Sveriges lantbruksuniversitet
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End-of-life scenarios for bioplastic food and drinking packages

– A study of Swedish bioplastic waste disposal habits and environmental impacts

End-of-life scenarion för mat och dryckesförpackningar gjorda av bioplast

- En studie om avfallshantering av bioplast samt dess konsekvenser på miljön

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Degree project • 15 credits

Bachelor's degree in Biology
Faculty of Natural Resources and Agricultural Sciences, Swedish University of Agricultural Sciences
Molecular Sciences, 2018:34
Uppsala 2018

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Credits:	15 credits
Level:	Bachelor
Course title:	Independent project in Biology, G2E
Course code:	EX0894
Programme/education:	Freestanding Bachelor's degree in Biology
Course coordinating department:	Department of Aquatic Sciences and Assessment
Place of publication:	Uppsala
Year of publication:	2018
Title of series:	Molecular Sciences
Part number	2018:34
Cover picture:	Tilda Hansson
Online publication:	https://stud.epsilon.slu.se
Keywords:	Bioplastic, biodegradable plastic, compostable plastic, biobased plastic, PLA, Bio-PET, consumer

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Abstract

The aim of this study was to investigate real end-of-life scenarios for some of the most common bioplastics, such as PLA and Bio-PET, for food and drinking packages in Sweden and to evaluate some of the potential environmental consequences of these scenarios. Life Cycle Analysis often evaluate intended end-of-life scenarios for bio-plastic products, but this study used an explorative research method, gathering information of the conduction and habits of bioplastics to evaluate if these scenarios were the ones occurring. For the bioplastic to take an intended life cycle path, all the actors such as producers, consumers and municipals, must perform. Bioplastics are material which have a growing market owing to strategies for an environmentally friendly and sustainable society. This study explored the paths of bioplastics from consumer discard to end-of-life scenario but also evaluated some of the potential environmental consequences that can occur due to these paths, using a descriptive literature study. The results showed that PLA and Bio-PET bottles are institutionally handled very differently. Bioplastics are incinerated, recycled or thrown as environmental litter. These scenarios give a variety of environmental consequences such as various amounts of greenhouse gas-emissions due to different treatment processes and physical damage to animals and ecosystems due to deficiency in biodegradation. This study explored and evaluated different paths of bioplastics in the society with the conclusion that there is a lack of institutionalized techniques and facilities, second hand markets and knowledge about bioplastics which, in the end, leads to a lack of sustainability.

Keywords: Bioplastic, biodegradable plastic, compostable plastic, biobased plastic, PLA, Bio-PET, consumer

Sammanfattning

Syftet med denna studie var att undersöka end-of-life scenarion för några av de vanligaste bioplasterna, såsom PLA och Bio-PET, i mat och dryckesförpackningar i Sverige samt att utvärdera några av de potentiella konsekvenserna som dessa scenarion kan ha på miljön. Livscykelanalyser utvärderar ofta tilltänkta livscykler för bioplast, men denna studie har använt en explorativ forskningsmetod genom att samla information om hanterande och vanor kring bioplast för att utreda dess livscykler. För att bioplast ska kunna färdas den avsedda vägen måste alla aktörer, producenter, konsumenter och kommuner, prestera. Bioplast är material som har en växande marknad på grund av strategier för en miljövänlig och hållbar värld. Denna studie utvärderade också några av de potentiella miljökonsekvenserna som kan uppstå till följd av dessa vägar med en deskriptiv litteraturstudie. Resultaten visade att PLA och Bio-PET, institutionellt, hanteras olika. Bioplaster bränns, återvinns eller blir till skräp i naturen, vilket leder till en rad olika konsekvenser för miljön. Några av dessa konsekvenser är olika mängder växthusgas-emissioner som följd av varierande avfallsprocesser samt fysiska skador på organismer och ekosystem till följd av otillräcklig nedbrytbarhet. Undersökningen gav slutsatsen att det saknas institutionaliserade tekniker och anläggningar, andrahandsmarknader och kunskap gällande bioplast som i slutändan leder till brist i hållbarhet.

Nyckelord: Bioplast, biologiskt nedbrytbar plast, komposterbar plast, biobaserad plast, PLA, Bio-PET, konsument

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Definitions

Biobased. There is no concrete definition of biobased plastics today. It can be defined as a material consisting completely, or in significant amount, of biological components or as organic material containing carbon, produced by biological processes from renewable resources (Alvarez-Chavez et al. 2011).

Biodegradable. Plastic defined by the ability to degrade biologically without impairing the environment. Plastics degrade by microorganisms with CO_2, H_2O and biomass as residues and the degradation process is considered complete (STFI 2016, Cambridge Dictionary n.d.). For a material to be labelled biodegradable, it must be tested in regard to degradation percent in a set time under biodegradable conditions (RISE n.d.).

Bioplastics. Plastics that consists of polymers from biomass, i.e. starch, cellulose and protein; polymers which are produced by microbial fermentation; polymers produced using a chemical synthesis from monomers that are bioderived or polymers produced in a chemical synthesis blend of petroleum-based and bio-derived monomers (Byun & Kim 2014, Song et al. 2009). Bioplastic also include petroleum-based plastic which are biodegradable (Rujnic-Sokele & Pilipovic 2017).

Climate change score. A score calculated by a materials' GHG emissions and impact on the environment counted in CO_2 eq. A high score gives a high impact.

CO_2 eq. A measure for greenhouse gas emissions which consider various gasses different impact on global warming. The impact is equated with the same amount of carbon dioxide needed to cause the same damage.

Compostable. Heterogeneous organic matter which biodegrades in moist and aerobic environment by microorganisms under compost conditions. The existing standards concerns industrial composting (Rujnic-Sokele & Pilipovic 2017). Standards specify that the bioplastic should be compostable under specific conditions concerning e.g. temperature, time and moisture-levels and the degradation should have no toxic side effects on the environment (Prieto 2016). It should biodegrade to 90% at minimum within six months in monitored compost conditions with CO_2 as a product from organic carbon. The material should also fragment sufficiently to small components that are non-detectable visually, <2 mm, in 12 weeks. The plastic degradation is also not allowed to pose any threat to plants and germination (Rujnic-Sokele & Pilipovic 2017).

Abbreviations

EOL – End-of-life, a term used to describe last stages of a products life

LCA – Life-cycle analysis, or Life-cycle assessment, is an analysis technique used to evaluate a products environmental impacts through out all stages of its life cycle.

MSW – Municipal solid waste, are a waste type which consists of a mixed variety of solid waste generated by households. Households do not bring this type of waste to recycling stations, instead it is collected by government bodies (BD Dictionary 2018).

PLA – Polylactic acid, a form of lactic acid used as thermoplastic material.

PET – Polyethylene terephthalate, a thermoplastic material commonly used for drinking bottles.

Bio-PET – Polyethylene terephthalate manufactured with partially or completely biobased material.

1 Introduction

1.1 Bioplastics

Environmental strategies and political frameworks to support the evolution of a sustainable social and market development have led to national investments in innovations in the bioplastic field (STFI 2016). In food packing industry, sustainability has become a decisive objective and the bioplastic market is rapidly increasing (Byun & Kim 2014). Bioplastics are important materials for food and drinking packages such as containers and bottles, catering products, film packaging and pouches (Rujnic-Sokele & Pilipovic 2017). Consumers often favour use of bioplastics regardless of limited knowledge about origin, ecological performance and preferred area of use (Brockhaus et al. 2016). The investment in bioplastic industry is one attempt of many for countries to steer developments towards a circular economy, a society in which reuse and recycling are norms and where fossil-based products are substituted, leading to a lifestyle within limits of the ecosystem (STFI 2016; Hedfors & Sigurjónsdóttir 2017). But is the loop of bioplastics closed in Sweden today?

Research and statistics concerning the conceptions, use and end-of-life (EOL) scenarios, of Bio-plastic in Sweden are scarce, however some universal life-cycle analysis (LCA) are accessible for some bioplastics (see Saibuatrong et al. 2017; Intini & Kühtz 2011; Patel 2005 e.g.). LCA, is a method used to evaluate and analyse environmental impacts for processes and products across their entire lifecycle. LCA in the field of bioplastics are however not often as comprehensive and meticulous as they should be, and this is reflected in the variety in research results. LCA examine system boundaries with different extendedness i.e. cradle to gate, cradle to grave etc. System boundary selection, including bioplastic graves and EOL scenarios, must be accurate to evaluate environmental impacts of bioplastics (Hottle et al. 2013).

If a great invention does not reach its intended design and EOL scenarios, when in the hands of consumers and government strategies, a new evaluation might be needed. The environmental costs and profits of bioplastic products would preferable be evaluated with the knowledge of the products actual path and EOL scenarios and not only their intended ones. Consumer behaviour is therefor of great importance to examine. This thesis covers a part of the gap of research today and knowledge of this matter should be considered crucial if alterations are to be made to reach a more sustainable society.

1.2 Aim of study

The aim of this thesis is to analyse the path of PLA and Bio-PET, some of the most common food and drinking bioplastics, from consumer discard to the products EOL scenario and also to examine some of the potential consequences this product path yields on the environment. The research questions that will be answered are:

Which are the real end-of-life scenarios for most common bioplastics in Sweden today?

What consequences might these bioplastic end-of-life scenarios have on the environment?

1.2.1 Demarcation

Since Bio-PET is indistinguishable from petroleum-based PET in material composition, research results concerning “PET” in general is used when possible. Since it is problematic to distinguish Bio-PET from petroleum-based PET once on the market, the term (Bio-)PET is used when no distinction is possible or needed. When a separation is needed, the terms Bio-PET and petroleum-based PET will be used.

Many of the bioplastic products are blends of different materials to reach a specific feature and quality. The blends can be composites of different polymers, both bio- or petroleum-based (STFI 2016). This study will concentrate on the two base materials mentioned above which are some of the most common bioplastics on the market (Hottle et al. 2017). Other environmental issues that can arise due to different product compositions and additives will not be addressed in this study.

1.3 Investigated materials

1.3.1 Polylactic acid

Polylactic acid (PLA) is, second to different starch blends, the most common biodegradable bioplastic produced today, representing 10.3% of the total bioplastic market (European bioplastics 2017). PLA is termed biobased, biodegradable and compostable and derives from starchy crops as corn, potato starch or sugar beets (Byun & Kim 2014). Hydrolysis is performed on starch resulting in glucose (Xiao et al. 2012). After that a fermentation process produces two isomers of lactic acid, L-lactic and D-lactic acid, which are further converted to PLA. The two isoforms can be used separately or mixed and give rise to three different PLA-structures. Two synthesis methods are often used, namely direct polycondensation and ring-opening polymerization, the latter being the most common one (Byun & Kim 2014). PLA with high molecular weight is colourless, glossy and solid and the material's tensile properties can vary depending on processing conditions and crystallinity of the material (Xiao et al. 2012, Garlotta 2001). PLA can be converted into a material by injection moulding or extrusion and is often used as packing material (Xiao et al. 2012, Byun & Kim 2014). PLA exhibits good thermal processability in comparison to bioplastics in general and its elastic modules and relatively high tensile strength makes it resemble (Bio-)PET (Byun & Kim 2014). PLA's weakness is sensitivity to hydrolysis in moist environments at temperatures of >50 °C. Another weakness is brittleness and insufficient gas barrier properties for some industrial applications, but which can be rectified with additive as plasticizers, starch or other polymers (Xiao et al. 2012, Byun & Kim 2014, STFI 2016).

Example of a blend on the market is PLA mixed with lignin, fatty acids and wax which is used in mechanical, toy and food industries, often as a replacement for (Bio-)PET (Soroudi & Jakubowicz 2013).

1.3.2 Bio-polyethylene terephthalate

Bio-polyethylene terephthalate (Bio-PET) is the most common biobased plastic but also the most common bioplastic in general and represent 26.3% of the market (European bioplastics 2017). It is most often only partly biobased and not biodegradable in nature (STFI 2016). It often consists of 30% biobased monomer called ethylene glycol (EG) from renewable carbon and 70% terephthalic acid (TPA) derived from petroleum. TPA can be derived from isobutanol or carbohydrates as fructose or glucose but this is a complex process which is problematic in large scale production. Bio-PET is identical to petroleum-based PET and therefor possesses the same properties (Storz & Vorlop 2013, Byun & Kim 2014, STFI 2016). The material is a semicrystalline polyester and the crystallization are achieved by heating to 190 °C (Cheremisinoff 2001). It possesses a high aromatic component ratio, which contribute a sustainability against biological attacks (Müller et al. 2001). Bio-PET entered the market around 2014, as direct replacements of the petroleum-based PET. The biobased market has since then changed its focus to an extent, to investigate and produce replacement copies of fossil-based plastics (STFI 2016). (Bio-)PET has a variety of using applications and are often used in food containers (Intini & Kühtz 2011) however the present study will focus on Bio-PET bottles.

Example of blend on the market is 30% biobased EG and 70% biobased PTA produced from paraxylene which is derived from beet sugars. This is an example of a packaging product, consisting of 100% Bio-PET which have entered the market (STFI 2016, Packaging News 2018, PTonline 2015).

1.4 National Waste Plan

In Sweden, producers hold a responsibility for collection of their product waste. Food and drinking packaging are one of eight product groups that are regulated by law to require collection systems and plans. The producers' collecting system in Sweden are 5800 unmanned recycling stations with plastic packaging collection vessels. Beyond that, packaging vessels are distributed at municipal recycling stations (Avfall Sverige 2018). It is the municipalities that are responsible for informing consumers about producer responsibility of food and drinking packages (Svensk Avfallshantering 2018).

1.5 Bioplastic labelling and marketing

Consumers are by law obliged to sort their waste, but 71% of the Swedish consumers are not aware of this according to a survey edited by the consumer association in Stockholm, KFS (KFS 2017). Although there is no Swedish law for labelling plastic products, there is a common symbol for sorting and recyclability in Sweden. Thermoplastics are considered recyclable and therefore labelled with a recycling symbol, which in Sweden are triangles with arrows, and a material classification number (Figure 1) (STFI 2016). Bioplastics are often labelled with classification number 07 which stands for "Other" plastics, but the group contains other plastics such as polytetraflouroethylene (PTFE) used in Teflon (Kretsloppsbloggen 2014). There is no common international plastic labelling system in place yet and this is troublesome in recycle systems since there is no information about material and additives that could be hazardous (STFI 2016).

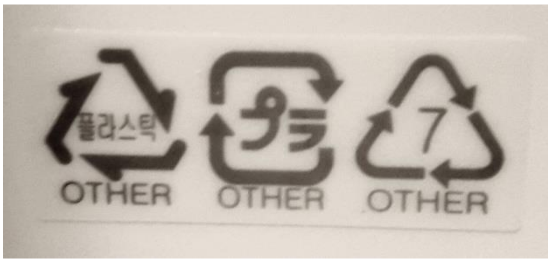

Figure 1. Some recycling symbols for plastic with classification number 7 which applies “Other” plastics. This class includes bioplastics of different materials.
Photo: Tilda Hansson

Some of the most important national and international organizations for standards with environmental aspects are the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). These organizations are working with standardization of biobased plastic in terms of degradability, compostability and the amount renewable raw material in commercial bioplastics. These standards declare requirements of experimental procedure and methods to calculate and measure (STFI 2016). A certificate is an official document that guarantees the quality of bioplastics and is accredited by organisations as DIN CERTCO and Vincotte in Europe, which are using common standards for bioplastics. Biodegradable products can also be certified in Sweden by the research institute RISE, which qualifies all waste qualities as mechanical recycling, biodegradation and energy recycling.

Certification qualifies corresponding labelling and RISE uses a labelling system for waste alternatives called Waste labelling, which covers industrial composting, home composting, biodegradable outdoors, digestion, mechanical recycling and energy recycling for certified products. Labelling products with the amount biobased content is not compulsory but can be voluntary labelled by producers (STFI 2016, RISE 2 n.d.). There is a positive attitude towards bioplastic and to experiment in the fields of bioplastics products from product developers. At the same time, there exists a chariness and scepticism concerning marketing bioplastics in fear of accusations of greenwashing (Brockhaus et al. 2016).

Despite certification systems, there are no standards for sorting and recycling of biobased plastic. This is however a current development area. Sweden, and Europe as a whole, are currently lacking operating systems for sorting and recycling as well for identification of biobased plastics (STFI 2016). Bio-PET is however an exception. Treated as petroleum-based PET, it is included in a PET recycling system with an appurtenant label and European Article Number code (EAN-code), making it possible to be sorted in available PET recycling machines (Returpack n.d.). Returpack, a company which is jointly owned by different actors in the breweries business and food merchants (Returpack 6 n.d.), is responsible for this recycling

(Returpack 2 n.d.). The activity is regulated by the Swedish Regulation (2005:220) of Recycle systems for plastic bottles and metal cans (SFS 2005). The deposit is an additional charge on the bottle being bought by the consumer which is refunded when pledged (Returpack 5 n.d.). Pantamera is a synonymous for Returpack and started as a commercial concept 2004 but has grown to a substitute brand for Returpack. Several commercial videos and songs have been released since then to increase consumer knowledge concerning (Bio-)PET and aluminium cans and the importance to recycle them. On the company' webpage, statistics of recycled bottles and energy saved due to this PET recycling system is presented to consumers in a graspable way (Returpack 3 n.d., Returpack 4 n.d.).

2 Method

The research questions required a study that had both an explorative and a descriptive design.

The question concerning the real bioplastic EOL scenarios in Sweden today required different methods of material collection and an inductive research logic which is needed in explorative research. Empiric material such as reports, information and statistics concerning plastic and bioplastic waste available on the web were examined in combination with interviews to complement for missing information. Available statistics and surveys of Swedish consumer habits and knowledge about bioplastic was also used. This material was used to answer the question of where the PLA and (Bio-)PET end up in their end of life scenarios. The result, occurring end-of-life scenarios, are presented under results.

The question of how the bioplastics effect the environment in the alternative scenarios derived from answering the earlier research question, were investigated with a literature study of prior knowledge of PLA and (Bio-)PET and their degradation processes in different environments. This issue was investigated with a more descriptive design and to answer this research question, scientific, peer-reviewed, literature was used. The results are presented under the title Environmental consequences which are found under each presented scenario under results.

Key words that were used in searching for material were "PLA degradation", "Bio-PET/BPET degradation", "bioplastic (PLA or Bio-PET)" in combination with "Life cycle analysis" or "LCA", "bioplastic consumer behaviour", "avfall bioplast statistik". Search engines that were used were Primo, Google scholar, Uppsala university library search tool and Google.

No or little statistics of quantities and end-of-life locations of bioplastics were found by any of the search engines but, in this study, it was assumed that bioplastics end up in about the same place as ordinary plastics.

3 Results

3.1 Bioplastics in plastic recycling system

In 2016, 212 500 tons of plastic packages were discarded in Sweden, (Bio-)PET-bottles exclusive, and only 99 700 tons of these where reported recycled, which is 47% (SMED 2018). In reality however, due to different conditions in the recycling system, only about 60% of the volume collected for recycling was actually recycled and converted into new materials (Material Economics 2018). In a survey made by the consumer association in Stockholm (KFS), consumers were asked how much more they were willing to pay for a shampoo bottle that was sustainable and made of recyclable material (NOVUS 2018). About 57% stated that they would be willing to pay approximately 1–8 SEK more for this product comparing to a bottle with unknown recyclability. Further, 24% of the respondents stated they were willing to pay 9 up to 20 SEK more, the latter being twice the price compared to the unknown bottle.

In another KFS survey, 57% of the consumers claim to always sort their plastic packages in home environment and 26% did it frequently (KFS 2018). All plastics packages, including the bioplastic ones, are intended to be recycled at recycling plants hired by Förpacknings & tidningsinsamlingen (FTI), a collection company for packages and newspapers, owned by different material companies in Sweden to meet the producer responsibility (FTIAB n.d.). When plastic food and drinking packaging reach the recycling plants, all plastic materials are being sorted for recycling purposes. This is conducted with Near InfraRed technique (NIR-technique), an automatic spectroscopic method for identifying and sorting different plastic materials, before processing the sorted materials into new products. A product which is not identified by the NIR technique is not recyclable in FTI hired recycling plants today (Interview Ahlström 2018).

Only a few bioplastics are being recycled in the recycling plants today and these are Bio-polyethylene (Bio-PE) and Bio-polypropylene (Bio-PP), which are biobased versions of the conventional synthetic materials and identical to them (Interview Ahlström 2018, Philip et al. 2013). Biodegradable and compostable plastics, such as PLA, are not being recycled in FTI hired recycling plants due to a perceived lack of quality in repeated use and reprocessing of the material (Interview Ahlström 2018; Soroudi & Jakubowicz 2013). PLA is problematic in conventional recycling due to an ageing processes that are highly affected by the material sensitivity to hydrolysis in moisture and increased temperatures, which leads to reduction in mechanical properties. The material can however be recycled at least two times in internal industrial environments before negative alterations, if the material is kept dry (STFI 2016). (Bio-)PET packages, other than (Bio-)PET recycling bottles, are not recycled since they often are laminates, a multilayer material of different materials, and therefore contaminated in a recycle perspective and the same goes for (Bio-)PET-bottles that are outside the PET recycling system (Interview Ahlström 2018; Interview Bergendorff 2018).

Recycling plastics and bioplastics are also problematic due to their diversity of various materials and chemical properties, which require customised treatments when processed into new materials. Another aspect which makes recycling problematic is the lack of research concerning possible recycling processes, mixability and durability. Durability of a material is important to examine since all plastics degrade through their life time (STFI 2016). Another criterion for material recycling is an existence of a second market for recycled material to become new products. Bio-PE and Bio-PP are examples of plastics that are both recyclable in terms of sorting processes and market desideratum. Because of deficiency in efficient ways to recycle PLA, but also an absence of second market for the recycled material, PLA is today being deported and used for energy recycling (Interview Ahlström 2018).

Environmental consequences

The Swedish organisation The Swedish Society for Nature Conservation (SSNC) is arguing that material recycling is a way to conserve some of the natural resources which makes it advantageous over energy recycling which consumes resources and emits CO_2 (Hedfors & Sigurjónsdóttir 2017). When it comes to biobased plastic materials, they are however commonly considered eco-friendly even though being used in energy recycling and incinerated. This is because of the concept of carbon neutrality which implies that the emitted CO_2 is converted by photosynthesis into new biomass which can be used for new products (Iwata 2015). Conventional petroleum-based plastics, on the contrary, are processed from fossil carbon which earlier was locked up in earth. Incineration of this fossil plastic therefore results in an increase in greenhouse gases (GHG) in the atmosphere (Hottle et al. 2013).

Climate change scoring is a score a material requires due to negative impact and emissions of GHG in a life cycle. A lower score means a lower negative impact on the environment. Materials have different scores in terms of end-of-life treatments. In comparison to the most common waste treatments, PLA demonstrate the lowest climate change score when recycled where the material regresses to new products. Since it has got a relatively high total net score of emissions from the production phase, the credit for recycling the material gets high. The impacts from recycling treatments are relatively low, with recycling process treatments having the most severe emission, giving PLA a net total score of around -0.70 kg CO_2 eq/kg PLA. This is comparable to industrial composting of PLA which has a net total climate change score of about 1.8 kg CO_2 eq/kg PLA and this is the highest net score of all EOL scenarios which are commonly institutionalized (Rossi et al. 2015). Facilities for industrial composting are however not instituted in Sweden or its vicinity today and this, together with earlier mentioned lack of knowledge and system for recycling bioplastic, is a reason why PLA ends up in energy recycling (Interview Ahlström 2018).

KFS claims that resent media cover about energy recycling as a replacing recycling method for plastic in Sweden is deleterious for the consumer trust of the recycling industry (KFS 2018). A consumer survey presented by NOVUS displayed that 96% of the respondents claim that they think recycling of plastic should increase and when given personal reasons for recycling plastic packages, 79% of the responders claimed that they want to contribute to a better environment and reduce resource consumption (NOVUS 2018).

3.2 Bioplastics in PET recycling system

Since Bio-PET from a molecular point of view is identical to petroleum-based PET (Prieto 2016) it is possible to recycle with petroleum-based PET-bottles. When it comes to (Bio-)PET-bottles, 21 300 of 26 000 tons were recycled which is 82%, but still under the goal of 90% (SMED 2018). Despite the high recycling rate, (Bio-)PET bottles consist only 10–-50% of recycled (Bio-)PET. To fulfil a circular economy the recycling percentage should be much closer to 100 (Hedfors & Sigurjónsdóttir 2017). (Bio-)PET has a high recycling value, only aluminium has a higher (Venkatachalam et al. 2012). Therefore, the recycling of (Bio-)PET is of high priority.

A recycling system that is separated from other plastic is an important aspect. This due to (Bio-)PET being very sensitive to contamination and if other plastic materials, such as PLA, is mixed into the recycling process it is problematic due to difficulties in distinguishing these two materials in the sorting process. The melting point of PLA is much lower than (Bio-)PET which would lead to defective product quality due to a high temperature in drying processes of (Bio-)PET production. In the initial stages of the recycling process, bottles are processed into flakes which are placed in water. These flakes do contain other plastics from labels and bottle caps, these plastics are however structurally different from (Bio-)PET and are easily removed by their lower density which makes them float in comparison to (Bio-)PET that sinks (Kuczenski & Geyer 2011).

Environmental consequences

Environmental impacts as global warming and usage of non-renewable energy in (Bio-)PET recycling industry have been investigated by Shen et al. (2011). The conclusion was that a recycling system which recycles (Bio-)PET one cycle could reduce environmental impacts with 20% in comparison to a system where (Bio-)PET is not recycled. Maximal reduction of impact was 26% in multiple recycling, but after three cycles, savings were negligible. Hottle et al. (2017) performed LCA on some of the most common bioplastics including bio-PET and petroleum-based PET. The end-of-life processes started with waste collection, followed by transfer station, material recovery facility and last recycling facility. According to LCA, Bio-PET and petroleum-based PET had the same impacts on the environment when recycled, but the difference was the production processes which resulted in different total impact on the environment. When it comes to environmental aspects as smog, acidification and ecotoxicity, Bio-PET had a much higher impact than petroleum-based PET. This was due to production aspects as farming and distillation which is needed to create ethylene for Bio-PET. Petroleum-based PET, on the other hand, showed higher emissions in global warming and fossil fuel depletion, unlike Bio-PET which even displays a negative value in terms of the latter aspect when recycled.

3.3 Bioplastics in incineration plant system

In the survey concerning consumers relations to plastic packages conducted by KFS, 11% of the consumer respondents answered that they sort their plastic occasionally and 5% that they never sort their plastic packages in home environment. The responders who answered that they never sort their plastic packages were given different pre-set statements for reasons for their behaviour. Of the respondents, 46% opined that they lacked the storage space for plastic packages. Some, 35%, claimed that distance to recycling stations were too long, and 22% claimed they lacked motivation due to other peoples’ evasion of sorting their waste. Some, 13%, claimed having trouble separating materials when packages are constructed of different materials. There were 13% who claimed the information about what happens to the plastic packages in recycle system is inadequate and 10% opined that sorting waste is unimportant (KFS 2018).

The consumer behaviour and arguments mentioned above are presumable reasons for plastic and bioplastic food and drinking packages end up in other waste systems. Between 1.2 and 2.1 kg packages and recycling paper are being misplaced in municipal solid waste (MSW), per person and week in Sweden today (Avfall Sverige 2 2018). The bioplastic placed in MSW are transported to the local incineration plant with other burnable waste and used for energy recycling. This waste process provides energy sources as heat and electricity to the municipality (Sopor.nu 2017).

The amount energy released in energy recycling varies for different bioplastics. PLA has a theoretical value of 18 MJ/kg, which is relatively low in comparison to Bio-PE with a theoretical value of 43 MJ/kg, which is about the same as fuel oil. However, in comparison to ordinary MSW which has an energy value of 8 MJ/kg, PLA produces about the double (STFI 2016). Remark could be made on the energy needed to produce PLA. The non-renewable cradle-to-grave energy required for PLA is 57 MJ/kg (Patel 2005). The energy recovered from incineration of (Bio-)PET is 30.2 MJ/kg which is about the same as for coal (Chanda & Salil 2007).

Environmental consequences

When it comes to GHG emissions and climate change, energy recycling PLA displays a relatively high climate change score compared to other waste processes; second highest to industrial composting which shows the highest GHG emissions (Rossi et al. 2015). The net total result of climate change score, including positive and negative aspects of the incineration process, is around 1.35 kg CO_2 eq/kg PLA. (Bio-)PET bottles that are not refundable or submitted to the PET recycling system should, and are often, transferred to the plastic recycling system and later deported to energy recycling (Returpack n.d., Interview Ahlström 2018). A study on biobased plastics from sugarcane ethanol such as Bio-PET and their GHG emissions and non-renewable energy use was conducted by Tsiropoulos et al. (2014). They concluded that GHG emissions from cradle-to-grave for Bio-PET is about 4 kg CO_2 eq/kg incinerated and that it requires about 60 MJ/kg non-renewable energy in a cradle-to-grave incineration scenario.

3.4 Bioplastics in the environment

Plastic, in forms of litter, is found everywhere where there are human activities in Sweden. Plastic is the most common waste on beaches and second most common in parks and urban environment. Globally 5–13 million tons of plastic end up in nature every year and Bohuskusten in Sweden is one of the most polluted areas in Europe. However, this area is shores of the North Sea and 80% of this litter is assumed to be waste from other countries (Hedfors & Sigurjónsdóttir 2017). Waste analyses show that one of the major waste groups which end up in marine environments is individual consumer packaging materials. It is assumed that most of this plastic litter in marine environments comes from land activities and 84% of Swedish consumers are aware of this according to KFSs survey (KFS 2017).

Seven out of ten Swedes think that littering is a big issue in urban environments and when it comes to plastics in the marine environments, eight of ten think it is a major issue (Håll Sverige rent 2018). One out of three Swedish consumers think that it would be more environmentally friendly not to use food packages according to a survey required by Tetra Pak (Unitedminds 2015). The consumption of fast food has increased, and a lot of the consumption is made "on-the-go". Fast-food plastic packages are often disposable packages and represent a lot of the environmental litter (Håll Sverige rent 2018).

The citizen-survey is an annual poll made by Statistics Sweden (SCB) to inquire citizens about their home municipal. Year 2017, the poll contained additional questions concerning littering, and one of the questions inquired were why the responders littered. Options were presented and multiple answers were selectable, the results were as follows: 15% of the respondents stated that they litter out of laziness; 18% stated that garbage cans are full; and 22% claimed that the litter could not be consider garbage. 39% claimed that there is no access to garbage cans. However, 41% of the respondents claimed that they are littering due to the materials composability (Håll Sverige rent 2018). Additionally, according to a KFS survey, 39% of Swedish consumers think that biodegradable plastic litter is harmless since they believe that the material is degradable (KFS 2017).

Environmental consequences

The rate of biodegradation of PLA and other biodegradable plastics is dependent on ageing processes affected by physico-chemical conditions of the environment, such as presence of oxygen, UV-light and temperature. Biological factors as specific microorganisms, bacteria and fungi, are also important as they excrete enzymes that degrade polymeric material and exploit the material for deriving energy (Rujnic-Sokele & Pilipovic 2017). The bioplastic molecular conformation, crystallinity, and material thickness are some of the most significant factors in the rate of biodegradation in different environments (Iwata 2015).

PLA degradation products are mainly CO_2 and H_2O and do not contain toxic substances and the material is even used for biomedical applications such as sutures and drug delivery systems since it is not hazardous to the human body (Xiao 2012, Du et al 2008). Some of the bioplastics, as PLA, can have positive effects on the soil, when degraded, including an increase in productivity and fertility (Fritz 2005). However, PLA degrade by a catalysed hydrolysis mechanism of ester bonds which is non-enzymatic and highly temperature dependent. In composts, with temperatures up to 70 °C, it can quite rapidly be depolymerised chemically and then metabolised by microorganisms. At common soil temperatures around 25°C however, the reaction is much slower due to the materials stiffer state below glass transition temperature, the temperature when a solid material softens and becomes rubbery but is not yet melted. PLA is therefore not suitable for home composting e.g. (Müller 2005, Rujnic & Pilipovic 2017). The rate of degradation is depended on the isomer ratio, of L- and D lactic acid, but also on the shape and size of the plastic (Garlotta 2001). A PLA material, which has a small surface in relation to material volume, has a slow and complicated hydrolysis (Haung 2005). PLA has in general a degradation rate of two years in soil environment, but the material can last more than ten years in dry conditions (Xiao 2012; InnProBio 2016, Haung 2005).

(Bio-)PET-packaging is accumulating in a high rate in the environment (Loakeimidis et al. 2016). The properties that makes (Bio-)PET a useful material in many aspects are also one of the reasons why it is deleterious to the environment; the high aromatic component ratio gives (Bio-)PET a high resistance to biodegradation due to microbial deficiency to attack these components (Müller et al. 2001). (Bio-)PET-bottles are not biodegradable and can therefore remain hundreds of years in Swedish nature, a general estimation of the degradation is 450 years (Pacheco-Torgal et al. 2012; Olshammar 2018).

Only a few bioplastics are considered degradable in marine environment (Rujnic-Sokele & Pilipovic 2017). Biobased non-biodegradable plastic as well as biodegradable plastic that do not degrade in an environment or do so in a slow rate pose a threat to the environment and the plants and animals within it (Iwata 2015). When animals ingest plastic waste, they are hazarding physical damage and blockage in gastrointestinal tract (Hedfors & Sigurjónsdóttir 2017). PLA are not considered biodegradable in marine environments (Byun & Kim 2 2014; InnProbio 2016). The biodegradation is too slow, a PLA-bottle degrades about 3.1% in 180 days and 5.7% in one year in marine environments (Greene 2012). If water-soluble and biodegradable plastic are accumulated and not degrade in a sufficiently high rate, the partly biodegraded plastic could create an acidic environment when accumulated which could affect the soil and plant growth.

The research concerning degradation rate for (Bio-)PET in marine environments are not conclusive, with a predicted degradation rate in different studies ranging from 16 to 93 years (Loakeimidis et al. 2016). (Bio-)PET is considered insensitive to degradation by hydrolysis (Prieto 2016). Regardless, hydrolysis is considered to be the most operative of the slow degradation processes and the rate could be different due to environmental conditions and photolysis from UV-light (Loakeimidis et al. 2016). Because of its high density, (Bio-)PET-bottles that end up in the ocean are sinking to the ocean floors (Loakeimidis et al. 2016). Low oxygen levels, lack of UV-light and less microorganisms makes the degradation in the ocean floors indolent, but eventually resulting in microplastics, which are plastic fragments that are smaller than 5 mm. (Bio-)PET, both in form of plastic and microplastic, would pose a threat to the marine biota in general since it can compile with invertebrates, microorganisms and microbial communities and many of the effects of plastics in the marine environment have not often been investigated (Hedfors & Sigurjónsdóttir 2017, Loakeimidis et al. 2016). There is however a relatively new discovery of an enzyme that could play an important role in future waste systems. PETase is an enzyme that has been discovered to digest (Bio-)PET, expressed by the bacterium *Ideonella sakaiensis 201-F6*, which possesses the rare ability to grow on (Bio-)PET. Due to this ability, this enzyme is a possible future degradation alternative in plastics waste systems (Yoshida et al 2016).

4 Discussion

4.1 Recycling end-of-life scenarios

PLA is compostable bioplastic for food and drinking packages but Swedish institutions handling plastic waste, e.g. FTI, are referring it, and collecting it, as recyclable plastic. Later, it is however treated as combustible material. PLA could favourably be recycled considering environmental factors as GHG emission in waste processes. Another aspect is the reduced non-renewable energy loss, due to higher production in incineration scenario. Recycling PLA has a negative total climate change score of -0.70 kg CO_2 eq/kg, making it a favourable option in comparison to a compost scenario. Composting PLA has a total climate change score of 1.8 kg CO_2 eq/kg, which actually is the highest of all commonly institutionalized end-of-life scenarios and therefore the least favourable option viewed in climate change scoring.

There is however a scepticism in material durability and quality when PLA is recycled. It is not considered performable. There is however interesting research conducted on recycled bioplastic blends (See Wu & Hakkarainen 2014 e.g.) such as PLA mixed with other additives as thermoplastic starch (TPS) to form PLA/TPS blends with good qualities, and research like this explore the field of recycling for future waste management.

Swedish citizens are by law obliged to sort their bioplastic food and drinking packages in recycling stations but only 71% of Swedish consumers are aware of this. When answering consumer surveys, 57% of the consumers claimed to always sort their plastics and 26% claimed to do it frequently. The waste statistics is however telling a slightly different story, only 47% of plastic packages reaches the recycling stations. When using and analysing consumer surveys, a special care should be taken, that people might be prone to state ideas about their consumption from social instituted norms. What people do and what they claim to do are often two different things and this is concluded in the Tucson Garbage Project which were a sociological and archaeological study of Arizona resident' waste. The project gathered quantitative data from the residents' waste bins and compared with information gathered from the residents themselves with the conclusion that respondents stated consumption habits not always reflect their real ones (Buchli & Lucas 2001).

Bio-PET is a bioplastic which are considered recyclable today and most Bio-PET bottles ends up in the recycling system. This is eligible in a circular economy. If the Bio-PET bottle is not appurtenant in the PET recycling system or lack the obliged EAN-code, it is also referred to as ordinary recyclable plastic and later treated as combustible material. (Bio-)PET recycling reaches a much higher collection percentage than other bioplastics, about 82%. There seems to be a notable difference in the investment for knowledge dissemination in this system. There is e.g. advertising and campaigns to inform consumers of the favourable environmental impacts of the PET recycling system. The negative environmental impacts of (Bio-)PET recycling are decreased for every cycle, there is a between 20-26% lower impact than incineration, until the third cycle where savings were negligible.

Could a deposit system along with campaigns about discard and environmental benefits, similar to those of (Bio-)PET, also affect consumer behaviour in terms of other bioplastics as PLA? Another question that rises is; could a stricter and more consequent labelling of plastics give better results concerning both misplaced plastic packages but also ease the sorting system leading to potential recycling of material that are currently incinerated? SSNC are proposing labelling of plastic products or a system where information about the material is given in a QR-code or a chip. They emphasize that clean plastic fractures facilitate recycling and a higher second material value (Hedfors & Sigurjónsdóttir 2017). But as Röper & Koch argue (1990) this would be costly and who is to pay the price? In the PET recycling system, a deposit is taken at the time of purchase, but would this be performable for bioplastic food packages?

According to earlier mentioned survey, a majority of the consumers were willing to pay more for a sustainable and recyclable shampoo bottle (NOVUS 2018). It should be noted however that this example only covers one product. What reactions would emerge if all plastic products had a deposit fee? This conception of customers willingness to pay for sustainable options are not supported by Brockhaus et al's study of developers' challengers concerning bioplastics (Brockhaus et al 2016). They found that developers are having trouble entering bioplastic products on the market despite consumer favouring these products. According to developers, consumers are often stating willingness to pay extra for bioplastic products but in real life scenarios, they are however not willing to pay the price.

4.2 Incineration end-of-life scenarios

Consumers that do not sort plastic packages in the institutionalized way, due to various reasons, most commonly lack of storage space and distances to recycling stations, are responsible for between 1-2 kg recyclable material being misplaced in MSW. These are incinerated together with other waste groups and energy is recycled in terms of heat and electricity. The question is, however, if this misplacement of bioplastics is more damaging to the environment at the time, than the institutionalized waste management which collect bioplastic and transport it to recycling plants. Since bioplastic at the time is incinerated and not recycled in FTI hired recycling plants, could incineration in local MSW incineration plants even be more favourable in terms of reduced GHG emissions due to potential shorter transport distances to incineration locations? The question is, however, if there, at the recycling plants, are special incinerators, modelled for plastic fuel and given higher efficiency in capture energy from the specific material.

PLA have a relatively high climate change score when incinerated in comparison to other waste methods, 1.35 kg CO_2 eq/kg. Only industrial composting has a higher value. Considering a relatively low energy release when incinerated, about 18 MJ/kg, and a relatively high energy needed to produce and incinerate PLA, about 57 MJ/kg, an energy loss of about 39 MJ occurs for every kg PLA incinerated. Bio-PET bottles which are incinerated have even higher GHG emissions, about 4 kg CO_2 eq/kg which is about three times more comparing to PLA. The energy needed to produce and incinerate Bio-PET is 60 MJ/kg and the energy released when incinerated is about 30.2 MJ/kg. This leads to an energy loss of 30 MJ/kg which is less then PLA but still relatively high. This aspect, in combination with high GHG-emissions makes incineration less favourable alternative for PLA and Bio-PET waste management.

4.3 Environment end-of-life scenarios

Plastic packaging litter is an issue in Sweden today, both in urban and natural environments. Common reasons for littering are lack of useable garbage cans, laziness and claims of items not being regarded as litter. The most common reason, however, is that the litter is regarded as compostable. Additional are 41% of Swedish consumers of the opinion that biodegradable plastic litter is harmless since the material is degrading in nature. There seems to be misconception of concepts as biodegradable and compostable, which also could be a relevant factor for bioplastics being misplaced and littered despite a quite good awareness of environmental impacts of common plastic litter.

Biodegradable plastics have degradation processes that are highly dependent on environmental circumstances such as temperature, UV-light and microbial activity. The results indicate that PLA does not qualify as compostable in temperatures below 70°C and that the material can be problematic in the Swedish environment due to a deficiency in biodegradation in colder and dryer conditions. PLA have a very slow degradation rate in marine environments which can have a large influence on marine life. PLA litter is a possible hazard for ecosystems and the labelling of PLA should most profitable declare discard declaration to avoid possible misunderstandings in terms of biodegradable bioplastics. Another remark should be issued concerning the fact that different additives are commonly used in bioplastics to alter the material properties e.g. hydrophobic properties (See Cyras et al. 2008; Baumberger et al. 1997), which potentially could impair the ability to biodegrade in environmental scenarios.

(Bio-)PET are as hazardous to the environment as petroleum-based PET, possessing an inert rate in terms of biodegradation. How inert is however still debateable considering varieties in research conclusions and could much likely differ due to material thickness of bottles, UV-light irradiation and environmental factors. Since the environmental factors can vary, the graves and end-of-life scenario for (Bio-PET) should be carefully investigated for Swedish environmental circumstances. When it comes to Bio-PET bottles which end up in marine environment it is assumable that the material moves from different water habitats and therefor affect other countries and environments. Thus, a more global approach would be required concerning marine end-of-life scenarios, with different water habitat degradation processes examined. This was performed by Tosin et al. (2012) who conducted a study of plastic degradation in three different marine environments but concluded that a test methodology which were based on six marine habitats was needed since plastic tends to move long distances

It was in general difficult to find information concerning consequences in ecosystem derived from biodegradation in examine studies. This is something Janik et al. (2018) also has noticed. The authors argue that studies are scarce which are analysing the final biodegradation where products as CO_2, H_2O and CH_4 and biomass are released in the marine environment after incubation of biopolymers. These aspects would be interesting issues for future research studies. When studying the results of different biodegradation experiments for PLA and (Bio-)PET, they are often only describing biodegradation to a certain percent. This was interesting since biodegradation is a process which is supposed to be complete (STFI 2016).

4.4 Conclusions

- End-of-life scenarios for PLA are incineration and slow or inadequate biodegradation as litter in Swedish urban and natural environments as well as surrounding marine environments. Bio-PET institutionalized end-of-life scenarios are recycling and incineration. In a third scenario it degrades in an extremely slow rate as litter in urban and natural environments as well as surrounding marine environments.
- Some environmental impacts from institutionalized PLA waste management are increasing GHG emissions in comparison to material recycling which decreases these impacts with a climate score value of - 0.70 kg CO_2/kg PLA. Environmental impacts from Bio-PET in institutionalized PET recycling system are a decrease in GHG emissions in comparison to incineration scenarios.
- Degradation of bioplastic packages, made of PLA and Bio-PET, is very depending on environmental biological and physico-chemical conditions such as certain microorganisms, temperature, moisture, UV-light and oxygen levels. Molecular properties and shape of the product are also affecting the degradation rate.
- PLA biodegradation in Swedish soil conditions are slow, it approximately degrades in 2 years but can last up to 10 years in dry conditions. In marine environments it could not be considered biodegradable since the degradation rate is too slow, only 5.7% degradation in one year.
- Bio-PET is not biodegradable and are estimated to remain hundreds of years in Swedish soils. Research of degradation rate in marine environments are scattered but estimates between 16-93 years.
- Slow or inadequate degradation of bioplastic packages leads to damage in the environment such as plastic fragments; compiling with marine invertebrates and microorganism; acidifying when accumulated, affecting soil and plant growth; damaging gastrointestinal tracts of various organisms. Environmental consequences of bioplastic and its degradation processes are still not sufficient studied and research in this area is momentous.
- There could be a danger in marketing and labelling bioplastic as biodegradable and compostable since these properties often require specific staged environmental conditions. More research of consumer behaviour and awareness, as well as knowledge dissemination from affected actors is needed to produce a clearer picture of actual EOL scenarios. Knowledge about these scenarios are of great importance in performing accurate LCA and would further make analyses of environmental consequences of these life cycles more accurate.

Recyclable materials from renewable resources with versatile and resistant properties, suitable for food and drinking packages, are favourable, but do they need to be biodegradable? This study shows that adroit biodegradation properties in different environmental habitats are still important material properties in a society and economy which still has not closed its circular loop.

4.5 Remarks

Care could be taken regarding that peoples' interest could affect the likelihood and willingness to answer voluntary surveys concerning a certain subject, and therefor leaving a misrepresented image, but a delving in these concerns are not possible within the limits of this study.

4.6 Acknowledgment

I would like to express a great gratitude to my eminent supervisor Kristine Koch and to Mikael Pell and the Department of Molecular Sciences for being open and encouraging to this unconventional bio-civic study.

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