycled with a high efficiency provided and end up in the right waste stream. As a result, biodegradability is not a key requirement for these products and will probably cause problems depending on the application environment (e.g. garden furniture).

Governing application properties

Polypropylene and ABS are plastic types that are often used in these applications and therefore selected as the reference material in this broad product category. Other frequently used plastics are polycarbonates and PVC. Sufficient mechanical stiffness, strength and impact resistance are the crucial properties that contribute to their durability. Processing is typically performed by means of injection moulding. If PHA polymers show similar performance on these aspects, then the biobased nature of PHA polymers could be a way to increase the sustainability of these products.

Table 4-44 Overview of state of the art materials for this application. Properties listed are indicative and based on publicly available literature.

SOTA Material	Modulus (MPa)	Strength at break (MPa)	Impact resistance (kj/m2)	Injection Moulding
PP	1500-1800	25-35	90	Possible
ABS	2300	45	180	Possible

Table 4-45 Properties of the selected PHA materials relevant for this application. Properties listed are measured at WFBR or copied from publicly available datasheets.

PHA type	Young's Modulus (MPa)	Strength at break (MPa)	Impact resistance (kj/m2)	Injection Moulding
CjBio PHA M2300	800	36	5	Possible
Enmat Y1000	3469 (±59)	40.1 (±0.2)	6.6 (±0.3)	Possible
Aonilex X131A	1546 (±12)	31.3 (±0.2)	37.4 (±6.0)	Possible
Aonilex X151A	796 (±30)	19.8 (±0.3)	67.7 (±13.8)	Possible
PB test grade	*665 (±13)*	*16.9 (±0.2)*	*>100 (did not break)*	*Possible*

Table 4-46 Overview of biobased and/or biodegradable alternatives for this application. Properties listed are indicative and based on publicly available literature.

Biobased and/or biodegradable plastic alternative	Modulus (MPa)	Strength at break (MPa)	Impact resistance (kj/m2)	Injection Moulding	Producers
Biobased HDPE	1200	30	>100 (did not break)	Possible	Braskem
PLA	3600	60	15	Possible	Total Corbion, Natureworks

Application assessment: potential for PHA plastics, but other biobased polymers might be preferred

Comparing the governing properties of the target PHA materials with those of PP and ABS it becomes clear Aonilex X131A shows a good fit. However, the impact resistance is slightly lower which might pose problems for this category of products as they show a lot of motion in use and thereby risk events of impact (e.g. toys dropped on the floor). In this respect, the Paques Biomaterials test grade could be an option, but in this case the other mechanical properties have to be significantly boosted by the use of filler material. Nevertheless, biobased HDPE might be a more favorable option than PHA as they are expected to show a more durable performance in a wider array of environments and biodegradation is not considered essential for this product category.

5 A note on intellectual property and the road to market for PHBV

5.1 PHA patent landscape

Patents can be vested for many reasons. Essentially, it is a way to protect investments in a finding to give its owner the time to commercialize its inventions. In the plastics industry, patents are obtained for the technologies to make the base material, to alter or compound it, and to develop processes for, and use, in applications. In this chapter, we demonstrate how investigating a specific patent landscape provides insight into commercial opportunities. The landscape illustrates the patent activity for a specific material and the parties involved therein. In this case we zoom in on PHA, in specific PHBV. The PHA industry has filed many patents in its history. An overview of the PHA patent history is shown in Figure 5-1.

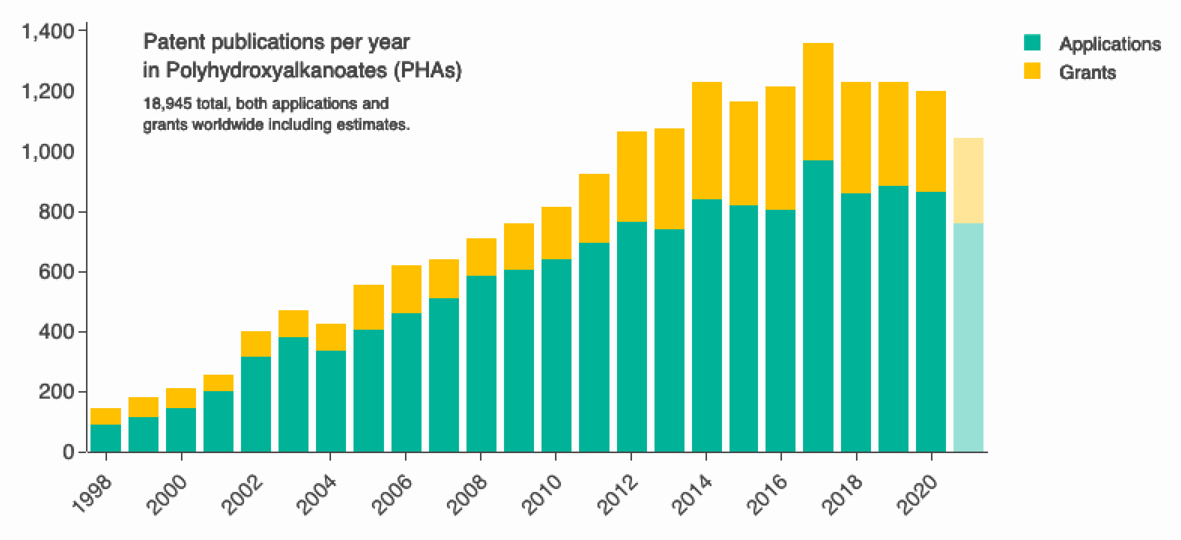


Figure 5-1 Overview of the patent history of the PHA industry (Source: Lux Research 2021)

The PHBV field is well known for the many application patents which were filed in the nineties, when Metabolix tried to secure potential markets to fill their large-scale plant. A graphical overview of the amount of annually filed PHA related application patents obtained from Quick Scan is depicted in Figure 5-2.

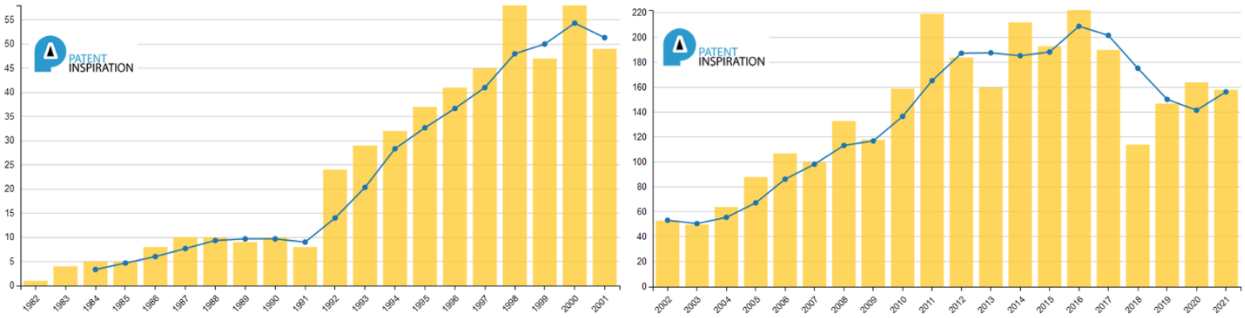


Figure 5-2 graphical overview of the amount of annually filed PHA related application patents (Quick Scan Innovative Partners 2021)

It was not in the scope of this Quick Scan to do an in-depth patent analysis. We present in Figure 5-3 some parts of a quick view on the total number of patents filed for the exact term 'PHBV' in its history

(3325), and of the major contenders in the space. Recently we saw a some new activities (only in week 49 of 2021, 8 patents naming PHBV were filed).

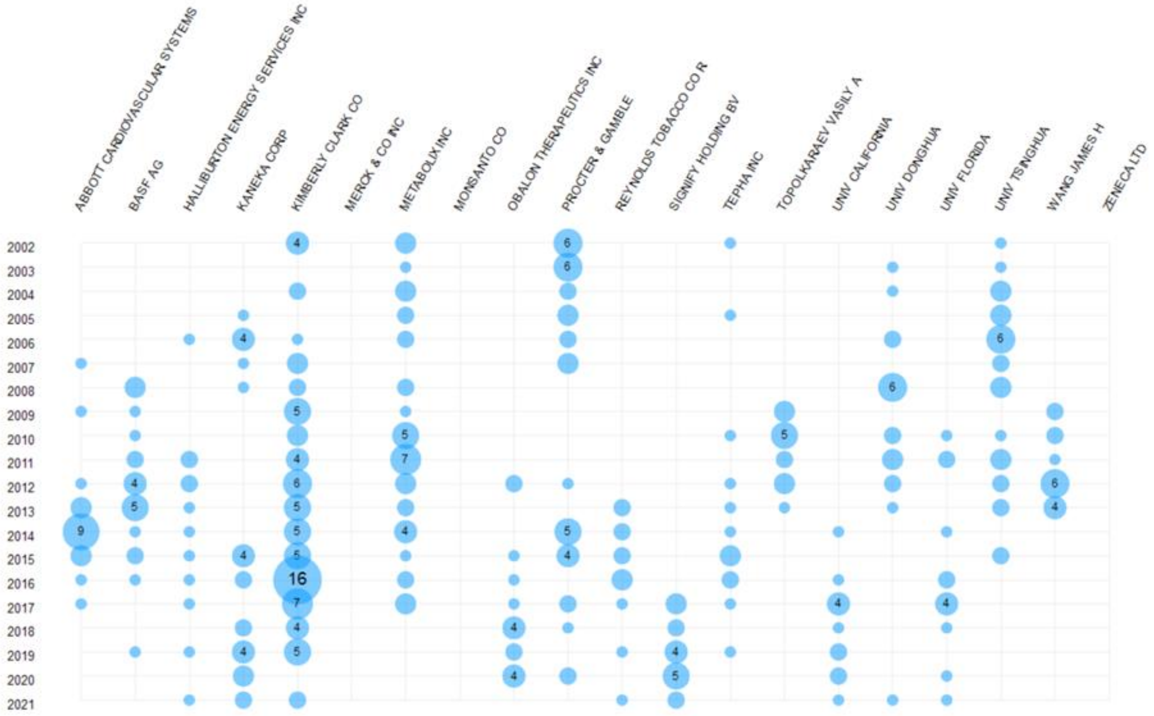


Figure 5-3 Quick view on the total number of patents filed for the exact term 'PHBV' in its history

When we investigate the top 20 companies who filed patents in the last 20 years, we see a clear activity from companies in the fields of:

- diapers and single use textiles (P&G (now Danimer), Kimberly Clark);
- therapeutic fields (Abbott, Obalon);
- packaging (Biotec);
- universities (Univ. of Washington);
- and material producers (BASF, Eastman, Metabolix (now CheilJedang), Kaneka, Roquette).

When taking the applications listed in Chapter 4 into account it is identified that it has been very difficult for companies in the field to take advantage of patents, because of issues in scaling up to sizable production volumes and in targeting the right applications.

5.2 Road to market

Without any further in-depth analyses but based on the amount of activity in combination with the top 20 applicants only, it's recommended to prepare a dual market approach.

A. Freedom to operate

Further in-depth patent research is necessary regarding the current technology and production process to increase the positioning and value of new patent applications. The result of this research will form the basis for the application of a patent with an international search report. In this way the real freedom to operate becomes clear in the fastest possible way. Benefits here are a final judgment if the technology and production process is patentable and the protection it offers once the patent is pending. As a result of this, open conversations with all interesting parties become possible which is beneficial for a successful market approach.

B. Inspiration of operation

To discover the best suitable market opportunities, a further patent search into the activities and applicants in the most mentioned domains should be executed. Entering these domains is probably not the most appropriate way. Inspiration where to operate is needed. Based on the technology and production process in combination with the research on material properties in Chapter 4, it is recommended to try and find which domains are not yet discovered. In other words: where are future customers located?

6 Conclusions & Recommendations

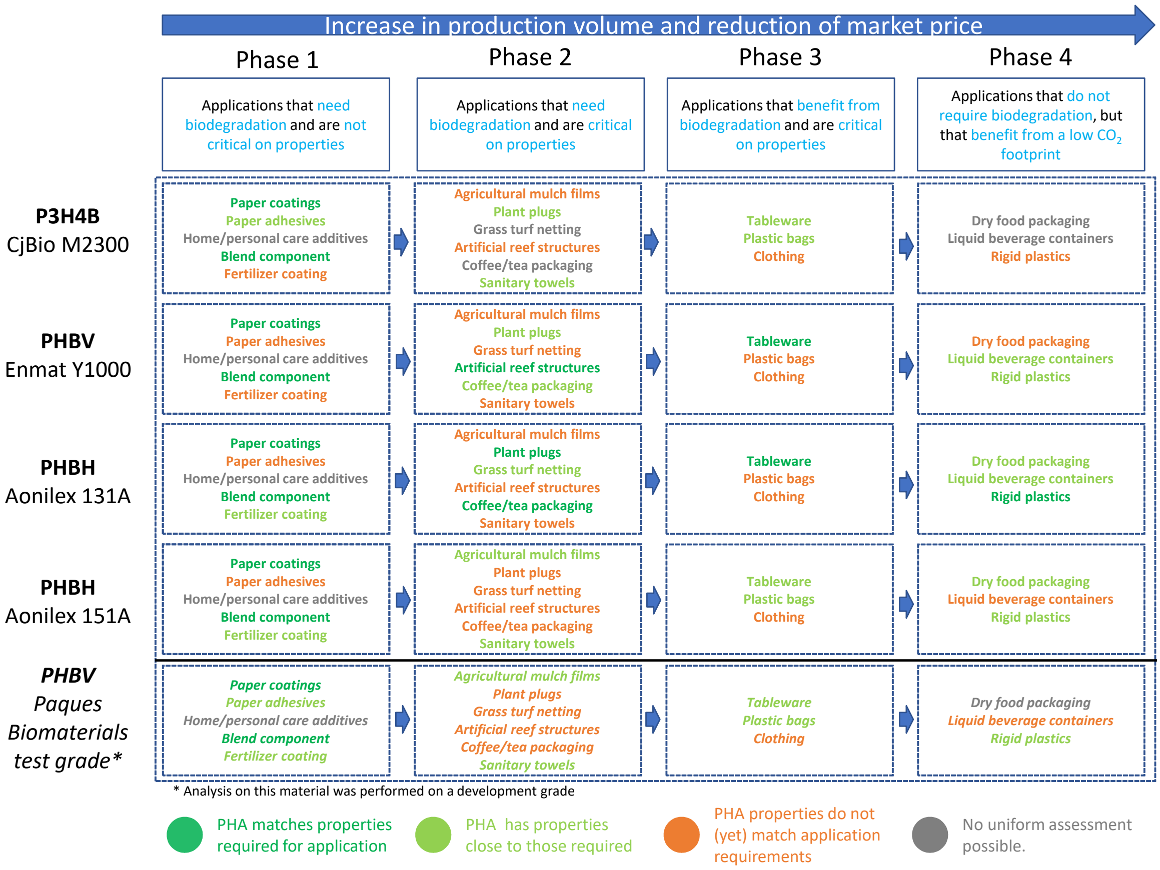
This report is the outcome of a market study on PHA materials that is performed by Wageningen Food & Biobased Research and Invest-NL. The study gives an overview of the current state of the art of the development of PHA materials and their potential to be used in a variety of application markets. It is described that the family of PHA materials differs from both fossil- and other biobased materials in many ways. The production routes via fermentation require different feedstock types and downstream processing routes, and the variation between individual PHA materials is much larger as in essence every type is a separate type of polymer. As a result, it is very complex to map the market potential of PHA materials in general.

The approach in this study was to select five grades of PHA plastics that are all substantially different in composition and thereby represent a wide range of different material properties that can be obtained by PHA materials. In this way we aimed to give a comprehensive overview of the market potential of PHA materials. In this approach the unique selling point of PHAs, biodegradability in a wide range of environments, has been given a central position.

Chapter 2 and Chapter 3 describe the communalities and differences in the production of these PHA materials and how this impacts their properties, production volume, price and CO_2 emissions. The production of PHAs is markedly different from the production of conventional plastics. PHAs are produced via (predominantly single culture) fermentation in batch operations. Downstream processing of PHAs including extraction is very specific and adds to the production complexity. Typically, process improvements target at using low cost (waste) substrates, higher PHA accumulation levels and improved down-stream processing. At present the PHAs are predominantly produced from virgin feedstocks. The use of organic waste streams is feasible but for specific waste streams competition with the use for biofuels and bioenergy can be expected (e.g. waste cooking oils). Of specific relevance for the production of PHAs are waste streams with a high-water content and negative value. The PHA family offers a broad range of properties that are beneficial in specific applications. Well known is the excellent biodegradability of PHAs in the natural environment that can be beneficial in applications where leakage into the environment cannot be prevented. Other specific benefits include a high HDT (maximum usage temperature) and good barrier properties as compared to most other biobased and biodegradable plastics.

Due to unfavourable feedstock conversion factors and the markedly more complex production process, it can be expected that PHAs will stay more expensive than fossil-based plastics. Production by mixed cultures in waste water treatment facilities could offer price reductions provided that efficient extraction processes can be used. In general PHAs have a more favourable environmental footprint than fossil-based plastics but large variations are reported. To obtain the most favourable environmental footprint we suggest the use renewable energy and production from waste streams, in mixed cultures and avoiding solvent extraction methods.

In Chapter 4 this information is coupled to a number of application markets. These are subdivided in 4 different phases, based on their need for biodegradable solutions and how strongly the market relies on a specific set of (mechanical) properties. The information reported in this chapter is summarized in an application roadmap that is depicted in the figure below.



Increase in production volume and reduction of market price

	Phase 1	Phase 2	Phase 3	Phase 4
	Applications that need biodegradation and are not critical on properties	Applications that need biodegradation and are critical on properties	Applications that benefit from biodegradation and are critical on properties	Applications that do not require biodegradation, but that benefit from a low CO_2 footprint
P3H4B CjBio M2300	Paper coatings Paper adhesives Home/personal care additives Blend component Fertilizer coating	Agricultural mulch films Plant plugs Grass turf netting Artificial reef structures Coffee/tea packaging Sanitary towels	Tableware Plastic bags Clothing	Dry food packaging Liquid beverage containers Rigid plastics
PHBV Enmat Y1000	Paper coatings Paper adhesives Home/personal care additives Blend component Fertilizer coating	Agricultural mulch films Plant plugs Grass turf netting Artificial reef structures Coffee/tea packaging Sanitary towels	Tableware Plastic bags Clothing	Dry food packaging Liquid beverage containers Rigid plastics
PHBH Aonilex 131A	Paper coatings Paper adhesives Home/personal care additives Blend component Fertilizer coating	Agricultural mulch films Plant plugs Grass turf netting Artificial reef structures Coffee/tea packaging Sanitary towels	Tableware Plastic bags Clothing	Dry food packaging Liquid beverage containers Rigid plastics
PHBH Aonilex 151A	Paper coatings Paper adhesives Home/personal care additives Blend component Fertilizer coating	Agricultural mulch films Plant plugs Grass turf netting Artificial reef structures Coffee/tea packaging Sanitary towels	Tableware Plastic bags Clothing	Dry food packaging Liquid beverage containers Rigid plastics
PHBV *Paques Biomaterials test grade**	*Paper coatings* *Paper adhesives* *Home/personal care additives* *Blend component* *Fertilizer coating*	*Agricultural mulch films* *Plant plugs* *Grass turf netting* *Artificial reef structures* *Coffee/tea packaging* *Sanitary towels*	*Tableware* *Plastic bags* *Clothing*	*Dry food packaging* *Liquid beverage containers* *Rigid plastics*

* Analysis on this material was performed on a development grade

● PHA matches properties required for application
● PHA has properties close to those required
● PHA properties do not (yet) match application requirements
● No uniform assessment possible.

Figure 6-1 Application roadmap for the 5 PHA grades investigated in this study

This figure shows that PHA materials have the best fit with markets that are highly dependent on biodegradation and are less demanding with respect to mechanical performance.

Paper coatings and blend components are marked as interesting application areas for all PHAs investigated in this study while for paper adhesives and fertilizer coatings other biodegradable polymers might be more relevant.

For applications that more heavily rely on their mechanical performance (phase 2) and require biodegradation there are substantially fewer ‘perfect matches’ with the investigated types of PHA. Nevertheless, specific compounds are interesting options to enter the markets of plant plugs, coffee/tea packaging and artificial reefs.

In phase 3, clear options appear for tableware based on the performed analysis, but this category of products is currently heavily affected by legislative regulations and hence it is highly unclear if this market is worth entering. The other markets in this phase (plastic bags and clothing) are less logical choices for the investigated PHA types.

Applications that do not need biodegradation but will need to transition towards biobased alternatives (phase 4) show limited logical entry options for PHA materials. In most cases other biobased plastics are a more feasible option but specific rigid plastic product markets might be accessed by certain PHA materials based on their most crucial mechanical properties.

A final part of this study was a short investigation of the PHA patent landscape in which many application related patents have been filed in the past decades. Due to the existence of this large quantity of PHA related patents a dual market approach patent search is advised. One aspect of this approach should identify in which identified market segments there is actually freedom to operate, while the other part should focus on identifying the potential future customers that are currently not yet discovered by the PHA market.

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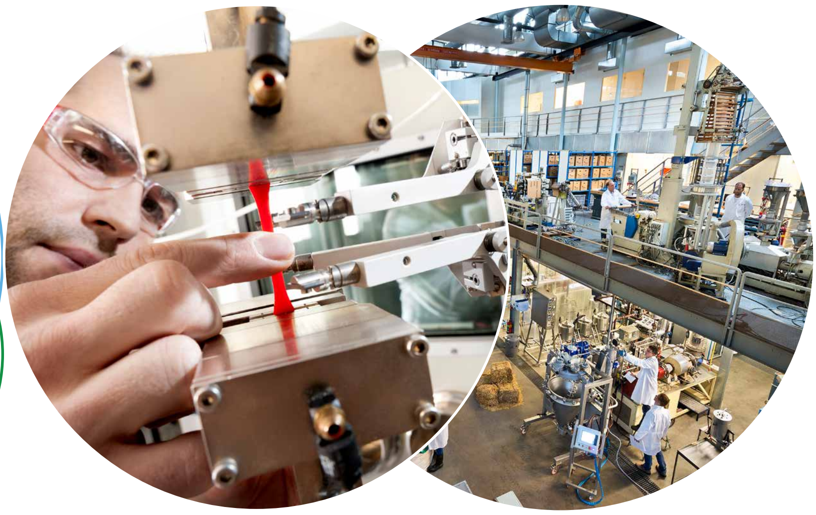

Wageningen Food & Biobased Research
Bornse Weilanden 9
6708 WG Wageningen
The Netherlands
www.wur.eu/wfbr
E info.wfbr@wur.nl

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