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SUSTAINABLE PLASTICS: A COMPARISON OF FULLY BIO-BASED BIODEGRADABLE PLASTIC AND FULLY FOSSIL-BASED NON-BIODEGRADABLE PLASTIC

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ABSTRACT

The aim of this thesis was to give more insight in the environmental impacts of plastic. Two plastic types -the fossil-based non-biodegradable plastic LDPE and the bio-based biodegradable plastic PLA- have been compared to each other in order to gain a level of sustainability. The Netherlands agreed to strive for a curtail in greenhouse gases and thereby to reduce global warming. Sustainability, and especially environmental sustainability is a critical component. In this thesis environmental sustainability is measured based on the emission of CO_2.

The question that has been answered is: To what extent is the production and disposal of bio-based biodegradable plastic more environmentally sustainable than the production and disposal of fully fossil-based non-biodegradable plastic in the Netherlands, when looking at the emission of CO_2? A literature study has been conducted in order to answer the research question. The results showed that PLA is indeed more sustainable, with a difference of 0.8 kg CO_2/kg plastic. In the life cycle of PLA, 2.1 kg CO_2/kg plastic is emitted, in contrary to 2.8 kg CO_2/kg plastic for LDPE. This difference is not exceedingly large, but it can be concluded that there is an urgent need to reduce the amount of plastic used.

SAMENVATTING

Dit onderzoek heeft meer inzicht gegeven in de milieueffecten van plastic. Twee soorten plastic -het op fossiel gebaseerde niet biologisch afbreekbare plastic LDPE en het op biomassa gebaseerde biologisch afbreekbare plastic PLA- zijn met elkaar vergeleken om een mate van duurzaamheid te bepalen. Nederland heeft afspraken gemaakt om te streven naar een beperking van broeikasgassen en daarmee de opwarming van de aarde te beperken. Duurzaamheid, en met name duurzaamheid van het milieu, is hierin een cruciaal onderdeel. In dit onderzoek wordt de duurzaamheid van het milieu gemeten op basis van de uitstoot van CO_2.

De vraag die beantwoord is, is: In hoeverre is de productie en afvalverwerking van het op biomassa gebaseerde biologisch afbreekbaar plastic duurzamer voor het milieu dan de productie en afvalverwerking van volledig op fossiele brandstoffen gebaseerde niet-biologisch afbreekbaar plastic in Nederland, wanneer gekeken wordt naar de uitstoot van CO_2? Een literatuurstudie is uitgevoerd om de onderzoeksvraag te beantwoorden. De resultaten toonden aan dat PLA inderdaad duurzamer is, met een verschil van 0,8 kg CO_2/kg plastic. In de levenscyclus van PLA wordt 2,1 kg CO_2/kg plastic uitgestoten, in tegenstelling tot 2,8 kg CO_2/kg plastic voor LDPE. Dit verschil is niet uitzonderlijk groot, maar er kan worden geconcludeerd dat het dringend nodig is om het gebruik van plastic te verminderen.

Table of Content

Abbreviations

CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
Gton	Gigaton
Kg	Kilogram
Kton	Kiloton
LDPE	Low density polyethylene
Mton	Megaton
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinylchloride

INTRODUCTION

Plastics are used excessively and for various purposes. There are many different types of plastic, that all have other production processes. The largest market for plastic is packaging. In 2015, 39.9 percent of all plastic was used for packaging, while the remainder was used for building & construction, automotive, electronics and others (PlasticsEurope, 2016). This would not be problematic if the product used had a sustainable life-cycle. However, in the process of making plastics, a lot of CO_2 is emitted into the atmosphere, which has adverse effects on the environment. Considering the enhanced greenhouse effect, sustainability is an important concept. The 2015 climate conference in Paris and the consecutive agreements that the global temperature must not increase with more than two degrees Celsius, resulted in the ratification of these agreements by the Netherlands in 2016. The Netherlands thereby agreed to strive for a curtail in greenhouse gases and to help reduce global warming (IPCC, 2018). The CO_2 emission should therefore be kept as low as possible in order to reduce global warming and its negative effects for the world's society. When talking about sustainability four aspects require consideration: environmental, social, cultural and economic. Amongst which, environmental sustainability is stated to be the most fundamental aspect (New Zealand Government, 2017). Environmental sustainability is defined by Morelli (2013, p.23) as follows:

> "A condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity."

This broad definition highlights the width of the concept of environmental sustainability. Environmental sustainability has different important components, of which climate change is one of. Thus, it is of great importance to eliminate as much of the influential factors, such as the production of plastic. Most plastics are made of fossil fuels and are not biodegradable, which leads to an increasing amount of waste that needs to be incinerated. One of the plastics that is most widely used is the fully fossil-based non-biodegradable plastic low-density polyethylene (LDPE). Most plastics are made on the basis of ethylene, of which 58 percent is converted to LDPE (Shen, Worrel & Patel, 2010). Most of the packaging for food and plastic bottles is made of this material. Not only in the process of producing the plastics is the emission of CO_2 alarming. CO_2 is also emitted in the disposal of the product. At the moment it is difficult to separate plastics efficiently, because of the different types of plastic used. For consumers it is nearly impossible to recycle all the plastic types separately. In the Netherlands, this leads to incineration of the plastics that were intended for recycling (CPB, 2017).

Thesis objective and research question

Fully fossil-based non-biodegradable plastics will not leave the ecosystem. The plastic soup is one of the best-known problems regarding the plastic accumulation. Luckily, in the course of time more biodegradable plastics have entered the market in order to achieve a more sustainable society. Since this plastic is degradable, incineration is not necessarily required. However, there are different types of biodegradable plastic, mainly fossil-based and bio-based. The production of biodegradable plastics results in a decrease of products that have to be incinerated. Fully bio-based plastics insinuate to be more sustainable, but the question remains if bio-based biodegradable plastics are indeed more sustainable than fossil-based non-biodegradable plastics. This thesis will give more insight in the environmental impacts of plastic. Environmental sustainability is, as said before, a broad concept and can be measured with regard to different aspects. This thesis focuses on the emission of CO_2 to give a quantitively analysis concerning the sustainability of plastics. In order to look at the difference in sustainability between bio-based biodegradable plastic and fossil-based non-biodegradable plastics based on the CO_2 emission I have come up with the follow research question:

To what extent is the production and disposal of bio-based biodegradable plastic more environmentally sustainable than the production and disposal of fully fossil-based non-biodegradable plastic in the Netherlands, when looking at the emissions of CO_2?

The subsequent sub-questions are:

1) How is bio-based biodegradable plastic produced and disposed?
2) How is fully fossil-based non-biodegradable plastic produced and disposed?

These two types of plastic will be taken into consideration for answering the research question because they are the most distinctive plastic products, which will give an interesting analysis. Additionally, there is an active academic debate about the CO_2 emissions of these products, providing the researcher with a lot of data. Herein, CO_2 is a suitable sustainable indicator. This thesis will only take domestic usage and disposal of the plastics into consideration, because there is a lot of data available and therefore a clear overview can be given of the impact in the CO_2 emissions in the Netherlands.

THEORETICAL FRAMEWORK

In order to know how bio-based biodegradable plastic and fossil-based non-biodegradable plastic compare to each other regarding sustainability, it is important to know which factors and theories are important considering environmental sustainability. Since there is no clear distinction for what is considered sustainable, both plastics will be compared to each other and from those results an order of sustainability will be established. In this study a comparison has been made on the basis of CO_2 emissions, because that is one of the most significant aspects when investigating sustainability (Flemström, 2003). This environmental aspect will be applied to bio-based biodegradable plastic and fully fossil-based non-biodegradable plastic.

What accounts for sustainability?

Sustainability can be interpreted as "the ability of the earth's various natural systems and human cultural systems and economies to survive and adapt to changing environmental conditions indefinitely." (Miller & Spoolman, 2009). As mentioned in the introduction, sustainability requires consideration of different aspects. One critical component of sustainability is environmental sustainability, or natural capital. This refers to the natural resources and natural services that support our economies and keep human beings and other forms of life alive (Miller & Spoolman, 2009). Humankind is dependent on the natural resources, which can be renewable or non-renewable. Examples of non-renewable sources are fossil fuels, like coal and oil. It is important to acknowledge that human activities can degrade natural capital. Environmental degradation, when the natural replacement rate of a resource is exceeded, happens regularly. The environmental conditions are changing fast, and climate change is a well-known aftereffect. The increasing amount of greenhouse gases in the atmosphere has severe effects on the greenhouse effect, causing the Earth's surface temperature to rise (Goose, 2015; Lashof & Ahuya, 1990). The emission of greenhouse gases is described as the carbon footprint, which is quantified as CO_2- equivalents. The less greenhouse gases that are emitted into the atmosphere by anthropogenic sources, the more it accounts as sustainable (Röös, Sundberg, Tidåker, Strid, Hansson, 2013). The emission of greenhouse gases is one level of measurement for environmental sustainability, other examples are land use, water use, or chemical pollution. These are of great importance as well but will not be examined in this research in order to give the specified view of the state of the emissions of carbon dioxide due to the production and consumption of plastics.

Plastic types and their share in waste

Plastic was invented in the 1860s, but the production strongly increased in the 1940s when it became one of the fastest-growing global industries. Plastics are human-made materials manufactured from polymers, various complex organic compounds, or long chains of repeating molecules (Geyer, Jambeck & Law, 2017). According to Gourmelon (2015), the plastic growth averaged 8.7 percent per year, from 1950 to 2012. The plastic production kept on growing as plastic gradually replaced materials like glass and metal. "By 2009, plastic packaging accounted for 30 percent of packaging sales." (Gourmelon, 2015, p.1). Europe produces 22.9 percent of the world production of plastic materials. The most common plastics are based on fossil fuels, a non-renewable source. Geyer et al. (2017) state that fossil hydrocarbons are used as the raw material for the vast majority of monomers used to make plastics, such as ethylene and propylene. They stress that none of the commonly used plastics are biodegradable. Van den Oever, Molenveld, van der Zee and Bos (2017) endorse this in their report, stating that only one percent of the plastics used is biodegradable. Hence, the plastics accumulate, rather than decompose in the natural environment. Even though the most common plastics are derived from fossil fuels, there are a total of six types of plastic, namely: fully fossil-based non-biodegradable, fully fossil-based biodegradable, partly bio-based non-biodegradable, partly bio-based biodegradable, bio-based non-biodegradable and bio-based biodegradable (Shen, 2017). The fully-fossil based non-biodegradable plastic is used most frequently.

In the category of fully fossil-based non-biodegradable plastic, PE plastics are the group most produced for packaging. Amongst which, low density polyethylene (LDPE) is the biggest producer. LDPE will be used to investigate the CO_2 emissions of fossil-based non-biodegradable plastics.

Sustainability of plastic

Most plastics are made of non-renewable sources and are therefore not contributing to a sustainable society. In the production process of plastic, greenhouse gases are emitted. This differs for the types of plastic and for the different groups, since they have different production processes. However, since most plastics are made out of fossil fuels, the greenhouse gas emissions are considerable. According to Miller and Spoolman (2009) 43 percent of the global CO_2 is caused by burning oil. This is however, including oil for transportation. Thus, the materials of which the plastics are made are of great importance for the amount of greenhouse gas emitted (Geyer et al., 2017). Since the Netherlands incinerate most of their waste, greenhouse gases are also emitted during the waste management (CPB, 2017). This is accountable for the non-biodegradable plastics. For the biodegradable plastics this does not have to be of importance, since these plastics can decompose in a relatively short time if well managed (Iwata, 2015). However, some of the fossil-based plastics are recycled and therefore are not contributing to an increase in greenhouse gases emitted.

The fully bio-based biodegradable plastic PLA

Bio-based plastic are plastics made from biomass. The production of bio-based plastics is expected to grow rapidly, since the environmental issues are becoming more illustrious. Thereby, is the depletion of fossil fuels another motivator to search for alternatives (Shen et al., 2010). According to Posen, Jaramillo and Griffin (2016), the bio-based plastics only accounted for less than one percent of the global thermoplastic production. This is expected to grow to 4.4 percent, reaching nearly seven million tonnes (Mt) by 2018. Polylactic acid (PLA) is a bio-based biodegradable plastic that is heat resistant and can be compared best to LDPE for tensile strength and usage (Shen, 2017). PLA is one of the most used alternatives for fossil-based plastics. It is described as follows by Shen, et al. (2010, p.35): "PLA is an aliphatic polyester, produced via the polymerization of lactic acid which is a sugar fermentation product.". PLA became the first bio-based plastic produced on a large-scale. PLA will be used to investigate the CO_2 emissions of bio-based biodegradable plastics.

Even though biomass can be renewable if well managed, and as a starting point carbon neutral, during the process towards the end product carbon is emitted. As van der Hilst et al. (2018, p.2) state: "[…] carbon is sequestered during growth of biomass and released when combusted. However, also the production of bioenergy and biobased materials causes greenhouse gas (GHG) emissions throughout the whole life cycle (cultivation, harvesting, transport, processing, distribution, use, and disposal).". This causes the biomass to be not fully carbon neutral by default.

Data analysis and conceptual model

The scientific concepts and theories have laid the fundament for this research. To give a clear overview of how the different variables connect to the research, a conceptual model is executed, see figure 2. The dependent variable is sustainability, illustrated by a yellow shape. This is influenced by the CO_2 emission in the Netherlands caused by plastics, illustrated by another yellow shape. The CO_2 emissions are initially influenced by two independent variables, and a mediating variable. They are illustrated by a yellow framework and a green framework. The variables are examined through a literature study. The findings of these studies will be combined in order to find explicit information. The first independent variable is the type of material used to produce the plastic, this could be either fossil-based or bio-based. The second independent variable is the disposal of the plastic; this could be either incinerated, recycled or degraded. The mediating variable is the production process, which influences the amount of CO_2 emitted for the material used.

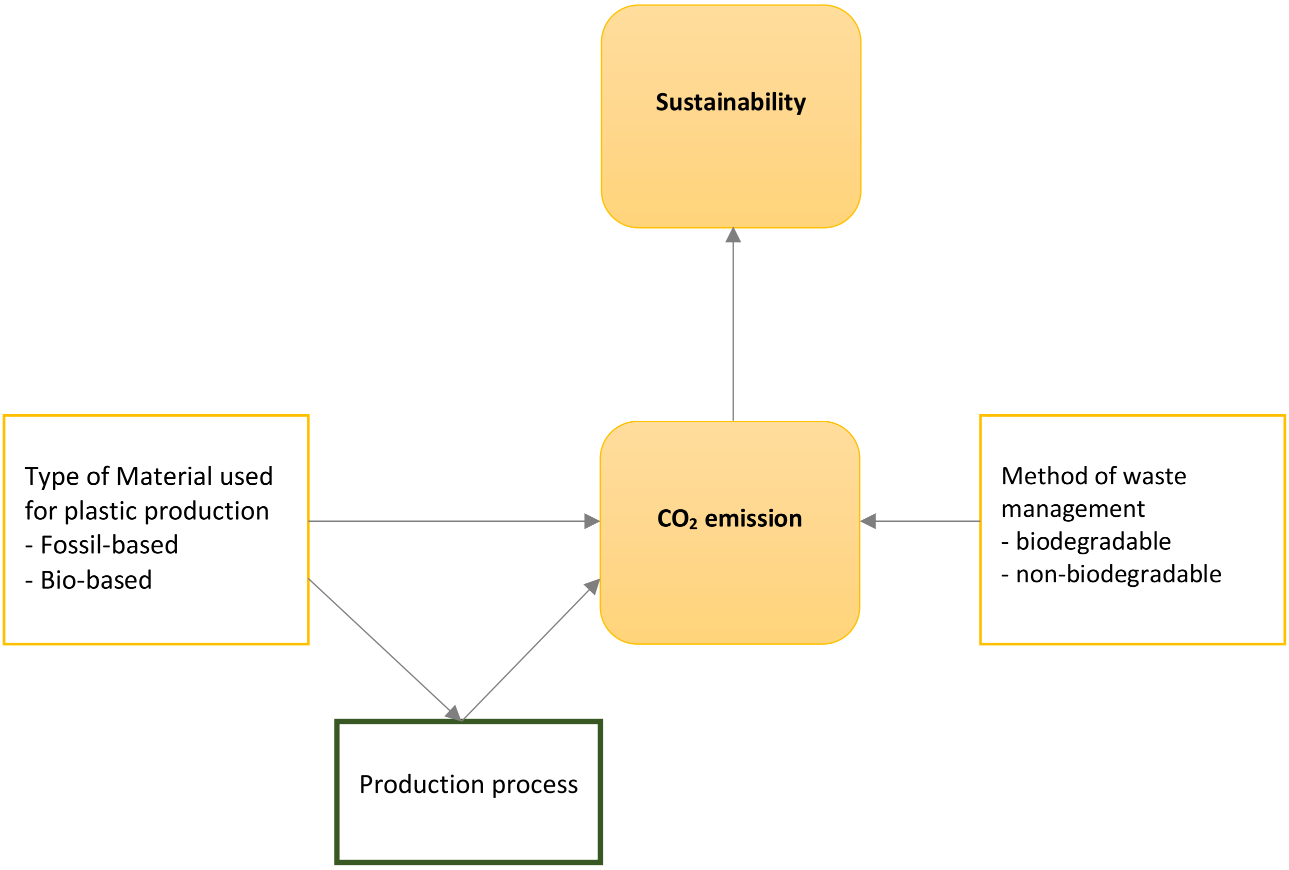

FIGURE 2: CONCEPTUAL MODEL WITH TWO INDEPENDENT VARIABLES; TYPE OF MATERIAL AND METHOD OF WASTE MANAGEMENT, A MEDIATING VARIABLE; PRODUCTION PROCESS AND THE DEPENDENT VARIABLES; CO2 EMISSIONS AND SUSTAINABILITY.

Method

This chapter shows how and with which data this research has been carried out. The information search plan describes how the data has been collected, and the data-analysis shows how this data has been processed.

Data collection

This thesis includes a literature review in the form of a research paper. In order to execute this research, different types of data are needed. The current academic debate will be analysed using articles, journals, and websites found with search engines like Google, Google Scholar, Scopus and Web of Science. The associated data is presented in table 1. This shows the type of data, the keywords and the information needed.

TABLE 1: DATA COLLECTION TABLE WITH CATEGORIES, INFORMATION, KEYWORDS AND TYPE OF DATA

Category	Information	Keywords	Type of Data
Sustainability	Information about what accounts for sustainability	Sustainability, sustainable, natural capital	Scientific articles, informative books
Types of plastic	Information about the different types of plastic and their distribution	Plastic types, categories of plastic	Scientific articles, scientific reports
Life cycle analysis fossil-based non-biodegradable plastic	Information about the production and disposal of fossil-based non-biodegradable plastic	LCA fossil-based non-biodegradable plastic, production fossil-based non-biodegradable plastic, disposal fossil-based non-biodegradable plastic	Scientific articles, statistics, scientific reports
Life cycle analysis bio-based biodegradable plastic	Information about the production and disposal of bio-based biodegradable plastic	LCA bio-based biodegradable plastic, production bio-based biodegradable plastic, disposal bio-based biodegradable plastic	Scientific articles, scientific reports, statistics
CO2 emitted LCA fossil-based non-biodegradable plastic	Information about the CO2 emitted in the LCA of fossil-based non-biodegradable plastic	Carbon footprint fossil-based non-biodegradable plastic, CO2 emission fossil-based non-biodegradable plastic	Scientific articles, scientific reports

CO2 emitted LCA bio-based biodegradable plastic	Information about the CO2 emitted in the LCA of bio-based biodegradable plastic	Carbon footprint bio-based biodegradable plastic, CO2 emission bio-based biodegradable plastic	Scientific articles, scientific reports
Disposal policy Netherlands	Information about the policy concerning the waste process of plastic	Netherland waste processing, Plastic recycling Netherlands, Disposal policy plastic Netherlands	Governmental website, newspapers

RESULTS

In this chapter the sub-questions will be answered. The two sub-questions relate to the extent in which the production and disposal of fossil-based non-biodegradable plastic is more sustainable than the production and disposal of bio-based biodegradable plastic, based on the emissions of CO_2.

Production and disposal of fossil-based non-biodegradable plastic

In this sub-chapter the production and disposal process of LDPE will be described. The share of incinerated plastics and recycled plastics will be investigated in order to determine the amount of CO_2 emitted in the life cycle of this product.

Production process of LDPE

As mentioned in the theoretical framework, LDPE is the most common fossil-based plastic. LDPE is a material produced with a high-pressure process and under high temperatures, which causes the polymer to melt. This process is typical for LDPE. In figure 3 the production process is shown. After production, the obtained polymer can be mixed with additives and be moulded into shape (Kolarz, Burchart-Korol & Krawczyk, 2010). It is unclear how much plastic is produced in the Netherlands. One of the reasons for this is that the quantity of plastics in products that consist partly of plastic are not registered. However, KIDV (2016) found that circa 475 kton of plastics annually enters the Dutch market of which 35.24 percent consists of PE plastics (van Velzen et al, 2013). This results in circa 167.39 kton of PE plastics, displayed in table 2, which is only two percent of the amount of LDPE in Europe (RIVM, 2014). Of the circa 475 Kton plastics, two third ends up with the household waste, see figure 4. This applies to all types of plastics.

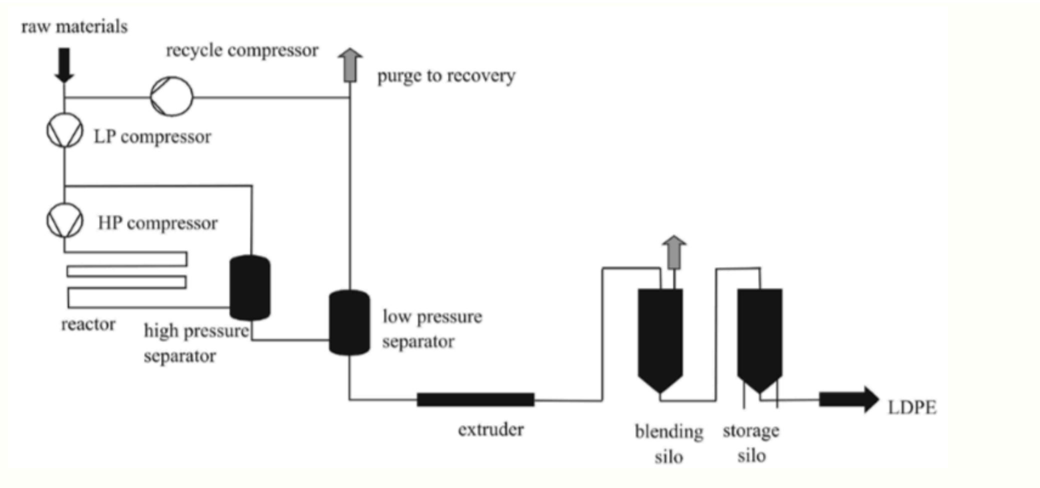

FIGURE 3: PRODUCTION PROCESS OF LDPE AS ILLUSTRATED BY CZAPLIVKA-KOLARZ, BURCHART-KOROL AND KRAWCZYK (2010)

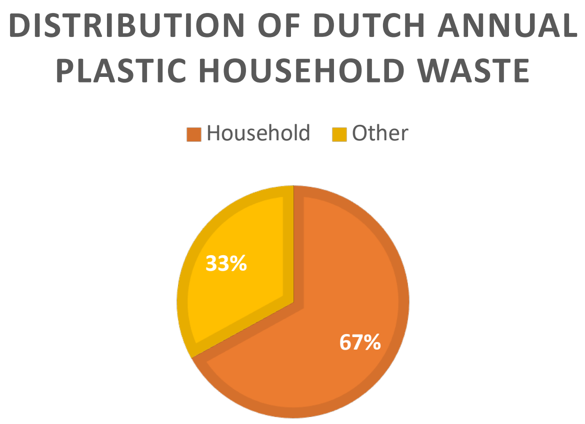

FIGURE 4: DISTRIBUTION OF DUTCH ANNUAL PLASTIC WASTE INTO HOUSEHOLD AND OTHER

In the production process of LDPE, the use of fossil fuels results in relatively high amounts of CO_2 emissions during its production. Around 20 percent of the global emissions come from the production of -amongst others- plastics. Other materials like paper, glass, iron, steel, and aluminium are included as well. Nonetheless, plastics are the material that is recycled least of all these materials (Ecofys, 2013). Furthermore, it is expected that the global use of fossil-based non-biodegradable plastics will strongly increase from 320 Mton to around 1.1 Gton in 2050 (CPB, 2017).

TABLE 2: ANNUAL AMOUNTS OF PLASTICS – POLYETHYLENE (PE), POLYETHYLENE TEREPHTHALATE (PET), POLYPROPYLENE (PP), POLYVINYLCHLORIDE (PVC), POLYSTYRENE (PS)- ON THE DUTCH MARKET; TOTAL -DOMESTIC AND COMPANY WASTE (VAN VELZEN ET AL., 2013).

	Quantity (Kton)	*Percentage*
PE	167.39	35.24
PET	89.49	18.84
PP	82.84	17.44
PVC	14.82	3.12
PS	21.42	4.51
Other	99.03	20.85
Total plastics	475	100

Disposal of LDPE

There are different household waste managements in the Netherlands and for fossil-based plastics the most common methods are recycling and incineration. The Dutch government has many methods, policies and local initiatives to separate the household waste as efficient as possible (Rijksoverheid, 2018). The different municipals in the Netherlands have their own separation methods for household waste. The separation of the household waste has been refined over the years. In 2009, a relatively low amount of 25.2 kton of household waste was collected separately, but this number has increased to 162 kton in 2014, as shown in table 3 and figure 5. Of the household waste that is collected separately, 90 percent is recycled (KIDV, 2016). The Netherlands have enacted landfills bans for plastics (Gourmelon, 2015), and since LDPE is a non-biodegradable plastic the other ten percent is incinerated. Figure 6 shows the distribution of waste management of the separated collected household waste. Even though the Netherlands are actively improving their household waste management methods, plastics do not always end up in the designated place. One to two percent of the bio-based household waste consists of plastics, which neither is recycled nor incinerated with the other plastics. Instead, it will be processed together with the green waste and ends up in the surface water via compost (CPB, 2017). Jonge (2004) states that even five percent of the green waste consist of plastic. Unfortunately, the article does not state what type of plastic is found with the green waste. However, it is likely that LDPE is present since most packaging is made of LDPE. Besides the green waste, residual waste also consists for fourteen percent out of plastics. The residual waste is incinerated, and CO_2 is emitted. Obermoser, Fellner and Rechberger (2009), examined the incinerators of several Western countries and state emissions differing from 293 kg CO_2 per ton residual waste to 557 kg CO_2 per ton residual waste. In the Netherlands, 914 kton of residual waste is incinerated each year (Rijkswaterstaat, 2016). Consequently, 267.8 million kg to 509.1 million kg CO_2 is emitted annually, displayed in table 4. Those emissions are partly the result of plastics, like LDPE, that get incinerated. However, other studies who investigated the emission of CO_2 in the life cycle of LDPE, do not take plastics into consideration.

TABLE 3: INCREASE FROM 2009 TO 2014 OF WASTE THAT GOT COLLECTED SEPARATELY IN THE NETHERLANDS (KIDV, 2016)

Year	*Household waste (Kton)*	*Recycled waste (Kton)*	*Incinerated waste (Kton)*
2009	25.2	22.68	2.52
2014	162	145.8	16.2

FIGURE 5: HOUSEHOLD WASTE MANAGEMENT IN THE NETHERLANDS OF THE SEPERATELY COLLECTED DOMESTIC WASTE

FIGURE 6: SEPARATED PLASTIC WASTE DISTRIBUTION

TABLE 4: EMISSIONS FROM RESIDUAL WASTE IN THE NETHERLANDS, INCLUDING FOURTEEN PERCENT PLASTIC (RIJKSWATERSTAAT, 2016)

Household waste (Kton)	*Minimal estimated CO2 emissions (in million kg)*	*Maximum estimated CO2 emissions (in million kg)*
914	267.8	509.1

CO_2 emissions in the life cycle of LDPE

Since there is no specific data available about the Netherlands, the numbers are based on the emissions of CO_2 with the life cycle of LDPE in Europe in order to give an indication of their emissions of CO_2 in the Netherlands. The Netherlands have together with eight other European countries -Austria, Belgium, Denmark, Germany, Luxembourg, Norway, Sweden, and Switzerland- enacted landfill bans. These countries therefore also recycle or incinerate their plastic waste (Gourmelon, 2015). Studies suggest that the emission of CO_2 in the life cycle of LDPE, range from 1.96 kg CO_2 per kg polymer (Harding, Dennis, Von Blottnitz & Harrison, 2007) to 3.04 kg CO_2 per kg polymer (Boustead, 2000). The different studies are displayed in table 5 and figure 7. For the Netherlands, this would probably be less since Dutch citizens use less plastics on average than other European countries.

TABLE 5: DIFFERENT OUTCOMES OF STUDIES ABOUT THE CO2 EMISSIONS IN THE LIFE CYCLE OF LDPE (HARDING ET AL., 2007; TURNER, WILLIAMS & KEMP, 2015; SGS SEARCH CONSULTANCY, 2015; BOUSTEAD, 2000; CPB, 2017)

Studies	*Kg CO_2 per kg polymer*
Study 1	1.96
Study 2	3.0
Study 3	2.9
Study 4	3.040
Study 5	2.9

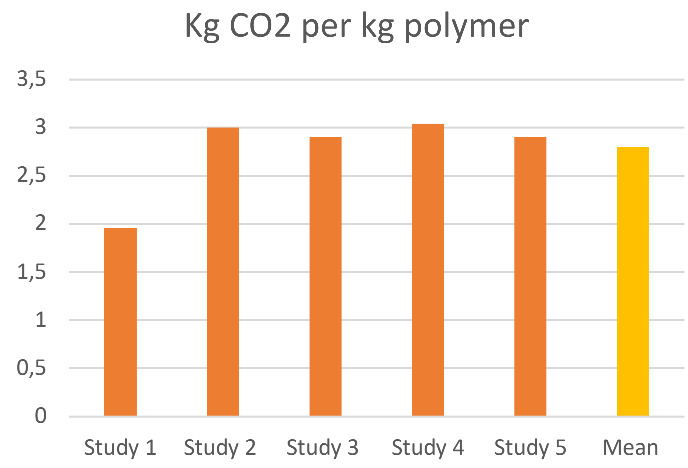

FIGURE 7: DIFFERENT OUTCOMES OF STUDIES ABOUT THE CO2 EMISSIONS IN THE LIFE CYCLE OF LDPE (HARDING ET AL., 2007; TURNER, WILLIAMS & KEMP, 2015; SGS SEARCH CONSULTANCY, 2015; BOUSTEAD, 2000; CPB, 2017) AND THE MEAN OF THE OUTCOMES

Production and disposal of bio-based biodegradable plastic

In this sub-chapter the production and disposal process of PLA will be described. The different raw materials for the production of PLA will be examined, together with the impact of disposal. By doing so, the CO_2 emissions in the life cycle of PLA will be shown. After which a comparison can be made between PLA and LDPE.

Production of PLA

PLA is made of biomass which is a compatible alternative for fossil fuels if well managed. PLA is the first bio-based form of plastic that is produced on a large scale since 2002 (Shen et al., 2010). Posen et al. (2016) stress that PLA plastics are chemically distinct from the fossil-based thermoplastics, but that they provide similar functionality. The Netherlands have a low potential for the production of PLA, which is partly due to limited space for (new) agricultural land (Ros & Prins, 2014). The majority of the material has to be imported (PBL, 2018; CPB, 2017). At the moment, corn, a first-generation feedstock, is the dominant feedstock for the production of PLA, but switchgrass is used as well, which is a second-generation feedstock and is considered to be more sustainable (Havlík et al., 2011). In figure 8 the pathways for the production of PLA are shown, including emissions from wet milling, fermentation and polymerization. The main emission sources are based on the electricity use, heat and chemical or enzyme production (Posen et al., 2016). 70 percent of the total production of PLA was used for packaging in 2007. It is expected that PLA will be mostly used for packaging and textiles in the future (Shen et al., 2016).

The production of plastics based on biomass is relatively inefficient, because in proportion, a lot of raw material is needed for the production of a kilogram of this type of plastic in comparison to other types of plastic. For fossil-based plastics the weight ratio is around one, but for the production of bio-based biodegradable plastics, like PLA, the weight ratio is around 1.5. This means PLA requires 1.5 times the mass of biomass in relation to the mass of plastic produced (WPI, 2009; CPB, 2017).

As stated above, corn is the dominant feedstock for producing PLA, but PLA on the basis of wheat, sugar beet, sugar cane and elephant grass is used as well. In 2013, Wageningen University examined the differences in CO_2 emission for these feedstocks. The research shows that sugar beet is the best option for the cultivation in the Netherlands where savings in greenhouse gas emissions are concerned (CPB, 2017; Bos, Meesters, Corre, Conijn & Patel, 2013). The analysis of different studies shows that the type of feedstock used for the production of plastics has the largest influence on the CO_2 emission. Not only the type of feedstock is important for the air pollution, the location of production is also of importance when looking at the carbon footprint. Transportation seems to be hardly of any significant influence (CPB, 2017).

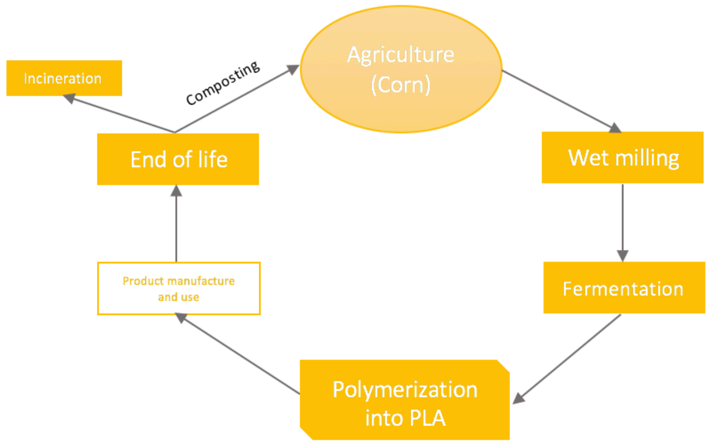

FIGURE 8: PATHWAYS FOR THE PRODUCTION OF PLA; EMISSIONS FROM WET MILLING, FERMENTATION AND POLYMERIZATION. END OF LIFE CONSISTS OF INCINERATION OR COMPOST. COMPOST COULD BE USED TO FERTILIZE THE FEEDSTOCK

Disposal of PLA

Biodegradable plastics are broken down by means of compost or by incineration. Just as for the LDPE plastics, PLA plastics can get mixed with the green waste. This could happen when the bio-based plastics are not carefully collected distinctly in the household waste and end up with the compost waste. The bio-based household waste (vegetables, fruit, etc.) is milled and gets in the surface water through compost. If the bio-based household waste is mixed with the plastic, these plastics get in the water too. In order to degrade PLA to compost, an industrial surrounding with heating is needed (CPB, 2017). Natural conditions are not sufficient for the degradation of PLA, as it is for green household waste. Furthermore, compostable bioplastics that have not been treated in composting plants for long enough and therefore do not break down completely, contribute to the hazard of microplastics in the environment as well (CE Delft, 2017; CPB, 2017). Microplastics are the result of the fragmentation of large pieces of plastic litter. These microplastics end up in the water and become a risk for the ecosystems in which they wind up. This is seen as a hazard to humankind and nature. The microplastics end up in the animal wildlife, who can then get infected or suffocate. Thereby, the microplastics are sometimes carcinogenic and there is the possibility of faster melting icecaps (de Souza Machado et al., 2018; Speksnijder, 2017; CPB, 2017). The composting of PLA with corn as its feedstock, gives an average emission of 1.7 kg CO_2-eq/kg plastic (Posen et al., 2016).

CO_2 emission in the life cycle of PLA

When comparing PLA to fossil-based non-biodegradable plastics, PLA generally has the lowest emission in its life cycle. For corn, this can lead to savings up to 1.4 kg CO_2-eq/kg PLA and 2.9 kg CO_2-eq/kg PLA for switchgrass (Posen et al., 2016).

In the table 6, the distribution of the influencing factors is displayed. This table is made out of the information given by Carus (2015) and CPB (2017).

TABLE 6: CRADLE TO GRATE EMISSIONS BIO-BASED BIODEGRADABLE PLASTICS PLA ON CORN (CARUS, 2015; CPB, 2017)

	PLA from corn (CO_2-eq/kg plastic)
Uptake of the atmosphere	-1.8
Production granulate	2.4
Production PLA	0.7
Incineration	1.8
Energy recovery	-1.1
Total	2.1

Comparison of the CO_2 emissions of LDPE and PLA

PLA and LDPE are two plastics that usually have the same function: the packaging of products. Both plastics have been examined for their carbon footprint. Both plastics have different emission sources, like the electricity use or the chemical production. PLA plastics emit relatively more CO_2-eq during the production of granulate than LDPE – PLA 2.4 kg CO_2-eq/kg plastic and LDPE 1.9 kg CO_2-eq/kg plastic. Additionally, PLA, since it has bio-based materials as its feedstock, is able to take up CO_2 from the atmosphere. As explained in the theoretical framework, the use of biomass for the production of plastics can be done carbon neutral, if well managed. Contrary to PLA, LDPE is not able to take up CO_2 from the atmosphere. In the disposal processes of both plastics, there are some resemblances. Parts of both plastics are incinerated. For LDPE this amount is ten percent. However, for PLA there is no specific data available since the use of the product is not on a large scale. The incineration of LDPE has more impact on the environment than the incineration of PLA. For LDPE this accounts for 2.8 kg CO_2-eq/kg plastic and for PLA 1.8 kg CO_2-eq/ kg plastic. In table 7 the two plastics are placed next to each other to give a clear overview. Other studies show roughly the same results for the total emission in the life cycle of LDPE, namely around the 3 kg CO_2-eq/ kg plastics (Harding et al., 2007; Turner, Williams & Kemp, 2015; Boustead, 2000).

TABLE 7: COMPARISON OF PLA AND LDPE FOR THEIR EMISSIONS OF CO2-EQ/KG PLASTIC (CARUS, 2015; CPB, 2017)

	PLA from corn (kg CO_2-eq/kg plastic)	*LDPE (kg CO_2-eq/kg plastic)*
Uptake from the atmosphere	-1.8	-
Production granulate	2.4	1.9
Production product	0.7	0.7
Incineration	1.8	2.8
Energy recovery	-1.1	-2.5
Total	2.1	2.9

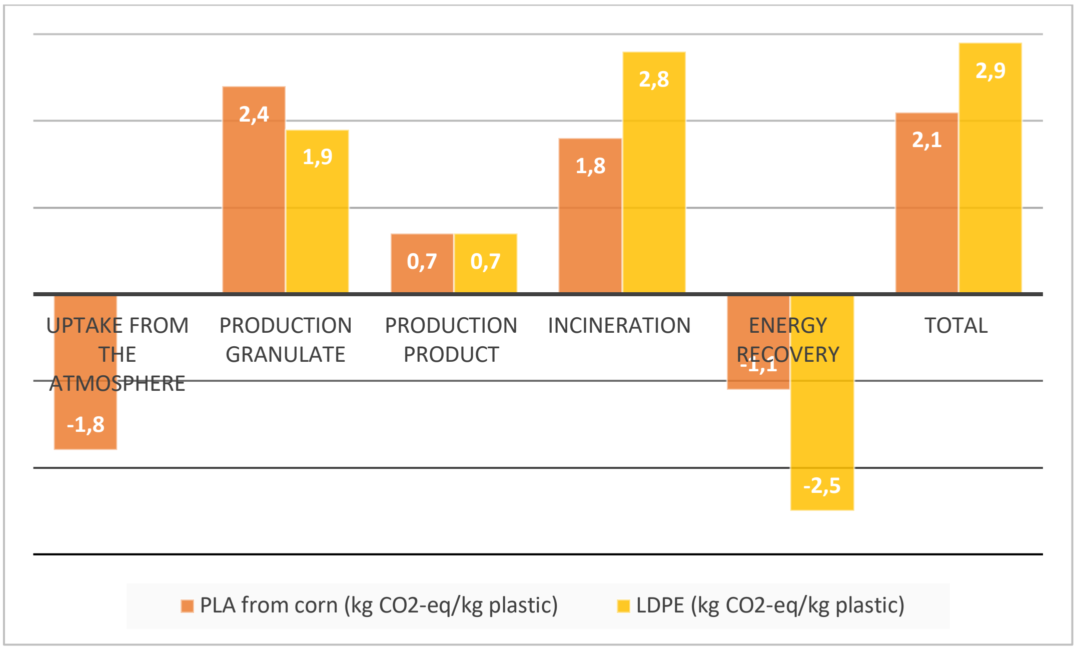

FIGURE 9: BAR CHART OF THE COMPARISON OF PLA AND LDPE FOR THEIR EMISSIONS OF CO2-EQ/KG PLASTIC

As can be found in table 7 and figure 9, PLA plastics have a lower amount of CO_2 emissions per kg than LDPE. PLA has a total carbon footprint of 2.1 kg CO_2-eq/kg plastics and LDPE has a total carbon footprint of 2.9 kg CO_2-eq/kg plastics. Transportation is not taken into account, since CPB (2017) stated that transportation has hardly any influence on the total carbon footprint.

DISCUSSION

In this chapter the results will be analysed and be reflected on. Thereby, the subjects with which this thesis could be extended, will be explained and any shortcomings will be discussed. Lastly, recommendations for further research will be reviewed.

Analysis of the results

In this thesis, a comparison has been made for the fossil-based non-biodegradable plastic LDPE and the bio-based biodegradable plastic PLA in order to determine which of the two types of plastic is more environmentally sustainable considering its carbon footprint. In order to get a clear overview of the emissions from the two types of plastic, two sub-questions have been drafted and answered. Both plastics emit CO_2 in the production process and while being disposed. It is unclear how much LDPE is produced in the Netherlands, but in the section about the production process of LPDE, it is stated that 167.39 Kton of PE plastics annually enters the Dutch market. This is relevant for all PE plastics, amongst which LDPE. The precise amount of LDPE on the Dutch market therefore remains unclear. The disposal of this product has been refined over the years, of which 162 Kton plastic is now collected separately. In this thesis, only household usage is taken into account and therefore these numbers are based on domestic usage. These numbers will be higher when factory usage is taken into account as well. 145.8 Kton of the domestic separately collected household waste is recycled, and 16.2 Kton is incinerated. Different studies showed that the emission of CO_2 in the life cycle of LDPE, contains around 3.0 kg CO_2/kg polymer. However, these numbers are based on European studies. For the Netherlands, research is lacking. It can therefore not be said with certainty if 3.0 kg CO_2/kg polymer is accurate for the Netherlands. The Netherlands are progressive with their waste management, and therefore It is suspected that emissions will be lower in the Netherlands. The production of PLA is relatively inefficient. A lot of biomass is needed in order to produce the product. Corn is the most dominant feedstock, and research of the emissions in the life cycle of PLA are based on corn. However, sugar beets are the best feedstock for cultivation in the Netherlands. PLA can either be composted or incinerated. The composting needs to take place under industrial surroundings and results in emissions of around 1.7 kg CO_2-eq/kg plastic. This does not differ much from the emissions of incineration, which accounts for 1.8 kg CO_2-eq/kg plastic. The total emission in the life cycle of PLA, regarding incineration, is 2.1 kg CO_2-eq/kg plastic. It can therefore be said that the bio-based biodegradable plastic PLA is more sustainable than the fossil-based non-biodegradable plastic LDPE when looking at the carbon footprint.

Reflection on research

In this thesis merely, the carbon footprint has been taken into account, in order to give a level of environmental sustainability. The carbon footprint is not the only way in which environmental sustainability of the plastic types can be measured. There are other factors in which the two products could be compared. Land use, chemical pollution and particulate matter are of importance as well. For example, the feedstock for PLA causes (indirect) land use change, uses scads of water and fertilizers (CPB, 2017; WUR, 2013). More research is necessary, so the consequences of other environmental factors can also be included. The biomass used for the plastics needs to grow on land area. This land might have been used for other purposes that are now continued on lands that are not managed in a sustainable fashion. This does however, depend on the type of vegetation used. Shen, Worrell and Patel (2010, p.39) state: "There is need to minimize the agricultural land use and forest, in order to avoid competition with food production and adverse effects on biodiversity and other environmental impacts." By determining the emissions in the life cycle, corn has been used as its feedstock. However, as research concludes, sugar beets are better for the cultivation in the Netherlands. Sugar beets can take up more CO_2 than corn, and CPB (2017) state that the overall emissions of CO_2 are reduced.

This research has tried to include as many factors of influence. However, it was difficult to find significant data. It turns out that it is challenging to determine how much plastic waste remains in the Netherlands and what happens to it. One of the reasons is that the Netherlands imports domestic residual waste (for energy recovery) and it is not known how much plastic this imported waste contains. Another problem is that data from different sources do not always match each other. They do not always measure the same quantity, and each have their own gaps (CPB, 2017, p. 32). Data is missing, and more research is needed to get more insight into the actual extent of the plastic problem and to get the possibility to give valuable recommendations.

Even though plastics pollute the environment, plastic packaging does help reduce the sustainable problem of food waste. It results in food that has a longer shelf life. So, when looking at food waste plastic packaging is a good thing (KIDV, 2016). Thereby, is it important to acknowledge that when there comes a constraint on plastic bags, a shift will take place to the use of other commodities. As to which the environmental burden will shift as well (PBL, 2018). Lastly, while both products can get incinerated and both emit CO_2 in that process, energy recovery has not thoroughly been taken into account. Incinerations has many benefits, compared to for example landfill. Landfill results in large amounts of methane emissions, which has even worse effects on the greenhouse effect than carbon emissions (Vroonhof & Croezen, 2006). More research to the advantages of energy recovery could help improve this research.

Conclusion

In the introduction the research question was stated as follows: To what extent is the production and disposal of bio-based biodegradable plastic more environmentally sustainable than the production and disposal of fully fossil-based non-biodegradable plastic in the Netherlands, when looking at the emissions of CO_2? This literature research has shown that even though the bio-based biodegradable plastic PLA has indeed a lower carbon footprint than the fossil-based non-biodegradable plastic LDPE, the difference is not exceedingly large. Both plastics have similar emissions during their production process, which is remarkable since both plastics are produced in different manners. LDPE emits more CO_2 during incineration, however in the production of the granulate PLA has a higher carbon footprint. The production and disposal of bio-based biodegradable plastic is more environmentally sustainable with a difference of 0.8 kg CO_2-eq/kg plastic. This answer is a result of an analysis of the life cycle of the plastics. However, it is difficult to adjust a conclusion because of the lack of data for some crucial points. This research is relevant in order to understand the need to use less plastic. Even though the use of plastic does have some benefits, a reduction in plastic use will certainly have a positive effect on the environment. A transmission to the usage of more bio-based biodegradable plastic is a step in the right direction, when considering the enhanced greenhouse gas caused by the emission of CO_2.

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