Biopolymer from industrial residues: Life cycle assessment of poly(hydroxyalkanoates) from whey

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ABSTRACT

Life cycle assessment (LCA) has turned into a powerful tool to critically and straightforward assess the holistic impact of bio-based plastics and other bio-based products. In order to assure at the same time ecological soundness and to support the economical success of a bioproduct, an early assessment already in the stage of product development is needed. This strategy helps to identify and subsequently to avoid ecological "hot spots". Assessment by using the sustainable process index (SPI), a member of the ecological footprint family, is considered as an especially viable strategy to realize this goal. The software *SPIonExcel* was developed to make the assessment methodology easily applicable and operator-friendly.

During the process of development for archaebacterial production of poly(hydroxyalkanoate) (PHA) biopolyesters from the industrial surplus material whey, a SPI assessment was accomplished to optimize the process in terms of ecological sustainability. As the major outcome, the resulting ecological footprint was comparable with that of competing fossil plastics. Additionally, optimization potentials to further increase the ecological competitiveness were highlighted and quantified. In addition, the developed PHA production process was compared with production of whey powder as the competing, conventional application of surplus whey. Also in this case, the novel PHA production process was superior according to the SPI calculations.

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1. Introduction

1.1. General

Since the early 1990s, significant industrial and academic efforts are dedicated globally to the development of process design strategies aiming at energy conservation and waste reduction for a broad range of industrial processes (Dunn and Bush, 2001; Stöglehner, 2003; Fijał, 2007; Merrild et al., 2008). Such endeavors are politically supported by the willingness of most nations to forcefully foster the market penetration of bio-based and biocompatible materials that are independent from the availability of fossil resources. These meritorious intentions are documented by the outcomes and conventions at the *Earth Summit in Rio de Janeiro* in 1992, the Kyoto Protocol to the *United Nations Framework Convention on Climate Change* (2005), or, more recently, at the *Durban Climate Change Conference* (2011) (Koller et al., 2012a).

Regarding the contemporary sustainability discourse, the application of renewable raw materials in processes currently based on fossil feed stocks is generally recognized as an important strategy toward sustainability (Dovì et al., 2009). This switch to new raw materials is of paramount importance especially in the area of such goods exerting considerable ecological pressures like bulk chemicals and here, most of all, those that are applied as plastic materials.

1.2. "Double optimization" for ecological and economic benefit

The industrial application of processes based on "renewables" and biocatalysts nowadays is well-known as "White Biotechnology". In this context it has to be emphasized that the

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utilization of renewable resources does not only require novel and innovative technologies, but will fundamentally change the global industrial structures (Gwehenberger and Narodoslawsky, 2008; Narodoslawsky, 2010). However, it has to be considered that products from natural resources, especially bio-based plastics, are not a priori superior to their fossil counterparts in terms of sustainability (Kurdikar et al., 2000). Therefore the ecological process evaluation already early during the stage of process or product development is not only an environmental but also an economical necessity to prevent dead ends and unexpected obstacles on the long and often cumbersome way to the product's final market launch (Narodoslawsky and Krotscheck, 2004). Minimizing the environmental impact must be taken into account during the technological development phase to the same extent as to decreasing costs for achieving economic competitiveness. Such "double optimization" in terms of ecological and economic benefit is shaping technology and influencing important engineering decisions. This concerns the choice of raw and auxiliary materials, the selection of process steps and equipment and the logistics along the entire life cycle of a product or service chain (Krotscheck et al., 2000; Narodoslawsky and Krotscheck, 2000).

1.3. Application of SPIonExcel

A complete life cycle analysis (LCA) for ecological assessment of processes is usually connected to large efforts to collect the necessary data and analyzing the impacts of a given technology. Moreover, the problem oriented approach that constitutes the base of conventional LCA (EN ISO 14040, 1997; Guinée, 2002) does not render itself easily to technological optimization: the work of engineers usually is concerned with finding viable compromises that, in many cases, merely shift impacts across environmental problems, e.g. by considerably reducing the greenhouse gas emissions while, at the same time, aggravating other negative impacts of the process. Therefore, development tools are required that, on the one hand, offer comparability of different impacts with a data requirement reduced to an absolute minimum while still considering the whole life cycle and, on the other hand, are compatible with the results of well-known in-depth LCA. The software *SPIonExcel* constitutes a tool meeting these challenges; it is based on the sustainable process index (SPI) methodology. This software was developed to enable engineers and industrial decision makers to optimize life cycle impacts already during technological development and also for existing processes (Sandholzer et al., 2005a,b; Sandholzer and Narodoslawsky, 2007).

Regarding the work at hand, the applicability of *SPIonExcel* to "real world" process development was demonstrated in the case of the process development to obtain poly(hydroxyalkanoate) (PHA) bio-based plastics from whey by the archaeal production strain *Haloferax mediterranei* DSM 1411. An ecological assessment using this software has been carried out in order to identify ecological "hot spots" and to provide decision support for process alternatives already early in the development phase. Due to the fact that not too many reliable commercial data are reported for large scale PHA production, complete and well-grounded LCA studies analyzing the entire environmental impact of PHAs are rather scare in literature. Some laudable attempts to quantify the environmental impact of PHA production via the tools of LCA are reported; unfortunately, they are mainly focusing on isolated aspects of the entire process like merely the polymer production itself, raw material aspects, CO_2 emissions or energy requirements (Gerngross, 1999; Gerngross and Slater, 2000; Harding et al., 2007; Pietrini et al., 2007).

1.4. The surplus product whey

Whey constitutes a surplus material from dairy and cheese industries. During cheese production, it accrues in a ratio of approximately 9 t of whey to 1 t of cheese. Reported amounts of whey that are produced globally vary from $1.15 * 10^8$ t (Peters, 2006) to $1.40 * 10^8$ t (Audic et al., 2003) per year. OECD and FAO even estimate $1.60 * 10^8$ t with an annual increase of 1–2% (values for 2008; Guimarães et al., 2010). Mainly in North America and Europe, huge quantities of whey are available; in 2008, the estimated accruing values are reported with $4 * 10^7$ t for the USA, and $5 * 10^7$ t for the EU-27. At present, the major part of whey is used to produce whey powder for human or animal nutrition. Other applications of whey, e.g. for pharmaceutical purposes or production of bioethanol, only amount to a minor extent. The quantities of whey produced nowadays, especially in the Northern hemisphere, surpass by far the requirements for production of whey powder. Hence, at the moment, whey constitutes a surplus material even causing severe disposal problems for dairy industry.

The process for production of whey powder requires high amounts of energy for concentrating the whey by evaporation, with the modest result of producing a good of exceptionally low market value. Due to this fact the process is highly uneconomic and should be regarded rather as a waste treatment as whey should not be committed to sewage in an untreated form because of its high biological oxygen demand (BOD_5 of 34,000 mg/kg) (Kim et al., 1995). Therefore, contemporarily a huge amount of whey just "vanishes" somewhere in the ecosphere, often in marine environments (Koller et al., 2007).

A growing demand in proteins, e.g. the pharmaceutically significant compounds lactoferrin or lactoferricin, recently led to additional amounts of whey that were processed (Koller et al., 2012b), resulting in large amounts of lactose-rich whey retentate remaining after removal of the said proteins. Hence, an even larger surplus exists and has to be treated as waste material. This constitutes the economic and ecologic background of the presented work.

2. Materials and methods

The standardized approach to life cycle analysis (LCA) is defined in the norm series ISO 14000 and constitutes the base to assess and compare industrial activities in terms of their sustainability (EN ISO 14040, 1997). A LCA gives detailed information on a given product, process, or service chain. However, in order to achieve this goal, considerable effort is necessary and ISO 14000 often is applied only after a product or process has already been introduced to the market. The development of innovative processes that strive for sustainability however requires effective oversight over the environmental pressures the process in question will exert in the life cycle of the product provided. For this reason highly aggregated environmental evaluation methods like the sustainable process index (SPI), a member of the ecological footprint family, have been developed and fast and convenient engineering tools like *SPIonExcel* (Sandholzer et al., 2005b; Sandholzer and Narodoslawsky, 2007) can be employed. The usefulness of the utilization of highly aggregated ecological footprint evaluations in planning and designing processes has been highlighted by Narodoslawsky and Stoeglehner (2008).

The SPI was developed by Narodoslawsky and Krotscheck (1995) and is based on the assumption that a sustainable economy has its fundaments on solar radiation as natural income (Krotscheck, 1995; Krotscheck and Narodoslawsky, 1996; Schnitzer et al., 2007). This radiation on earth's surface drives most natural processes and, in a

sustainable economy, this income may be used to provide products and services, too.

Human activities, however, impact on the environment by their need for resources, energy, manpower and area for installations as well as emissions, waste and noise (Schnitzer and Ulgiati, 2007). The SPI evaluates these ecological pressures according to their impact on the availability of our planet's surface to sustainably convert solar income to services for society. It calculates the area necessary to embed an industrial process sustainably into the eco-sphere, retaining the water and soil compartments as well as the atmosphere in a sustainable state. This area A_{tot}, the total ecological footprint of the process, is calculated by [Eq. (1)–(3)].

$$A_{tot}\,(\mathrm{m}^2) = A_R + A_E + A_I + A_S + A_P \qquad (1)$$

$$A_R\,(\mathrm{m}^2) = A_{RR} + A_{RF} + A_{RN} \qquad (2)$$

$$A_I\,(\mathrm{m}^2) = A_{ID} + A_{II} \qquad (3)$$

The areas on the right hand side of Eq. (1) are called "partial areas" and refer to the impacts of different aspects of a life cycle. A_R, the area required for the provision of raw materials, is the sum [Eq. (2)] of the areas to provide renewable raw material (A_{RR}), fossil raw material (A_{RF}) and non-renewable raw material (A_{RN}). A_E is the area necessary to provide process energy including electricity. A_I, the area to enable the installation for the process, is the sum [Eq. (3)] of the direct use of land area (A_{ID}) and the area for provision of buildings and process installations (A_{II}). A_S is the area required for support of staff and A_P is the area for sustainable dissipation of emissions and waste products sustainable to the ecosphere.

Comparing different processes or process alternatives requires relating the ecological footprint to a product/service unit. This is represented by the specific footprint of a product/service a_{tot} [Eq. (4)].

$$a_{tot}\,(\mathrm{m}^2/\mathrm{unit}\ \ \mathrm{a}^{-1}) = \frac{A_{tot}}{N_P} \qquad (4)$$

N_P in this equation is the number of goods or services supplied by the process in one year (Krotscheck, 1997).

LCA following the ISO norms usually employ the problem oriented CML (Center of Environmental Science Leiden) method (Heijungs et al., 1992). This method assesses the ecological impact of a process in different effect categories like eco-toxicity or green-house gas potential. It has been shown that, although the problem oriented approach and the SPI method differ in their methodological basis as well as in the structure of their analysis, the results of both procedures identify the same problems concerning environmental pressures (Niederl and Narodoslawsky, 2004a,b). The SPI evaluation is therefore compatible with the method of choice for LCA evaluations and may therefore be employed as a "quick and reliable" evaluation approach supporting process design.

Depending on the evaluation case the life cycle limits have to be drawn. In this particular study the SPI for the production of a bio-polymer will be compared to fossil alternatives that fulfill basically the same specifications and may be used in the same applications. Therefore the inventory taken into account in the life cycle comprises all material and energy flows from raw material generation until the gate of the plant producing the polymers as the use phase as well as the disposal phase is assumed the same for all alternatives.

Regarding the optimization scenarios accomplished in the work at hands, increase of the PHA biopolymer productivity by biotechnological means, optimization of the energy requirements (sterilization, drying steps etc.) and logistic aspects (mainly transportation) were taken into account.

3. Calculation

Any LCA has to be defined in terms of the system boundaries which in turn is already a normative step and dependent on the question the LCA has to answer. This means that the evaluation with the SPI during design has also to take system boundaries into account that represent a reasonable life cycle. Evaluation in the current study is based on the following assumptions:

- Whey is a by-product of a process serving a different sector (food production) and will be produced regardless if it is converted to PHA or not.
- There exists an alternative pathway to utilize whey that has to be taken into consideration, namely the production of whey powder.
- PHA from whey is in direct competition with other polymers produced from fossil raw materials. Properties and technical application of PHA are similar to those of other polymers (detailed in the comparison below), so that the use and disposal phase exerts the same ecological pressure for all alternatives and does not contribute to differences in life cycle ecological pressures exerted by the different materials used for comparison in this study.

Consequently the life cycle for this study includes all steps from the emergence of whey in food production (with no ecological pressure from the agricultural pre-chain attached to it) to the final production of PHA. The comparison with fossil based polymers also includes the whole life cycle from the generation of the raw material to the final polymer product.

The goals of LCA for PHA production starting from whey were the identification of ecological "hot spots" in the developed process and the comparison of PHA biopolymers from whey with fossil polymers and the production of whey powder. The system boundaries of the ecological assessment are shown in Fig. 1. Infrastructure and employees have not been included because of their marginal influence on the overall footprint. This influence is usually between 1% and 3% for industrial processes. It becomes relevant however in energy technologies such as wind and water power or photovoltaic panels. Data of supporting processes like electricity, transport or chemicals were taken from ESU-ETHZ (1996).

The impact assessment was carried out for a so called "base case". This was calculated with the data provided by the project partners based on bioreactor experiments on 300 L scale. The EU-27 average electricity mix was used for this case. The nutrient solution used for fermentation was calculated based on a recovery rate where 50% of the needed salts were reused. This reuse of salts is of considerable importance due to the fact that the microbial PHA-production strain used in this study, *Haloferax mediterranei* DSM 1411, is requiring extremely high concentrations of inorganic salts in the nutritional medium because of its halophilic nature (Koller et al., 2007). Due to the definition that whey is a waste from dairy industries, the pre-chain for whey production (mainly the agricultural production of milk) was excluded.

4. Results

The results of a SPI analysis contain diverse information. The a_{tot} as calculated by Eq. (4) gives an indication of the "cost" in terms of ecological sustainability of a given product or service. The partial areas in Eq. (1)–(3) allow the identification of the largest contribution to the overall impact in terms of impact categories. The evaluation of the contribution of different steps to the overall footprint in Eq. (4) allows identifying the most problematic step in the life cycle from the view point of sustainable development
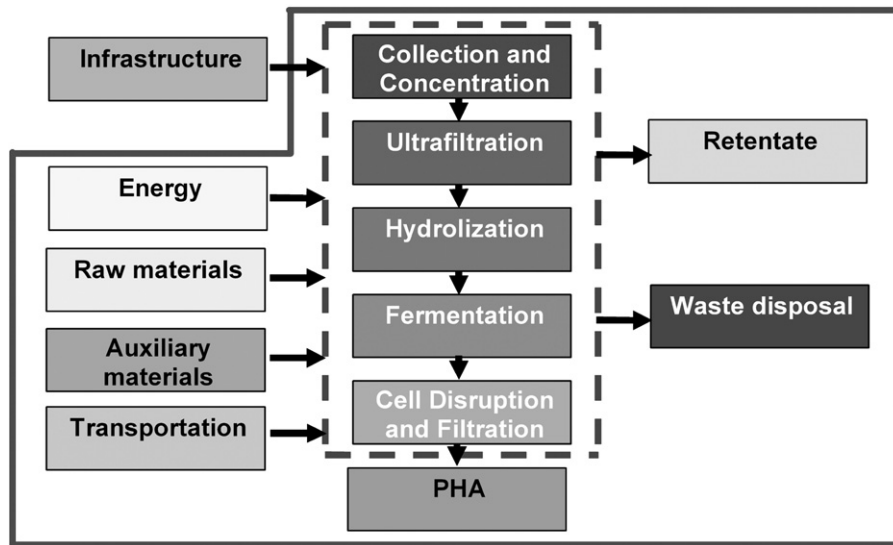
Fig. 1. Process steps, inputs and outputs of the PHA-production process. The broken line incorporates the process steps, the full line the system boundaries of the life cycle assessment.

4.1. Ecological assessment of the process

The presented ecological assessment is based on evidence and data gathered in laboratory experiments as well as preliminary experiments on the scale of 300 L bioreactors. This is a common situation in process development, indicating the final laboratory step and the transition to the pilot scale. From the point of view of designing a sustainable process, this step is of particular interest as it indicates those production factors and process unit operations that merit particular engineering effort to decrease ecological pressures for the whole life cycle.

For simplified assessment, the process has been divided in five separate process steps (Fig. 1). In the first step, whey has to be collected from dairies in the vicinity (an average distance of 50 km was assumed) and transported to the facility where it is concentrated to higher protein and lactose content (with a concentration factor of five). In the next step, an ultrafiltration process separates a retentate containing high quantities of proteins that can be utilized as a marketable co-product (Koller et al., 2012b). The remaining whey concentrate (containing 20% weight lactose) is treated in a chemical hydrolysis step to split the disaccharide lactose into the monomeric sugars glucose and galactose. Afterwards the bio-based plastics PHA is produced biotechnologically in the fermentation process.

To recover the polymer from the biomass in the last process step, the cells are disrupted and filtered.

These process steps require various materials and energy inputs and generate emissions from the process as well as the pre-chain (e.g. electricity provision, transport, etc.) The overall footprint of the developed process, based on pilot plant data, amounts to 10,432.92 m²a/kg PHA. Taking a closer look to the five process steps reveals that the fermentation process (step 4) contributes the largest pressure (Fig. 2).

Analyzing this step reveals that the main part of the ecological footprint is caused by electricity provision (Fig. 3). This high electricity input is generated by the need for agitation in the bioreactor. The fermentation process in the pilot plant takes relatively long time (over 100 h).

The other flows in this process step – heating energy for fermentation and pasteurization, the necessary process chemicals and emission of used nutrient salts to water – provide only about an eighth part of the overall footprint.

Considering the whole process, electricity input to fermentation is still the largest contributor to the entire ecological footprint of the life cycle (Fig. 4). Chemicals, process energy and transportation of the whey to the facility additionally contribute to the life cycle ecological footprint, but to a much smaller extent.
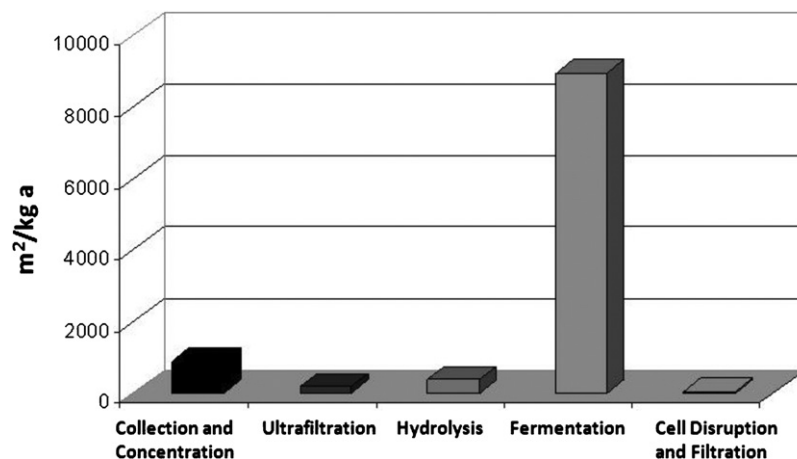
Fig. 2. The ecological impact of the five process steps according to the SPI.
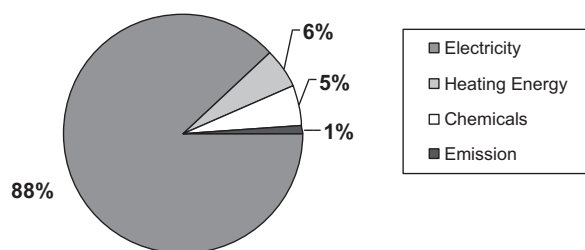
Fig. 3. Percentage distribution of the ecological footprint of the fermentation step according to the origin.
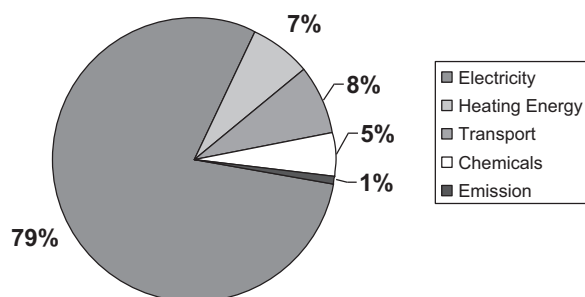

Fig. 4. Percentage distribution of the ecological footprint of the whole PHA process according to the origin.

Considering these results the fermentation step must become the main focus for further process optimization from the environmental sustainability point of view.

4.2. Comparison of PHA with fossil polymers

Data obtained from ESU-ETHZ (1996) were used to determine the ecological footprint of different fossil polymers. These selected polymers where chosen according to the potential of PHA to replace them. Poly(ethylene terephthalate) (PET), poly(styrene) (PS), poly(ethylene) (PE) and poly(propylene) (PP) show very similar specifications to PHA in their main applications and are therefore prime targets for replacement.

As visualized in Fig. 5, the production of 1 kg PHA based on 300 L scale experiments inflicts a higher ecological pressure than the production of equal amounts of all comparable fossil polymers. This result makes clear that products based on renewable resources, even on by-products, are not automatically more environmentally benign than products based on fossil resources.

It has to be taken into account that the production process for PHA from whey is still a new process just entering the state

of pilot plant scale. In contrast, production of fossil polymers has been perfectly optimized during the last decades. The discussed process for PHA may reach ecological competitiveness if it undergoes the same optimization procedure for final marketability. In order to guide future process development from the ecological sustainability point of view, different scenarios with a variation of parameters like yield or energy consumption were established. These scenarios shall guide engineers by quantifying the impact of process optimization on the life cycle wide environmental pressure. Engineering design is however based on compromises. It is therefore important to state in what manner different optimization options will interrelate with each other as there is a certain danger that improvements in one part may lead to increased environmental pressure in other parts of the process.

4.3. Optimization scenarios

Ecological assessment using the SPI shows that energy consumption (in particular electricity consumption) is of paramount importance to the ecological pressure of PHA production. The cause for the high electricity consumption is the relatively long fermentation time and low end product concentration in the pilot plant. Although industrial bioreactors are generally characterized by higher energy efficiency (which will be discussed separately), low productivity can be regarded as the root of the high ecological impact incurred by the fermentation step. This puts the engineering focus on increasing the productivity of the fermentation.

One strategy in this direction is to increase the yield of PHA respective to the raw material at the same energy input. The 300 L scale pilot plant produced about 0.008 kg PHA per kg whey, corresponding to a yield of 0.188 kg PHA per kg whey lactose. Laboratory research on a 10 L scale has shown that an increase of PHA production to about 1.7 weight percent (yield of 0.418 kg PHA/kg lactose) is possible without prolonging fermentation time. Using this optimization potential, the ecological footprint is lowered significantly to 4785.95 m^2a/kg from 10,432.92 m^2a/kg in the base case based on the pilot plant experiments (Fig. 8).

The discussed pilot process based on whey now uses about 14 kWh per kg PHA. As already mentioned, industrial scale bioreactors use by far less energy per unit of product. Implementing available experience from existing industrial scale PHA production based on cane sugar (Nonato et al., 2001; Ortega, 2002) as a guideline, where bioreactors on a m^2 scale are used, the fermentation process can be optimized to an energy requirement of 1 kWh/kg of produced PHA. The decrease of the ecological footprint utilizing the electricity optimization potential according to this experience is substantial, resulting in 3113.08 m^2a/kg PHA produced (Fig. 8).
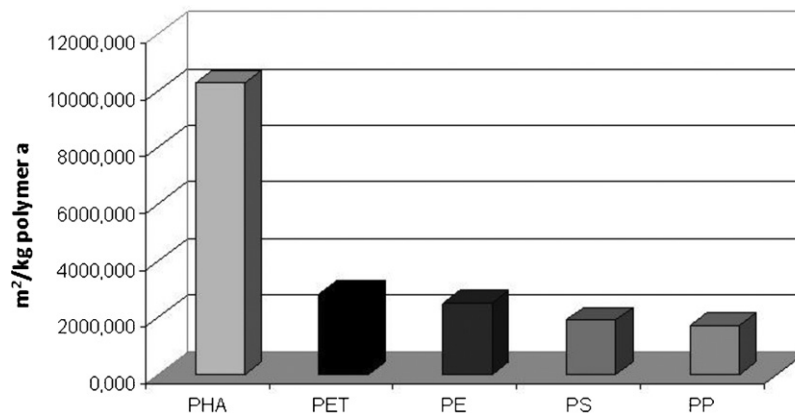

Fig. 5. Comparison of the ecological impact of PHA from whey with fossil polymers.
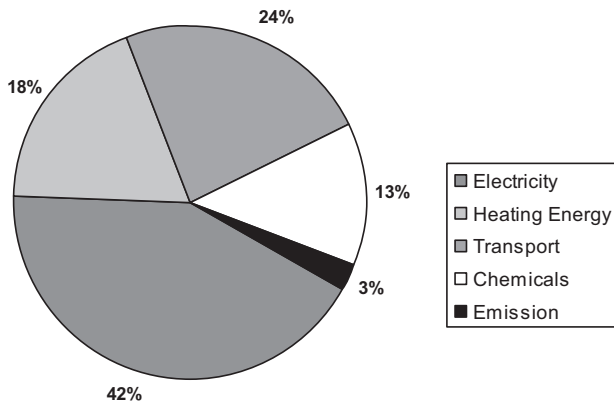
Fig. 6. Percentage distribution of the ecological footprint of the energy and yield optimized PHA process according to the origin.

The limit of optimization of the process is reached when both optimization options are completely implemented. In this case, PHA from whey is reaching the range where its ecological pressure is in the same order of magnitude as calculated for polymers based on fossil resources. The decrease of the ecological footprint due to these optimizations results in 1784.80 m²a/kg PHA. In comparison, PP, the fossil polymer with the lowest ecological footprint, accumulates 1726.39 m²a/kg (Fig. 6).

Looking at the distribution of the ecological footprint after integrating the two discussed optimization scenarios (Fig. 6) to their full potentials it can be seen that, although electricity consumption still inflicts the highest percentage of the pressure, transportation becomes of increasing importance.

As currently concentration of whey happens in centralized sites, transportation is mainly required for collecting whey in local dairies and delivering it to the factory where it is concentrated. This means however that only a fifth part of the transported good is processed further, whereas the remaining 80% (water) are evaporated. If this sequence of process steps is reversed, meaning first concentration of whey and then transportation, the footprint would decrease further to 1454.90 m²a/kg PHA. This means that even if a substantial difference in the efficiency of the de-central concentration step is supposed, this order of process steps will be superior to centralized concentration. Moreover available waste heat at local diaries may be utilized to further reduce the ecological impact of PHA production from whey. As shown in Fig. 7, ecological superiority compared to fossil polymers can be finally reached then if all these optimization potentials along the life cycle are realized to their full potential.
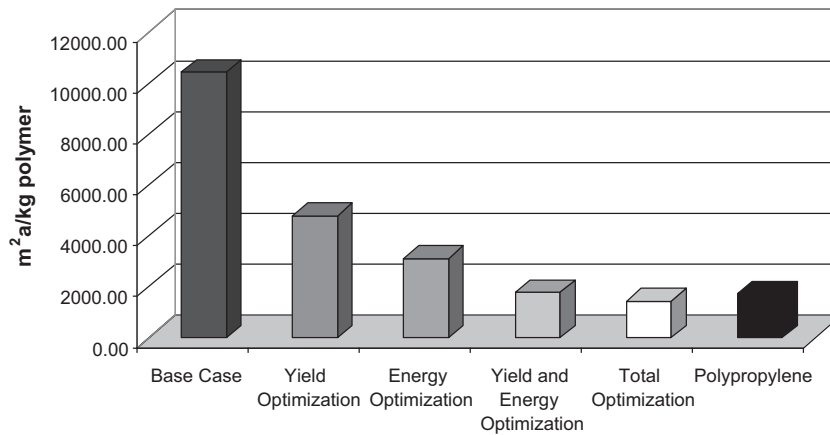

Fig. 7. Decrease of the ecological footprint of PHA production due to application of optimization potentials in comparison to classical production of the petrochemical polymer PE. Total optimization includes energy, yield and logistic optimization.
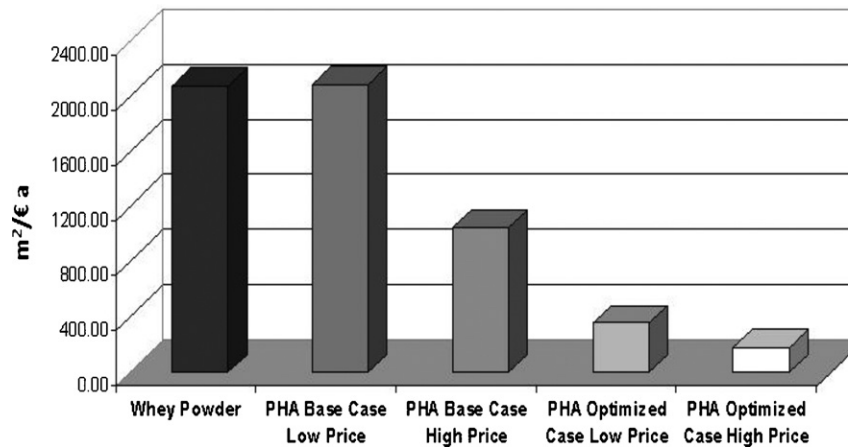
Fig. 8. Comparison of PHA from whey with whey powder according to value.
Note: The value for "Whey powder" corresponds to marketing of this material at 0.5 €/kg; "PHA Base case low price" corresponds to marketing of PHA for 5 €/kg; "PHA base case high price" corresponds to marketing for 10 €/kg; "PHA optimized case low price" corresponds to marketing for 5 €/kg; "PHA optimized case high price" corresponds to marketing for 10 €/kg.

4.4. Comparison of PHA from whey and whey powder

At the moment, many dairies process whey to whey powder which can be used as milk powder substitute. The ecological footprint calculated for whey powder amounts to 1036.60 m^{2}a/kg powder. In order to compare whey powder to PHA from whey, the ecological impact was calculated according to the price of the products. The price of whey powder is approximately 0.5 €/kg (personal communication Dr. L. Sibilin, Latterie Vicentine, Italy). A price for PHA from whey of 5–10 €/kg was estimated for economic assessment based on typical values reported in literature (Koller et al., 2007). With the prices of both possible products the ecological footprint of the contribution to the value chain was calculated (Fig. 8), leading to the ecological pressure based on the product value created by the process. In figure, 5 €/kg of PHA were used as "low price", 10 €/kg of PHA were used as "high price".

It can be seen that, depending on the market price, PHA is able to ecologically compete with the process of whey powder production, even with pilot plant data. If the optimization potentials in yield and energy consumption are applied, PHA is by far superior in comparison to the contemporary practice of producing whey powder. The production of PHA leads to a decrease of the environmental impact per € earned over the value chain compared to whey powder even if it is not yet ecologically competitive with fossil polymers.

5. Discussion and conclusion

At the present stage of development the process of producing PHA bio-based plastics from whey still has a high impact on the environment. This is due to the fact that the process is not yet completely optimized.

As the main reasons for the high impact, the high mechanical energy requirement for the fermentation process and a low amount of PHA output per kg whey input can be pointed out. These are the two most obvious process optimization potentials. Achieving optimal values in both directions, increasing the yield while decreasing electricity consumption per kg PHA produced is a formidable engineering challenge. It calls for shortening the fermentation times, using highly efficient stirrers and optimal fermentation conditions as well as stringent process control.

Another optimization potential is the logistical aspect of the process. Here it can be seen that a centralized evaporation step causes high transportation needs. Decentralized evaporation directly at the dairies decreases the amount that has to be transported and therefore the ecological pressure considerably.

The strong impact of the logistic steps on the ecological impact is a quite common feature for processes based on renewable resources. They typically have low transport density and/or low concentration of the substance used in the further production chain. In many cases like in whey, the major part of the raw material is water. These unfavorable logistic parameters are responsible for the fact that transport plays a much more prominent role in life cycle optimization of processes based on renewable resources than of current fossil based processes.

The evaluation reveals another interesting strategic aspect. The ecological pressure of PHA production from whey is almost completely dependent on the ecological pressure exerted by electricity provision. Calculations in this study were carried out with the EU 27 mix of technologies for providing electricity which causes high ecological footprints due to the high fraction of fossil based and nuclear energy used in European power plants. Differences in the ecological footprint for power generation are however dramatic: they range from 1.4 m^{2}a/kWh for hydro power to 1112.9 m^{2}a/kWh for nuclear energy (see www.fußabdrucksrechner.at). Compared to the EU-27 mix footprint of 4557 m^{2}a/kWh the mix for Austria causes only

45% of the ecological footprint. This means on the one hand that the ecological footprint of PHA production from whey is context dependent: even when only part of the optimization potential is realized the process may become environmentally advantageous to fossil alternatives in countries like Norway, Sweden and Austria that already implement "greener" electricity in industrial processes to a larger extend. It also means that the process will become automatically more sustainable as electricity provision becomes more sustainable. As the ecological pressure of fossil alternatives is mainly caused by their fossil raw material they may not profit from greener electricity to the same degree.

Comparing PHA production to the production of whey powder, which nowadays is the main pathway for processing whey, shows that a product with much higher market value may be produced. This means that, for the current situation, the change of product from low-value whey powder to value-added PHA biopolymers definitely constitutes a progress that decreases the ecological pressure per € value addition in the whole production chain.

Summarizing it can be emphasized that PHA production is a step forward in whey processing and has the potential to ecologically outperform fossil polymers.

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