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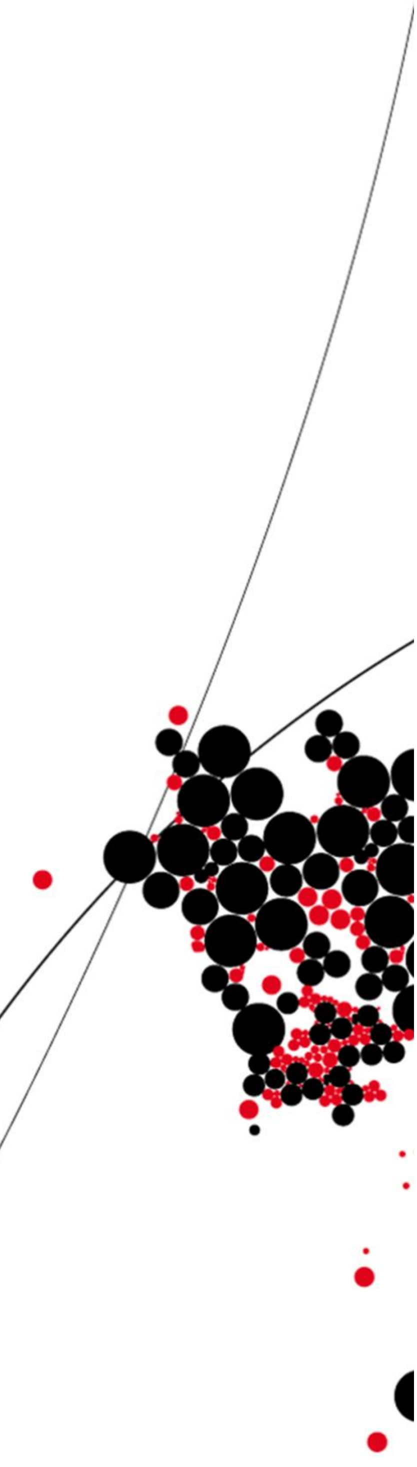

The water and land footprint of bioplastics

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SUMMARY

Petroleum-based plastics production has increased from 15 million tonnes in 1964 to 311 million tonnes in 2014 and it is estimated double in the next 20 years. Plastics derived from fossil resources are causing different concerns, such as the greenhouse gas emissions (GHGs), resource depletion, and rise of oil prices. These concerns with petroleum-based plastics are generating interest in bioplastics. Many studies have focused on GHGs of bioplastics but studies focusing on water and land footprints of bioplastics are rare.

This study aims to calculate the water and land footprint of bioplastics in several scenarios where all plastics are bio-based and assume different types of biomaterials and recycling rates. Calculation of such scenarios are carried out through a number of steps. The step to calculate the water and land footprint are: (i) listing the inventory of different biomaterial, (ii) estimating the efficiency of biomaterials, (iii) estimating the water and land footprint of sources materials, (iv) calculating the water and land footprint of final products, and (v) calculating the total water and land footprint if all fossil feedstock plastics were replaced by bioplastics. The types of bioplastics studied in this research are polyethylene (PE), polyethylene terephthalate (PET), polylactic acid (PLA), polyurethane (PUR), polypropylene (PP), and polyvinyl chloride (PVC). These plastics are selected because they are the main types of plastic materials used globally. Over 70% of the total demand of plastics is satisfied through these five types of plastics. Moreover, polylactic acid (PLA) is also studied because it is the most promising bioplastic and it can replace many functionalities of fossil-based plastics.

In this study, nine sets of assumptions are used. Three sets of assumption relate to the types of biomaterials used and three sets of assumption relate to different recycling rate. The types of biomaterials used is selected based on the result of water and land footprint calculation. Biomaterial with the highest water and land footprint value represents the ‘high’ value assumption, the lowest value represents the ‘low’ value assumption, and an average value represents ‘average’ value assumption. However, only PE, PET, and PLA have more than one type of biomaterial. For the recycling rate, there are three scenarios as well which are 10%, 36%, and 62%. The selected rates correspond to the recycling rates for today, the target recycling rate of EU in 2020, and a rate of all plastics that are possible to recycle.

This study shows that the water footprint of bioplastics vary between 1.4 m^3/kg to 9.5 m^3/kg. The land footprint of bioplastics vary between 0.7 m^2/kg to 13.75 m^2/kg. The water footprint if all the fossil-based plastics replace with bio-based plastics varies from 307 billion to 1,652 billion m^3 per year. If this number compare to global annual average water footprint (9,087 billion m^3/year), it accounted about 3% to 18% of the global annual average water footprint. The land footprint of a complete shift varies from 30 million to 219 million hectares per year. If it compares to free arable land in 2020 which account about 360 million hectares, the land footprint of this replacement will take about 8% to 61%.

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Contents

1 INTRODUCTION

1.1 Background

Plastics are used in all aspect of life from the pharmaceutical industry to household use (DiGregorio, 2009). Petroleum-based plastics production has increased from 15 million tonnes in 1964 to 311 million tonnes in 2014 and it is expected to double in the next 20 years because of their combination of low cost, versatility, durability and high strength-to-weight ratio (WEF, 2017). This enormous production of petroleum-based plastics which are derived from limited resources urges people to seek out more sustainable alternatives from renewable sources (Emadian et al., 2017). Besides the increasing demand for plastics, the concern for climate change, and the security of industrial feedstock supply contributes to the growth of bioplastics (Weiss et al., 2012).

Bioplastics consist of biodegradable plastics (plastics produced from fossil materials or bio-based material) or bio-based plastics (plastics synthesized from biomass or renewable resources) (Yutaka et al., 2009). Not all bio-based plastics are degradable and not all biodegradable plastics are bio-based plastic. It is necessary to avoid the confusion about the terms of bioplastics (Yutaka et al., 2009). Shen et al. (2010) define bio-based plastics as “man-made or man-processed organic macromolecules derived from biological resources and used for plastic and fiber applications”.

Bio-based plastics are mostly made from carbohydrate-rich plants such as corn, sugar cane, cereal, and sugar beets (EuropeanBioplastics, 2017). Bio-based polymers include polylactide (PLA), polyhydroxy butyrate (PHB) and starch derivatives as well as, for example, bio-polyethylene (PE) (Yutaka et al., 2009). The most common bio-based plastics are polyurethanes (PUR) and bio-based polyethylene terephthalate (PET), accounting respectively about 40% and 20% of total production of 4.16 million tonnes per year (EuropeanBioplastics, 2017; Mostafa et al., 2015). By 2019, the production capacity is expected to increase to 7.8 million tonnes (EuropeanBioplastics, 2017).

The bio-based plastics are beneficial in terms of fossil resources reduction and GHG emission reduction but they may come with an environmental problem related to cultivation and processing of feedstock (Grabowski et al., 2015). The associated problems are land use change, eutrophication of ground and surface waters, or fragmentation of habitats (Piemonte & Gironi, 2011). Despite many studies that assess the impacts of bioplastics in energy use, GHG levels, economic effects, there are limited studies on the assessment of water and land footprint of bioplastics.

The water footprint concept is introduced by Hoekstra (2003). It indicates the total of grey, green, and blue freshwater use both direct and indirect water use of a consumer or producer, and it differs from the classical measure of water withdrawal (Hoekstra et al., 2012). The water footprint includes three components: the green water footprint (evapotranspiration of rainwater from the field to produce for example a crop); the blue water footprint (net withdrawal of water from surface water or groundwater); and the grey water footprint (the volume of freshwater required to assimilate pollutants).

The water footprint of bioplastics can be calculated as water footprint of a product. The water footprint of product is the total of all water footprints of input products and process water footprints (Hoekstra, 2011). The input products of bioplastics mostly come from food crops such as corn, sugar cane, cereal, and sugar beets. The global water footprint of crop products (corn, sugar cane, cereal, and sugar beets) varies from 60 m^3/ton to 1800 m^3/ton (Mekonnen & Hoekstra, 2011). By knowing all the water footprint of all the input products of bioplastic and all water footprint of the processes, the water footprint of bioplastic can be obtained. The water footprint of bioplastics can vary between crops and countries that are linked to differences in crop yields, climate and agricultural technologies across countries (Mekonnen & Hoekstra, 2011).

The land footprint is defined as the real amount of land that is needed to produce a product or a service and expressed in area per unit of a product (Ibidhi et al., 2017; Weinzettel et al., 2013). Based on FAO (2013), 38% of total land is used for agriculture. The land footprint of a crop product is the land requirements for growing the crop (Bosire et al., 2016). According to Giljum et al. (2013), the total land requirements of crop product (ha) can be calculated by total harvested amount of the product (ton) divided by the yield of the product (ton/ha) using data from FAO (2016).

European Bioplastics has calculated that the land needed to grow the feedstock for bio-based plastics amounted to 0.01% of the global agricultural area in 2013 and it may grow to 0.02% by 2018. In 2014, the global production capacities for bioplastics amounted to around 1.7 million tonnes and translates into approximately 680,000 hectares of land (EuropeanBioplastics, 2017). Although in the near future, the bioplastics industry will not be a threat to the agricultural land, the impact must still be taken into account.

Based on previous research, replacing the petroleum-based plastics with bioplastics can reduce the GHGs emissions (Harding et al., 2007; Piemonte & Gironi, 2011; Shen et al., 2012; Weiss et al., 2012; Yates & Barlow, 2013). Although these studies focused on the effects of GHG reduction of bioplastics, studies focusing on water and land footprints are rare. In this research, the water and land footprint of bioplastics will be determined with a focus on the bio-based plastics.

1.2 Research Objective

Research question

The research aims to assess the global land and water footprint of a total shift from fossil-based to bio-based plastic consumption.

The main research question is defined as:

What are the implications of a total shift from fossil-based to bio-based plastics on global land and water requirements?

To answer the main research question the following sub-research questions will be addressed:

1. *What is the inventory of types of biomaterials that can be used for producing different sorts of bioplastics and of alternative production pathways?*
2. *What are the land and water footprints for a selected number of biomaterials and pathways, in terms of* m^2 *and* m^3 *per kg of bioplastic?*
3. *What are the total land and water footprints if worldwide fossil-feedstock based plastics were replaced by bioplastics, accounting for different sets of assumptions on types of biomaterials used and different recycling rates?*

Research scope

Bioplastics may refer to biodegradable plastic or bio-based plastics. This study will focus on bio-based plastics which are the plastics produced from biomass or renewable sources (European standard EN 16575). The types of bioplastics studied in this research are polyethylene (PE), polyethylene terephthalate (PET), polyurethane (PUR), polypropylene (PP), and polyvinyl chloride (PVC). These plastics are selected because they are the main plastic material demands globally. Total demand of all these plastics is over 70% globally (Nova Institute, 2016). Moreover, polylactic acid (PLA) is also studied because it is the most promising bioplastic and can replace many functionalities of fossil-based plastics today (Mekonnen et al., 2013).

2 SYSTEM DESCRIPTION OF BIOPLASTICS

Bioplastics are broadly classified as bio-based and/or biodegradable (Ashter, 2016). Bio-based plastics are derived from biological resources (Shen et al., 2010), meanwhile, biodegradable plastics can be plant or oil-based plastics and can be broken down by microorganisms (bacteria or fungi) into the water, carbon dioxide (CO2) and some bio-material (Futurenergia, 2017). Not all the bio-based plastics are biodegradable and vice versa.

Figure 1 shows the classification of plastics based on their bio-based content and biodegradability. It is divided by bio-based, biodegradable, fossil-based, and non-biodegradable. The plastics are classified as follows:

- Group 1 – Bioplastics that are bio-based and non-biodegradable such as bio-based PE, PET, PA, and PTT.
- Group 2 – Bioplastics that are bio-based and biodegradable such as PLA, PHA, PBS, and Starch blends.
- Group 3 – Conventional plastics that are non-biodegradable and fossil-based such as conventional PE, PP, and PET.
- Group 4 – Bioplastics that are fossil-based and biodegradable such as PBAT and PCL.

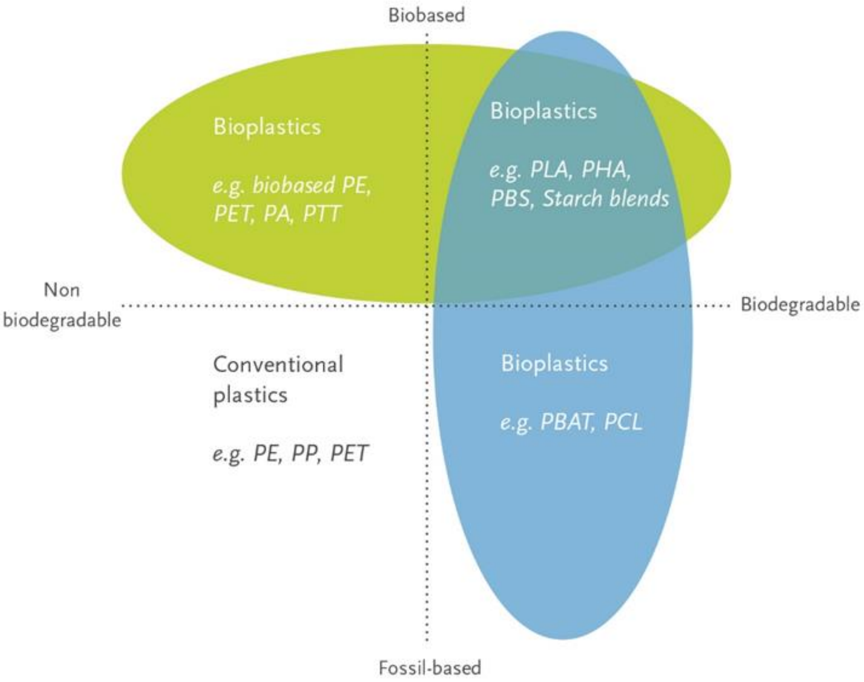

Figure 1. Classification of biodegradable and bio-based plastics (EuropeanBioplastics, 2017)

In 2016, global production capacity of bioplastics was 4.16 million tones (Figure 2). According to the latest market data compiled by EuropeanBioplastics (2017) in cooperation with the research institute nova-Institute, the global production capacity of bioplastics is predicted to grow by 50 percent in the medium term, from around 4.2 million tonnes in 2016 to approximately 6.1 million tonnes in 2021. Bio-based, such as polyurethanes (PUR) and bio-based PET, are the main product of bioplastics, with 40% and 20% of global production capacities, respectively. Most of the bioplastics are used for packaging and consumer goods (39% and 22% of total global production, respectively) (Nova Institute, 2016).

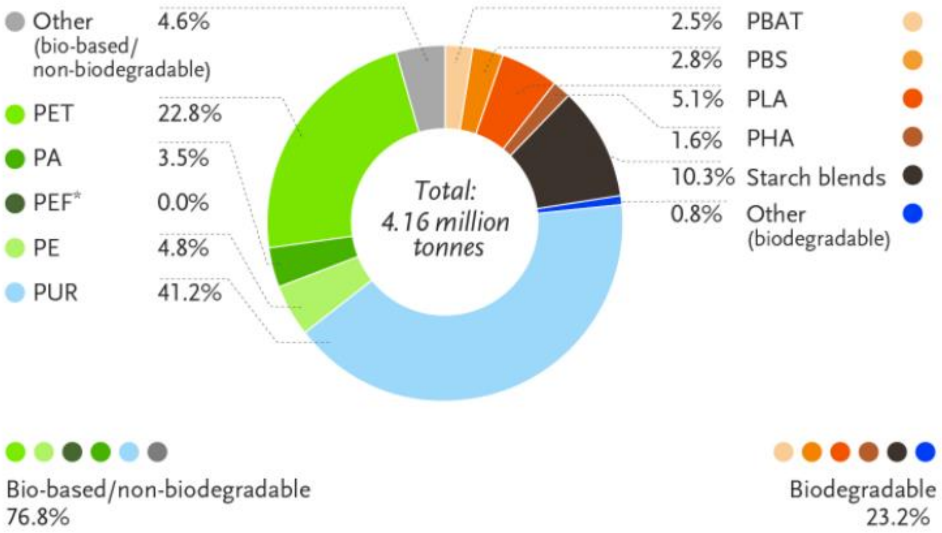

Figure 2. Global production capacity of bioplastics by material types in 2016 (Nova Institute, 2016)

2.1 Polyethylene (PE)

Polyethylene (PE), which is obtained by the polymerization of ethylene, is one of the most important commercially available polymers (Reddy et al., 2013). Bio-based PE was produced massively by two large Brazilian companies, Braskem and Dow Crystalsev. According to Coutinho et al. (2013), bio-based PE has the same functionality as petrochemical PE, it can be used for different application. The process of production of bio-based PE starts by processing biomass (sugar cane, sugar beet, or wheat) to bioethanol by anaerobically fermented process. Ethanol is distilled to remove water and to yield an azeotropic mixture of hydrous ethanol. Ethanol is then dehydrated at high temperature to produce ethylene. The final process is polymerization ethylene to polyethylene. The production process scheme of PE can be seen in Figure 3 below.

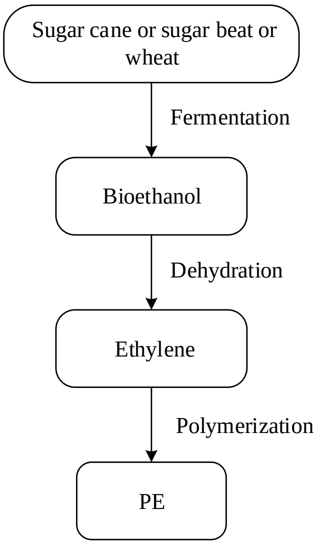

Figure 3. Production of bio-based PE

2.2 Polyethylene terephthalate (PET)

Bio-based PET is the overall market leader and is expected to grow quickly from 35.4% in 2014 to 76.5% in 2019 (Prieto, 2016). PET products that are made from bio-based monoethylene glycol (MEG) are produced by catalytic dehydration of bio-based ethanol and petrochemical PTA (purified terephthalic acid) (Akanuma et al., 2014; Shen et al., 2012). In Brazil, fresh sugar cane juice is directly fermented and distilled to ethanol whereas in India only sugar cane molasses are used (Tsiropoulos et al., 2014). After MEG is produced in India, the polymerization for making PET is done in Europe. The production process scheme of PET can be seen in Figure 4 below.

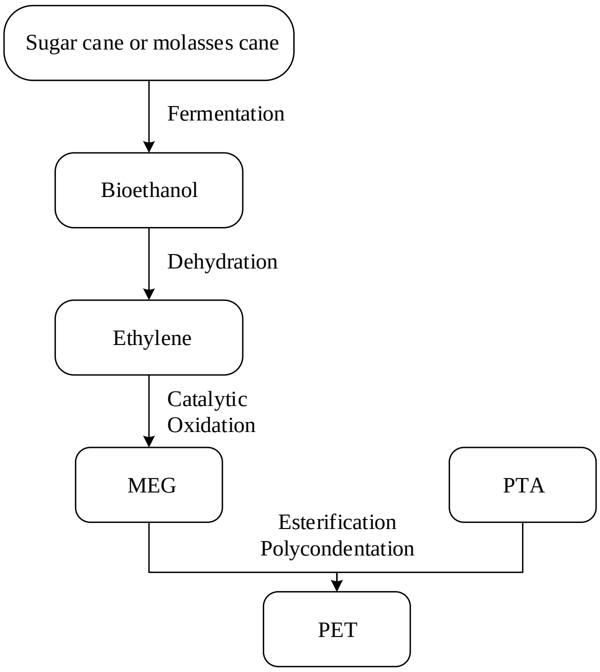

Figure 4. Production of bio-based PET

2.3 Polylactic acid (PLA)

PLA production capacity was around 200,000 tonnes in 2014 and is expected to reach about 450,000 tonnes in 2020 (Prieto, 2016). PLA results from the polymerization of purified lactic acid acquired from the fermentation of several renewable biomaterials, such as cornstarch, milk whey, sugar cane, or sugar beet (Queiroz & Collares-Queiroz, 2009). NatureWorks, a US company with a large-scale PLA production facility uses corn as their feedstock (Vink et al., 2007). Meanwhile, in Thailand, PLA is produced from sugar cane (Groot & Borén, 2010).

Based on Vink et al. (2004), the cradle-to-factory gate PLA production system is divided into five major steps (Figure 5):

1. Biomass production and transport to the processing facilities
2. Biomass processing and the conversion into dextrose (from corn) or glucose (from sugar cane)
3. Conversion of dextrose into lactic acid
4. Conversion of lactic acid into lactide
5. Polymerization of lactide into polylactide polymer pellets

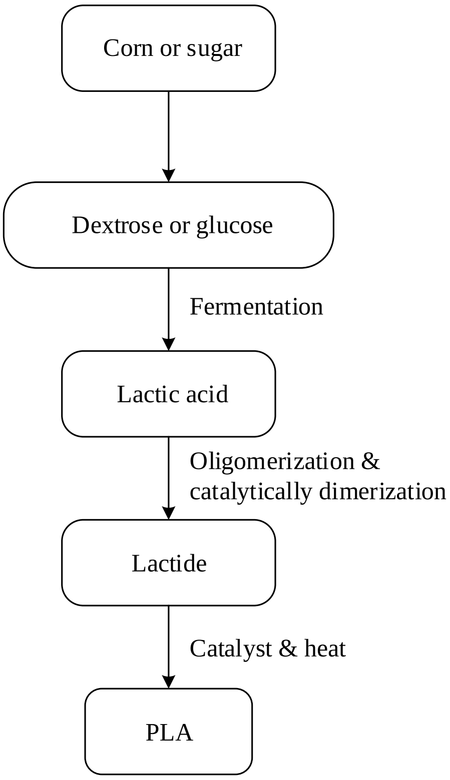

Figure 5. Production of bio-based PLA

2.4 Polyurethane (PUR)

Two main ingredients of PUR are polyol and isocyanate. There are two primary isocyanates: toluene diisocyanates (TDI) and methylene diphenyl diisocyanate (MDI). TDI is used primarily in the production of flexible foams, meanwhile, MDI is used to produce a wide variety of rigid, flexible, semi-rigid, and thermoset foams. In this study, MDI is used to produce flexible foam of PUR. The polyol is made from bio glycerine, propanediol (PDO), Phthalic Anhydride (Pht), and Succinic acid (SA). Pht is derived from fossil feedstock. Meanwhile, bio glycerine is produced from palm oil. For PDO and SA, both are derived from fermentation of corn starch. The production process scheme of PUR can be seen in Figure 6 below.

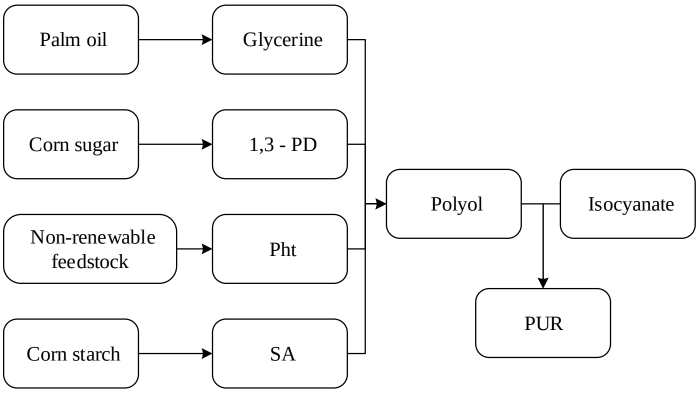

Figure 6. Production of bio-based PUR (Garcia Gonzalez et al. (2017)

2.5 Polypropylene (PP)

One main route of producing PP is biochemical (typically fermentation) beside thermochemical (involving gasification) route. The biochemical route involves using an enzyme in the fermentation process to convert sugars into ethanol and butane. Metathesis of ethylene and butane produces propylene monomer. The production process scheme of PP can be seen in Figure 7 below.

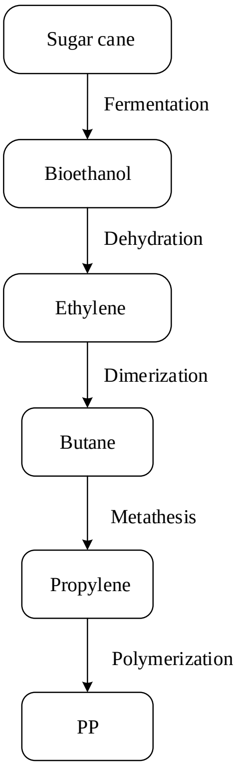

Figure 7. Production of bio-based PP

2.6 Polyvinyl chloride (PVC)

PVC is produced from chlorine (57%) and ethylene (43%). For the production of bio-based PVC, ethylene is produced from bioethanol (the same process as bio-based PE). Chloride is manufactured by electrolysis of a sodium chloride solutions. Ethylene is reacted with chlorine to produce ethylene dichloride (EDC). EDC is then converted into vinyl chloride monomer (VCM). The final process is polymerization of VCM to PVC. The production process scheme of PVC can be seen in Figure 8 below.

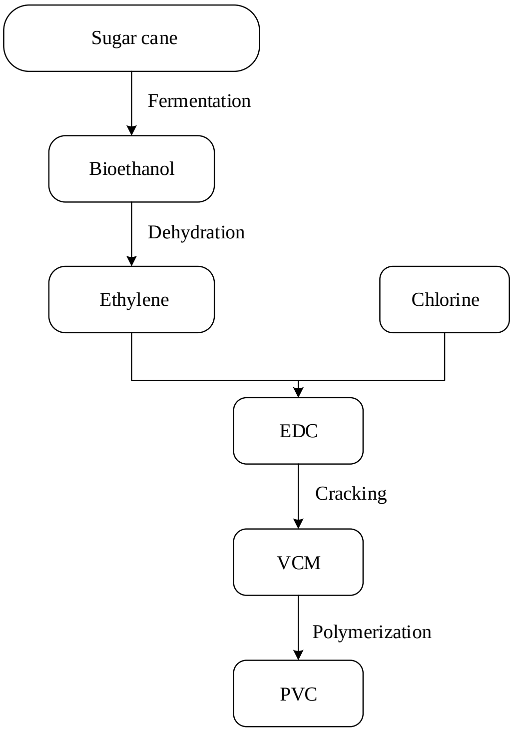

Figure 8. Production of bio-based PVC

3 METHOD AND DATA

3.1 Method

The sub-research question as mentioned in the first chapter will be answered by following these consecutive steps.

1. Making inventory of different biomaterials
2. Estimating the efficiency of biomaterials
3. Estimating the water and land footprint of source materials
4. Calculating the water and land footprint of final products
5. Calculating the total land and water footprint if all the fossil-feedstock plastic were replaced by bioplastics

Inventory of different biomaterials

The first step is to make the inventory of biomaterials as a raw source of bioplastics and also an alternative to production pathways. Bioplastic feedstocks are divided into first generation (traditional agricultural crops), second generation (cellulosic crops as well as residue and agricultural waste products), and third generation (non-traditional organism like some forms of algae and non-agricultural wastes)(BFA, 2015). Most of the feedstock bioplastics come from food crops, so-called 1st generation feedstock (EuropeanBioplastics, 2017).

Table 1 shows the feedstocks, biomass content, and country of origin for PE, PET, PLA, PUR, PP, and PVC. The inventory of feedstock for bioplastics is derived from Life Cycle Assessment (LCA) studies and research related to bioplastics. Bio-based PE, partially bio-based PET, bio-based PUR, and bio-based PLA has been mass produced. Meanwhile, for 100% PET, bio-based PP, and bio-based PVC, they have not been commercially produced. Fully bio-based PET, bio-based PP, and bio-based PVC are currently in development and predicted to be available in mass production scale in 2020.

Table 1. The feedstock and country of origin for PE, PET, PLA, PUR, PP, and PVC

Bioplastics	**Average biomass content of polymer**	**Feedstocks**	**Country of origin**	**Reference**
Polyethylene (PE)	100%	Sugar cane	Brazil	Borealis (2008); Kochar et al. (1981); Terry (2012)
		Sugar beet	Belgium	Belboom and Léonard (2016)
		Wheat	Belgium	Belboom and Léonard (2016)
Polyethylene terephthalate (PET)	30% -100%	Sugar cane	Brazil	Tsiropoulos et al. (2015)
		Molasses cane	India	Tsiropoulos et al. (2015)
		Wheat [a]	-	Akanuma et al. (2014)
		Corn [a]	-	Akanuma et al. (2014)
		Poplar [a]	-	Akanuma et al. (2014)
Polylactic acid (PLA)	100%	Corn starch	USA	Vink and Davies (2015)
		Cassava	Thailand	Papong et al. (2014)
Polyurethane (PUR)	30%	Palm oil Corn starch	Malaysia USA	Garcia Gonzalez et al. (2017)
Polypropylene (PP) [a]	100%	Sugar cane	Brazil	Kikuchi et al. (2017)
Polyvinyl chloride (PVC) [a]	43%	Sugar cane	Brazil	Tötsch and Gaensslen (1992)

a Lab scale production predicted to be available in the market in 2020

Estimating the efficiency of biomaterials

The water and land footprint of bioplastics can vary depending on where the crops grow, it is due to differences in crop yields between countries and crops, differences in climate and agricultural technologies (Mekonnen & Hoekstra, 2011). In addition to crop yields, it is important to know an efficient conversion from raw material to a product. It is called "feedstock efficiency". Feedstock efficiency describes as the conversion ratio of feedstock weight to final plastic polymer weight and is a combination of theoretical efficiency (which differs per type of bioplastic) in combination with the production efficiencies (Corbion, 2016). This means that different types of bioplastics require different amounts of feedstock. The feedstocks efficiency for each bioplastics can be seen in Table 2.

Table 2. Feedstock efficiency

Bioplastics	**Feedstocks**	**Country of origin**	**Feedstock efficiency (per 1 kg of bioplastic)**	**Reference**
PE	Sugar cane	Brazil	27.5 kg	Terry (2012)
	Sugar beet	Belgium	23.92 kg	Belboom and Léonard (2016)
	Wheat	Belgium	6.84 kg	Belboom and Léonard (2016)
PET	Sugar cane	Brazil	5.47 kg	Tsiropoulos et al. (2015)
	Molasses cane	India	1.85 kg	Tsiropoulos et al. (2015)
	Wheat	-	4.41 kg	Akanuma et al. (2014)
	Corn	-	3.25 kg	Akanuma et al. (2014)
	Poplar	-	5.05 kg	Akanuma et al. (2014)
PLA	Corn starch	USA	1.53 kg	Vink and Davies (2015)
	Cassava	Thailand	4.42 kg	Papong et al. (2014)
PUR	Palm oil Corn stach	Malaysia USA	0.66 kg 1.44 kg	Garcia Gonzalez et al. (2017)
PP	Sugar cane	Brazil	34.94 kg	Kikuchi et al. (2017)
PVC	Sugar cane	Brazil	12.62 kg	Tötsch and Gaensslen (1992)

Estimating the water and land footprint of source material

Raw materials for bioplastics mostly come from crops such as corn, sugar cane, cereal, and sugar beets. The water footprint of crops data was taken from Mekonnen and Hoekstra (2011). The water footprint of crop products (corn, sugar cane, and sugar beets) varies from 60 m^3/ton to 1,800 m^3/ton (Table 3). Meanwhile, the land footprint of crop products (ha/ton) is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table 3. The water and land footprint of source material

Feedstock	**Country of origin**	**Water footprint (m^3/ton)[a]**				**Land footprint (m^2/ton)[b]**
		Blue	Green	Grey	Total	
Sugar cane	Brazil	5	122	10	137	141.50
Molasses cane	India	354	306	42	702	369.35[c]
Corn starch[d]	USA	110	909	307	1326	1791.7
Sugar beet	Belgium	-	51	13	64	122.30
Wheat	Belgium	-	403	181	584	1062.37
Cassava roots	Thailand	-	435	32	467	449.34
Palm oil	Malaysia	-	824	34	858	472.80
Wheat	Global	342	1277	207	1826	2936.88
Corn	Global	81	947	194	1222	1773.02
Poplar	Global	-	794.5	-	794.5[e]	2325.58[f]

a: Source: Mekonnen and Hoekstra (2011)

b: Source: dividing the total area harvested by the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

c: Based on calculation; LF of molasses cane = (LF sugar cane x value fraction/product fraction). LF sugar cane is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016). Value fraction and product fraction from Mekonnen and Hoekstra (2011) are 0.13 and 0.05, respectively.

d: Based on calculation; value fraction of corn starch and corn 1 (Mekonnen & Hoekstra, 2011); weight fraction corn starch 0,574 (Vink & Davies, 2015); weight fraction of corn starch 1 (Mekonnen & Hoekstra, 2011)

e: Source: Gerbens-Leenes et al. (2009). Average of 4 countries which are Netherlands, USA, Brazil, and Zimbabwe. There is no distinction between blue and green water footprint. It is assumed that 100% water footprint is a green component.

f : Source : Dillen et al. (2013)

Calculating the water and land footprint of final product

In this study, the calculation of water footprint proposed by Hoekstra (2011) is used. The used method is stepwise accumulative approach. This method calculates water footprint based on all the water footprints of the input products that were necessary for the last processing step to produce that product and the process water footprint of that processing step (Hoekstra et al., 2012). If we assume that bioplastic is a product, water footprint of bioplastics are the total amount of water footprints of input products and the process water footprint.

The formulae for the calculation of water footprint of a product is (Hoekstra et al., 2012):

$$WF_{prod}\,[p] = (WF_{proc}\,[p] + \sum_{i=1}^{y} \left(\frac{WF_{prod}\,[i]}{f_p\,[p,i]}\right) \times f_V\,[p] \qquad (1)$$

where WF prod [p] is water footprint (volume/mass) of output product p, WF prod (i) is the water footprint of input product i and WF proc [p] is the process of the processing step that manufactures the input into the output. Meanwhile fp [p,i] is the product fraction and fv is value fraction. The product fraction is defined as the weight of the primary product obtained per ton of primary crop (Chapagain & Hoekstra, 2003). Based on this term, the product fraction is reciprocal of feedstock efficiency.

Land footprint of bioplastics will be calculated similar to the water footprint calculation, by adding all of the land footprints of the input products and the land footprint of the processing step can be neglected. The formulae for calculating the land footprint of product i (ha/ton) is derived from:

$$LF_{prod}\,[p] = \sum_{i=1}^{y} \left(\frac{LF_{prod}\,[i]}{f_p\,[p,i]}\right) \times f_V\,[p] \qquad (2)$$

where LF prod [p] is water footprint (volume/mass) of output product p, LF prod (i) is the water footprint of input product i and LF proc [p] is the process of the processing step that manufactures the input into the output.

The WFproc and LFproc include the water footprint and land footprint of electricity, heat, transportation. The water and land footprint of electricity can be seen in Table 4 below. For heat, it is assumed that 100% heat comes from natural gas. The water footprint of natural gas is 0.66 m^3/GJ (Mekonnen et al., 2015) meanwhile the land footprint is 0.03 m^2/GJ (IINAS, 2017). For transportation, the water and land footprint is the same as the water footprint for diesel. It is assumed that the transportation is using diesel engine truck. Since diesel is a product of crude oil, the water and land footprint of diesel can be calculated with the water and land footprint of crude oil with a consideration of the product and value fraction as stated in formulae 1 and 2.

Table 4. The water and land footprint of energy sources for electricity generation

Electricity sources	**Water footprint(m^3/GJ)[a]**	**Land footprint (m^2/GJ)**		
		Typical[b]	EU[c]	USA[d]
Natural gas	0.66	0.06	0.03	0.28
Coal	1.09	1.39	0.06	0.17
Nuclear	0.73	0.03	0.28	0.03
Crude oil	0.70	0.11	0.03	1.67
Hydropower	425.15	2.78	0.97	0.94
Solar	1.15	2.7-4.2	2.17-2.42	4.16-5.36
Wind	0.01	0.28	0.19	0.36
Biomass	275	138.89	125	225

a: Obtain from the average value of water footprint of electricity from Mekonnen et al. (2015)
b: Source: Fritsche et al. (2017)
c: Source: IINAS (2017)
d: Source: Trainor et al. (2016)

Calculating the total water and land footprint if all the fossil-feedstock plastic were replaced by bioplastics

If all the fossil-feedstock plastics were replaced by bioplastics, there are several assumptions that need to be made such as types of biomaterials used and different recycling rates. Based on PlasticsEurope (2016), the plastic production increased to 322 million tonnes in 2015, or 3.4% growth compared to 2014. The plastic materials demand is dominated by polyolefin plastics such as PE and PP that account for 27% and 19% of global demand, respectively (Figure 9). For polystyrene (PS) and expanded polystyrene (EPS), the water and land footprint are not calculated, the water footprint and land footprint of PLA are used. Since PLA can substitute PS and EPS by the same functionality.

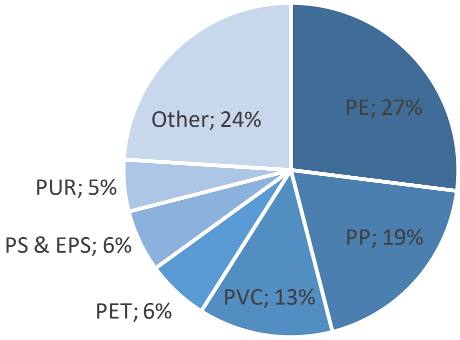

Figure 9. Plastic materials demand 2015 by types (PlasticsEurope, 2016)

In this study, nine sets assumption are created. Three sets assumption based on types of biomaterials used and three sets assumption based on different recycling rate. The types of biomaterials used is chosen based on the calculation result of water and land footprint value. There are three scenarios: ‘high’, ‘average’, and ‘low’ value assumption. For example, there are three types of biomaterial studied for PE, for the high assumption, the highest water, and the land footprint is used, etc. For PP, PUR, and PVC, since only one biomaterial is calculated, the same value is applied to three scenarios.

For the recycling rate, there are three scenarios as well. Scenario 1 assumes recycling 10%, scenario 2 assumes 36% recycling, and scenario 3 62%. Scenario 1 is selected because it is the recycling rate for today (WEF, 2017). Scenario 2 corresponds to the target recycling rate of EU for 2020 (Mudgal et al., 2013). Scenario 3 corresponds to the possible recycling of all plastics (Mudgal et al., 2013).

3.2 Data

The data used in this study are presented in Table 5.

Table 5. Data used in this study

Bioplastics	**Producing processes step**	**Reference**
PE	Sugar cane to bioethanol	Terry (2012) Liptow and Tillman (2012); Tsiropoulos et al. (2014)
	Sugar beet and wheat to bioethanol	Belboom and Léonard (2016)
	Bioethanol to ethylene	Belboom and Léonard (2016); Kochar et al. (1981)
	Ethylene to PE	Borealis (2008)
PET	Molasses cane to hydrous ethanol	Tsiropoulos et al. (2014)
	Sugar cane to hydrous ethanol	Tsiropoulos et al. (2014)
	Ethanol to ethylene	Kochar et al. (1981)
	Ethylene to MEG	DPT (2001)
	Fossil-based PTA production	DPT (2001); Papong et al. (2014)
	Bio-based PTA production	Akanuma et al. (2014)
	MEG and PTA to PET	Papong et al. (2014)
PLA	Cassava to cassava starch	Papong et al. (2014)
	Cassava starch to glucose	Siriluk et al. (2014) and Renouf et al. (2008)
	Glucose to lactic acid	Groot and Borén (2010)
	Lactic acid to lactide	Groot and Borén (2010)
	Lactide to PLA	Groot and Borén (2010)
	Corn starch to PLA*	Vink and Davies (2015)
PUR	Palm oil to bio glycerine	Jungbluth et al. (2007)
	Corn starch to propanediol	Urban and Bakshi (2009)
	Pht production	Althaus et al. (2007)
	Corn starch to succinic acid	Verghese (2009)
	Polyol production	Garcia Gonzalez et al. (2017)
	MDI production	PlasticsEurope (2012)
	Polyol and MDI to PUR	Garcia Gonzalez et al. (2017)
PP	Sugar cane to bioethanol	Terry (2012) Liptow and Tillman (2012); Tsiropoulos et al. (2014)
	Bioethanol to ethylene	Kochar et al. (1981)
	Ethylene to propylene to PP	Worrell et al. (2000)
PVC	Sugar cane to bioethanol	Terry (2012) Liptow and Tillman (2012); Tsiropoulos et al. (2014)
	Bioethanol to ethylene	Kochar et al. (1981)
	Chlorine production	Ayers (1997)
	Ethylene and chlorine to VCM	Tötsch and Gaensslen (1992)
	VCM to PVC	Tötsch and Gaensslen (1992)

* In the document, there are no further explanation processes of each step

4 RESULTS

4.1 Water footprint of bioplastics

Table 6 shows the water footprint of six different kinds of bioplastics in m^3 per kg of bioplastics. Sugar cane based PET has the lowest water footprint, which is 1.39 m^2/kg. Meanwhile, 100% bio-based PET has a relatively large water footprint, seven times larger than the water footprint of sugar cane based PET. A low percentage of bio contain has a relatively low value of total water footprint. For example, sugar cane-based PET with 30% of bio contain has one-seventh water footprint value of the wheat-molasses cane-based PET. A lower share of bio contained in bioplastics does not necessarily mean that they have a low value of water footprint. For example, 45% bio-based PVC has larger water footprint than 100% PLA. The water footprint for sugar cane based plastics varies between 1.39 m^2/kg to 9.18 m^2/kg.

Table 6. Water footprint of bioplastics in m^3/kg.

Type of bioplastics	Bio feedstocks	Bio contain (% weight)	Feedstock efficiency (kg/kg of polymer)	Water footprint (m^3)			
				Blue	Green	Grey	Total
PE	Sugar cane	100%	27.5	0.83	3.43	0.28	4.53
	Sugar beet	100%	23.92	0.02	1.36	0.31	1.69
	Wheat	100%	6.84	0.02	2.91	1.24	4.17
PET	Molasses cane	30%	1.85	0.93	0.59	0.08	1.60
	Sugar cane	30%	5.47	0.62	0.72	0.05	1.39
	Poplar-molasses cane	100%	5.05 - 1.85	0.81	4.59	0.08	5.48
	Corn-molasses cane	100%	3.25 - 1.85	1.07	3.66	0.71	5.44
	Wheat-molasses cane	100%	4.41 - 1.85	2.32	6.21	0.99	9.52
	Poplar-sugar cane	100%	5.05 - 5.47	0.37	4.72	0.06	5.14
	Corn-sugar cane	100%	3.25 - 5.47	0.63	3.78	0.69	5.10
	Wheat-sugar cane	100%	4.41 - 5.47	1.88	6.34	0.97	9.18
PUR	Palm oil-corn starch	35%	0.66 - 1.44	0.19	1.12	0.28	1.59
PLA	Cassava	100%	1.53	0.13	2.01	0.14	2.28
	Corn starch	100%	4.42	0.19	1.39	0.47	2.06
PP	Sugar cane	100%	36.10	0.62	4.44	0.36	5.42
PVC	Sugar cane	45%	13	1.17	1.71	0.13	3.01

Figure 10 shows the percentage of the water footprint of production, bio feedstock, and the total of bioplastics. The water footprint is dominated by green water footprint, 71% of the total water footprint. The water footprint of bio-feedstocks is dominated by the total water footprint of bioplastics. For 100% bio-based plastics, the water footprint of bio-feedstocks is responsible for more than 90% of the total water footprint. Meanwhile, for partially bio-based plastics, the water footprint of bio-feedstocks varies from 54% to 81% of the total water footprint. The water footprint of the production of plastics is relatively small which is 0.03 to 1.23 m^3/kg of plastics.

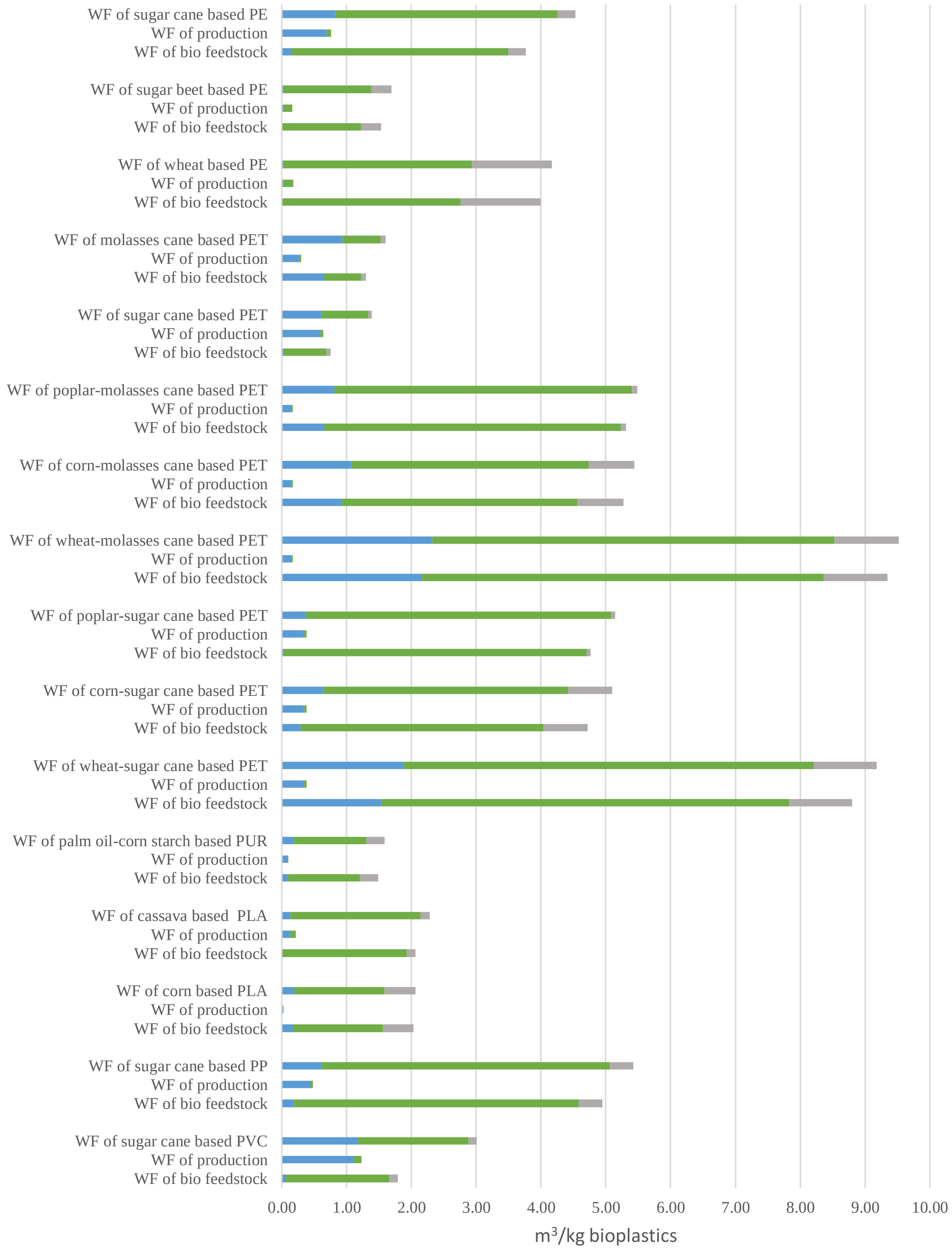

Figure 10 Blue, green, grey water footprint of production, bio feedstock, and total of bioplastics (the colors on figure indicates component of water footprint)

4.2 Land footprint of bioplastics

The land footprint of bioplastics varies between 0.70 m^2/kg for molasses cane based PET to 13.75 m^2/kg for wheat-sugar cane based PET. For bio-based PE, the largest land footprint from wheat-based PE, two times higher than sugar beet-based PE. For a partially bio-based PET, sugar cane PET has the smallest land footprint of all. The land footprint of wheat-based PET is relatively high than other bio-based PET. The highest land footprint of 100% bio-based PET is wheat-sugar cane (12.75 m^2/kg) and the lowest is corn-molasses cane (6.46 m^2/kg). PLA has the smallest land footprint among the fully bio-based plastics. The land footprint of cassava-based PLA and corn starch PLA are 2.11 m^2/kg and 2.83 m^2/kg, respectively. Over 95% of LF of bioplastics is LF of bio-feedstock. The land footprint of production is very small and ranges from 0.01 to 0.12 m^2/kg bioplastics. The complete result can be seen in Figure 11.

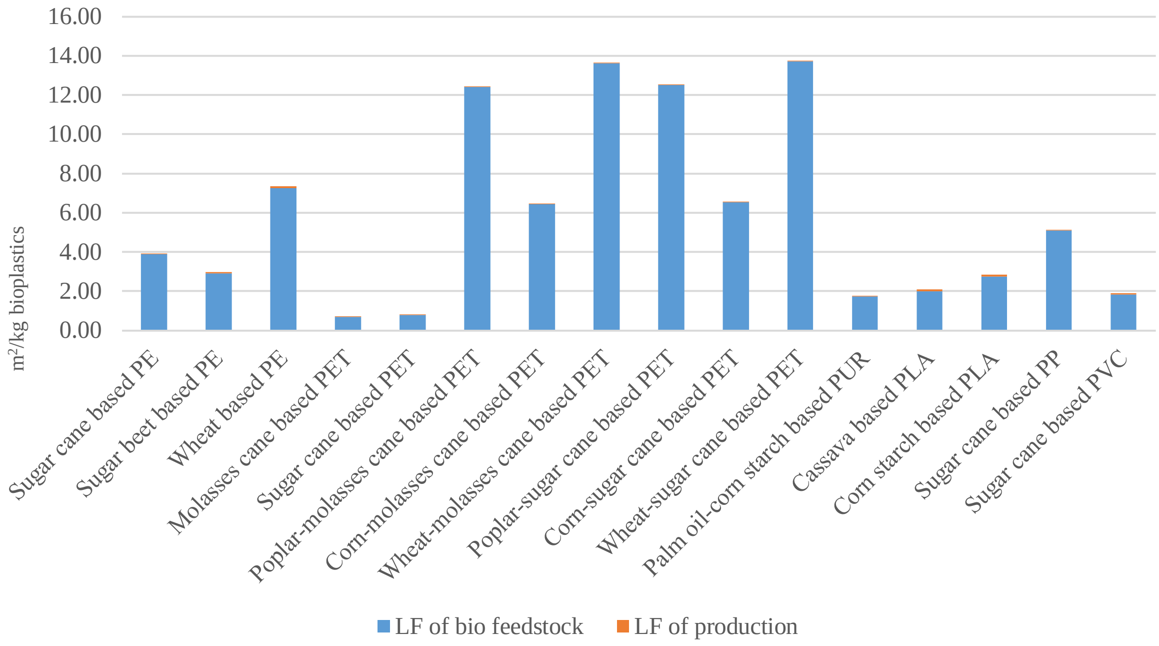

Figure 11. Land footprint (m^2/kg) of bio-feedstock and production of bioplastics

4.3 Calculation of water and land footprint of bioplastics in 2016

Based on EuropeanBioplastics (2017), the global production of bioplastics in 2016 was 4.16 million tonnes. PUR has taken the biggest share at 41.2% of the total global production. PET was the second at 22.8% of total 4.16 million tonnes (Figure 2). Starch blend, PLA, and PE were 10.3%, 5.1%, and 4.8% respectively. Using simple calculation, without considering the recycling rate and using an average value for water and land footprint of each bioplastic, the total water and land footprint of bioplastics during 2016 can be calculated. The water footprint of all bioplastics production in 2016 was 7.72 billion m^3 of water (19% blue, 67% green, 14% grey). Meanwhile, the land footprint of bioplastics was 0.8 million hectares to produce 4.16 million tonnes bioplastics in 2016.

Table 7. The water and land footprint of global production bioplastics in 2016

Bioplastic types	**Percentage**	**Demand in million tonnes**	**Water footprint (billion m^3/year)**				**Land footprint (million ha /year)**
			Blue	Green	Grey	Total	
PUR	41.20	1.7	0.32	1.92	0.48	2.72	0.30
Starch blends [a]	10.30	0.4	0.07	0.65	0.13	0.85	0.10
PET	22.80	0.9	0.73	0.62	0.06	1.42	0.07
PLA	5.10	0.2	0.03	0.36	0.06	0.46	0.05
PE	4.80	0.2	0.06	0.51	0.12	0.69	0.09
Other [b]	15.8	0.7	0.24	1.11	0.23	1.59	0.18
Total	100	4.16	1.46	5.17	1.09	7.72	0.80

a: Obtain from the average value of starch blends plastics such as PLA and PUR

b: Obtain from the average value of PUR, starch blends, PET, PLA, and PE.

4.4 Complete change from fossil-based stock to bio-based plastics

Table 8, Table 9, and Table 10 shows the water footprint and land footprint values that are used to calculate complete change from fossil-based plastics to bio-based plastics using ‘high’, ‘average’, and ‘low’ value scenarios, respectively. For plastics PS and EPS, the water and land footprint of PLA are used since PLA can substitute PS and EPS by the same functionality. For PP, PVC, and PUR, since only one pathway of production is studied per each plastic, the water footprint and land footprint for three values (high, average, and low) are using the same value. Besides the listed types of plastics, there are other undetailed plastics which shares 20% of the total production. The water and land footprint values of these other undetailed plastics are the highest, average, and lowest from each assumptions. For example, for ‘high’ assumption, the highest water footprint and land footprint among all studied material is used. It is applied to ‘low’ scenario, the lowest water footprint and land footprint among all material is used. Meanwhile, for ‘average’ assumption, the average water footprint and land footprint of all studied bioplastics are used.

The water footprint of sugar cane based PE, wheat-molasses cane based PET, and cassava-based PLA are chosen for the ‘high’ value scenario. Meanwhile, for the land footprint ‘high’ value scenario, the land footprint of wheat-based PE, wheat-sugar cane based PET, corn starch-based PLA are used. The complete list for the ‘high’ scenario can be seen in Table 8.

Table 8. The water and land footprint used in 'high' value scenario

No	**Bioplastics types**	**Bio feedstocks**	**Water footprint (m^3/kg)**				**Bio feedstocks**	**Land footprint (m^2/kg)**
			Blue	Green	Grey	Total		
1	PE	Sugar cane	0.83	3.43	0.28	4.53	Wheat	7.34
2	PP	Sugar cane	0.62	4.44	0.36	5.42	Sugar cane	5.13
3	PVC	Sugar cane	1.17	1.71	0.13	3.01	Sugar cane	1.92
4	PET	Wheat-molasses cane	2.32	6.21	0.99	9.52	Wheat-sugar cane	13.75
5	PS & EPS	Cassava	0.13	2.01	0.14	2.28	Corn starch	2.83
6	PUR	Palm oil, corn starch	0.19	1.12	0.28	1.59	Palm oil, corn starch	1.75
7	Other	Wheat-molasses cane based PET	2.32	6.21	0.99	9.52	Wheat-sugar cane based PET	13.75

Table 9 shows the water footprint and land footprint values that are used to calculate complete change from fossil-based plastics to bio-based plastics using 'average' value scenarios. For PE, PET, PS and EPS, there are several bio-feedstocks are studied per each plastics. For PP, PVC, and PUR, since only one pathway of production is studied per each plastic, the water footprint and land footprint for 'average' value is using the same value as 'high' and 'low' scenarios.

Table 9. The water and land footprint used in 'average' value scenario

No	**Bioplastics types**	**Water footprint (m^3/kg)**				**Land footprint (m^2/kg)**
		Blue	Green	Grey	Total	
1	PE	0.29	2.57	0.61	3.46	4.75
2	PP	0.62	4.44	0.36	5.42	5.13
3	PVC	1.17	1.71	0.13	3.01	1.92
4	PET	1.08	3.83	0.45	5.36	8.36
5	PS & EPS	0.16	1.70	0.31	2.17	2.47
6	PUR	0.19	1.12	0.28	1.59	1.75
7	Other	0.74	3.06	0.43	4.23	5.93

Table 10 shows the water footprint and land footprint values that are used to calculate complete change from fossil-based plastics to bio-based plastics using 'low' value scenarios. For the 'low' value scenario, the water footprint of sugar beet-based PE, sugar cane based PET, and corn starch-based PLA are chosen. For the 'low' value scenario, the land footprint of sugar beet-based PE, molasses cane based PET, and cassava PLA based are used.

Table 10. The water and land footprint used in 'low' value scenario

No	Bioplastics types	Bio feedstocks	Water footprint (m^3/kg)				Bio feedstocks	Land footprint (m^2/kg)
			Blue	Green	Grey	Total		
1	PE	Sugar beet	0.02	1.36	0.31	1.69	Sugar beet	2.99
2	PP	Sugar cane	0.62	4.44	0.36	5.42	Sugar cane	5.13
3	PVC	Sugar cane	1.17	1.71	0.13	3.01	Sugar cane	1.92
4	PET	Sugar cane	0.62	0.72	0.05	1.39	Molasses cane	0.70
5	PS & EPS	Corn starch	0.19	1.39	0.47	2.06	Cassava	2.11
6	PUR	Palm oil, corn starch	0.19	1.12	0.28	1.59	Palm oil, corn starch	1.75
7	Other	Sugar cane based PET	0.62	0.72	0.05	1.39	Molasses cane based PET	0.70

By using three scenarios and three different values, the water footprint and land footprint are calculated. Scenario 1 is using 10%, scenario 2 is using 36%, and scenario 3 is using 62% as their recycling rate. Table 11 shows the calculated water footprint of the complete shift from fossil-based plastics to bio-based plastics by assuming different sets of scenarios. The results vary from the lowest 307 billion m^3 to the highest 1652 billion m^3 which is 5 times higher than the lowest water footprint.

Table 11. The water footprint if total shift occurs from fossil-based plastic to bio-based plastic in billion m^3/year

Value	Scenario		
	Scenario 1	Scenario 2	Scenario 3
High	**1652**	**1155**	**698**
Blue	349	248	147
Green	1164	837	492
Grey	139	97	58
Average	**1131**	**804**	**476**
Blue	177	126	75
Green	835	594	353
Grey	119	84	50
Low	**728**	**518**	**307**
Blue	141	100	60
Green	521	370	220
Grey	66	47	28

Table 12 shows the calculated land footprint if a total shift occurs from fossil to bio-based plastics. The result varies from 2188 billion m^2 to 301 billion m^2 per year.

Table 12. The land footprint if complete change from fossil-based plastics to bio-based plastic in billion m^2/year

Value	Scenario		
	Scenario 1	Scenario 2	Scenario 3
High	2188	1557	925
Average	1348	960	570
Low	1186	507	301

5 DISCUSSION

The water footprint of bioplastic varies between 1.39 m^3/kg to 9.52 m^3/kg. The water footprint of bioplastics is dominated by green water footprint, 52% to 92% of the total water footprint. The water footprint of bio-feedstocks is dominated by the total water footprint of bioplastics. The land footprint of bioplastic varies between 0.70 m^2/kg to 13.75 m^2/kg. Over 95% of the land footprint of bioplastics is the land footprint of bio-feedstocks. The land footprint of production is very small and ranges from 0.01 to 0.12 m^2/kg bioplastics.

Based on Hoekstra and Mekonnen (2012), the global water footprint related to agricultural and industrial production and domestic water supply was 9,087 billion m^3/year (74% green, 11% blue, and 15% grey). Agricultural production takes the largest share about 92% of the global water footprint. The water footprint of all bioplastics production in 2016 is 7.72 billion m^3 of water (66% green, 18% blue,14% grey). The water footprint of bioplastics is really small if it is compared to the global annual average water footprint.

Meanwhile, the land footprint of bioplastics is 0.8 million hectares to produce 4.16 million tonnes bioplastics in 2016. Compared to the total global agricultural area which is 5 billion ha EuropeanBioplastics (2017) and Carus (2011), it accounted about 0.016% of this land. EuropeanBioplastics (2017) has calculated the land use for bioplastic in 2014 and 2019. In 2014, the global production capacities of bioplastics amounted to 1.7 million tonnes, which required approximately 680,000 hectares of land (0.01% of global agricultural area). In 2019, it may account about 0.02% which would be 1.4 million hectares. Today, bioplastics are not a significant user of land and they are not predicted to become a competitor in near future (BFA, 2015).

The water footprint of a total shift to bio-based plastics varies from 307 billion to 1,652 billion m^3 water per year. To place this number in a perspective, the global annual average water footprint is 9,087 billion m^3/year. The complete change to bio-based plastics are accounted about 3% to 18% of the global annual water footprint.

The land footprint of a complete change to bio-based plastic varies from 30 million to 219 million hectares per year. According EuropeanBioplastics (2017) and Carus (2011), the available global agricultural area is about 5 billion hectares. The complete change to bio-based plastics would need 0.6% for the lowest scenario and 4.4% for the highest scenario of this land. In 2008, 5 billion ha of land was used as pasture ground (71%) and the rest of cropland (29%). The cropland was used to produce food (5.2%), feed (20.6%), and bioenergy (1.1%). Based on Carus (2011), 570 million hectares of the free agricultural area were still available in 2006. To substitute 322 million tonnes of plastic in the world with bio-based plastics would need 38% of this land at the extreme case and 5% at the lowest case. However, the global additional demand for land use by 2020 for food, residential area, and biofuels was estimated at 210 million hectares, leaving 360 million hectares free (Vink & Davies, 2015). The complete change will take about 8% to 61% of the free arable land.

Carus (2011) stated that in principle there are sufficient and sustainable biomass resources available for food, feed, bioenergy, and industrial material use including bio-based plastics. To achieve that, the crucial steps must be taken into action which is optimized biomass allocation by improving the technology and infrastructure, invest in agricultural, political reforms, optimizing human food habits to sustainability. For the bioplastics, it is important to choose the feedstocks wisely with the high yield and the maximum feedstocks efficiency.

The variation of the water and land footprint of bioplastics are highly influenced by water and land footprint of crops because the crop production dominates the water and land footprint of bioplastics. The water and land footprint of crops can vary depending on where the crops grow, it is due to differences in crop yields between countries and crops, differences in climate and agricultural technologies (Mekonnen & Hoekstra, 2011). Besides that, the water and land footprint of bioplastics are affected by the conversion ratio of feedstock weight to final plastic polymer weight or the feedstock efficiency. In terms of feedstock efficiency, PLA is the most efficient. For 1 kg of PLA, it needs 1.6 kg of cassava roots as feedstock. Corbion (2016) stated that other bioplastics can require 2.5 to 3 times more starch feedstocks to produce the same amount of plastics. The production pathway of bioplastics does not seems too important to most of the cases. For partially bio-based bioplastics that still highly depend on fossil-based feedstocks, the fossil-based production pathways can affect the magnitude of water and land footprint of bioplastics.

The water footprint of bioplastics comes mostly from growing crops. For all studied bioplastics, the water footprint of bio-feedstocks shares 90% of the total water footprint. The outliers are sugar cane based PE, sugar cane based PET, and sugar cane based PVC. The water footprint of bio-feedstocks for these three bioplastics are 83%, 54%, and 59%, respectively. The water footprint of bio-feedstocks for sugar cane based PET (30% bio-based contain) and sugar cane based PVC (45% bio-based contain) has almost the same water footprint of its production. For sugar cane based PET, the water footprint of Brazilian sugar cane is 137 m^3/ton, relatively small compared to India molasses cane which is 702 m^3/ton. For the production itself, the water footprint for producing sugar cane based PET is twice the amount of molasses cane based PET. The water footprint of production goes mostly to electricity (94%). The water footprint of electricity in Brazil is relatively high, almost double the water footprint electricity of India. The oddity of sugar cane based PET because of the small water footprint of bio-feedstocks and the high water footprint of electricity. For sugar cane based PVC, the water footprint of bio-feedstock share is small. It is because, chlorine which is the main input product of PVC, is the energy-intensive product. To produce 1 kg chlorine, 10 MJ of electricity is needed, it is about ten times higher than the electricity needed for the polymerization of plastics. It makes the water footprint of production PVC much higher than other bioplastics.

Several recycling rates are set to calculate complete change from fossil-based plastics to bio-based plastics which are 10%, 36%, and 62%. The calculation of water and land footprint of recycling process itself are not taken into account. WEF (2017) stated that from 14% recycling rate of plastic, about 4% is losses in the process itself. This 4% equals to around 28.6% of the total recycling rate. It means that this portion of the material is lost during the recycling rate process which is not considered in the calculation. If the energy for recycling rate and material losses during recycling process are taken into account, the water and land footprint will be higher.

The water footprint of bioplastics based on all the water footprint of the input product that was necessary for the last processing step to produce that product and the process water footprint of that processing step. For water as input product, the net water consumption is directly added to the blue water footprint. The water emission during the process is simply neglected. It overestimates the blue water footprint, meanwhile, estimation of the grey water footprint is probably under-estimated.

The calculation of water and land footprint of bioplastics do not consider the surplus electricity during the production of bioplastics. For example, electricity production during the production stage of the hydrous ethanol from sugar cane through producing biogas. The surplus electricity is about 0.6 MJ/kg hydrous ethanol. The surplus electricity can be sold to the grid or used for the production itself. If it considers use for the production of bioplastic, the electricity needed for producing bioplastic will decrease. It will decrease the small amount of water footprint of bioplastic (accounted about 3%) but it will not change the land footprint of bioplastics because most of the land footprint of bioplastic (98%) is used for growing crop.

For 100% bio-based PET, the water and land footprint of PTA only consider water and land footprint of the feedstocks which are wheat, corn, and poplar. This leads to under-estimation of the water and land footprint of a fully bio-based PET. If we assume, the energy of bio-based PTA is the same as the energy of fossil-based PTA, the water footprint will increase about 2-5%. For the land footprint, only the small amount will increase, about 0.1 to 0.2% of the calculated result. It is because land footprint of production is small if it compares to the total land footprint of PET.

The result of water and land footprint of bioplastics considers water and land footprint of transportation from crop plantation to the production facilities. Meanwhile, the transportation using ship is not included in the calculation. For example, it is an important pathway of producing PET. After MEG is produced in India or Brazil, it is shipped to Europe to be polymerized with PTA. A simple calculation of water and land footprint of ship transportation uses the energy consumption of ship which is 0.017 kWh/t-km from MacKay (2008), the capacity of 40,000 ton and the distance of 10,000 km. If this transportation is taken into account, the maximum water footprint will increase 2% of the accounted water footprint. Meanwhile, for the land footprint, it will increase about 0.3% of the accounted land footprint.

6 CONCLUSION

The water footprint of bioplastics varies between 1.4 m^3/kg to 9.5 m^3/kg. The land footprint of bioplastic varies between 0.7 m^2/kg to 13.75 m^2/kg. The water footprint of a complete change to bio-based plastics varies from 307 billion to 1,652 billion m^3 per year. To understand this number, the global annual average water footprint is 9,087 billion m^3/year. The complete change from fossil-based plastics to bio-based plastics will take about 3% to 18% of the global annual average water footprint. The land footprint of a complete change to bio-based plastic varies from 30 million to 219 million hectares. In 2020, the free arable land accounts about 360 million hectares. The complete change from fossil-based plastics to bio-based plastics will take about 8% to 61% of the free arable land.

This study provides important information on the water and land footprint of bioplastics. The study shows how different feedstocks and pathway are contributed to water and land footprint of bioplastics. The study analyzed the implication of a complete move from fossil-based to bio-based plastics on global land and water requirement by using a different set of biomaterials and different recycling rates. The study contributes to understanding useful information to predict the water and land requirements for bioplastics. The drawbacks of this study are the study focuses on first generation bioplastics. It is important to know the water and land footprint of bioplastics from second (cellulosic crops as well as residue and agricultural waste products) and third generation (non-traditional organism like some forms of algae and non-agricultural wastes). It is important to know the water and land footprint of bioplastics from second and third generation feedstock to understand the implication of bio-based plastics on global land and water requirements in the future.

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Appendix I. Calculation of water and land footprint of Brazilian sugar cane based PE

The input products for sugar cane based polyethylene (PE) production is shown in Table I.1. The first step of PE production by generating bioethanol from sugar cane in Brazil. The data is retrieved from Braskem company, a leading producer of PE from Brazilian sugar cane. The second step is ethylene production. There is no industrial data regarding ethylene production, so data from Kochar et al. (1981) in Liptow and Tillman (2012) are used. The last is polymerization of ethylene. Data from Borealis (2008) in Liptow and Tillman (2012), a Swedish PE producer are used.

Table I.1. Input products for producing sugar cane based polyethylene

Process	**Unit**		**Sources**
Bioethanol production			
Sugar cane	t/t PE	27.5	Terry (2012)
Water	m^3/t bioethanol	24.7	Tsiropoulos et al. (2014)
Diesel consumption	MJ/t bioethanol	217.0	Liptow and Tillman (2012)
Transportation	km	21	Gonzales et al. (2010)
Ethylene production			
Internal fuel	kJ/kg ethylene	3736.0	Kochar et al. (1981)
External fuel	kJ/kg ethylene	1675.0	Kochar et al. (1981)
Electricity	kJ/kg ethylene	1116.0	Kochar et al. (1981)
Polymerization			
Internal fuel	t/yr	1748.0	Borealis (2008)
External fuel	t/yr	1159.0	Borealis (2008)
Electricity	MJ/yr	1.5×10^9	Borealis (2008)

To simplify the data to be used in the further calculation, Table I.2 is made to show the list of products required to produce 1 kg of PE. The conversion ratio of each input products can be seen in the footnote below Table I.2.

Based on Liptow and Tillman (2012) and Tsiropoulos et al. (2014), 1 tonne PE is produced from 2,400 liter bioethanol and the density of bioethanol is 0.789 kg/liter. Based on these values, the water and diesel consumption in the bioethanol production for producing 1 kg of PE can be calculated.

The optimal distance from sugar cane plant to ethanol production is 21 km by using 32 tonnes truck capacity (the common industrial heavy truck capacity). The total distance from sugar cane plantation to the factory and back again to the plantation is 42 km. It is assumed that truck is fully loaded from plantation to ethanol production plant and it is empty when coming back to the sugar cane plantation. Based on Mårtensson (2006), the fully loaded heavy-duty truck needs 50 liters per 100 km, meanwhile empty loaded truck needs 30 liters per 100 km. So, for transporting sugar cane to ethanol plantation needs 42 km multiplied by 0.4 liters per km which is 16.8 liters of diesel. The diesel contains 38 MJ per liter. The energy for transporting 1 kg sugar cane can be obtained by multiplying diesel needed and energy contained in diesel, it is then divided by the truck capacity in kg. It is known that 27.5 kg of sugar cane is needed to produce 1 kg of PE. As a result, the transportation energy for producing 1 kg

PE equals to the energy for transporting 1 kg sugar cane multiplied by 27.5. The result can be seen in Table I.2

During ethylene production and polymerization process, fuel, and electricity are needed. There is no detailed information about the types of fuel used in this process. Hence, it is assumed to be using diesel fuel. During the polymerization process, the available values are in ton per year for fuel and MJ per year for electricity. To convert this values to GJ per kg PE, energy content in diesel and capacity production per year are needed. From Nylund and Erkkila (2005), the energy content of diesel is known to be 38 MJ per liter. The capacity production data is taken from Borealis (2008) which is 450,000 ton PE per year.

Table I.2. Input products to producing 1 kg sugar cane based polyethylene

Input product	**Unit**	
Bioethanol production		
Sugar cane	ton	2.75 x 10^{-2}
Water	m^3	4.68 x 10^{-2} [a]
Diesel consumption	GJ	4.11 x 10^{-4} [a]
Transportation	GJ	5.49 x 10^{-4} [b.d]
Ethylene production		
Internal fuel	GJ	3.74 x 10^{-3} [c]
External fuel	GJ	1.68 x 10^{-3} [c]
Electricity	GJ	1.12 x 10^{-3} [c]
Polymerization		
Internal fuel	GJ	1.76 x 10^{-4} [d.e,f]
External fuel	GJ	1.17 x 10^{-4} [d.e,f]
Electricity	GJ	3.33 x 10^{-3} [e,f]

a: Based on 1 ton PE is produced from 2,400 liter bioethanol and bioethanol density of 0.789 kg/l (Liptow and Tillman (2012); Tsiropoulos et al. (2014))

b: The transportation is using 32 tonnes diesel truck . Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006).

c: Based on Terry (2012), 1 ton PE is produced from 1 ton ethylene

d: Diesel contains 38 MJ per liter (Nylund & Erkkila, 2005).

e: 1 ton of diesel equal to 1,192 liters (Hofstrand, 2008).

f: Based on Borealis (2008), polyethylene capacity production is 450,000 ton/year

The water footprint and land footprint of material for producing PE are shown in Table I.3 below. The water footprint of sugar cane was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of sugar cane is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table I.3. Water and Land Footprint for producing sugar cane based polyethylene

Input product	Water footprint					Land footprint	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bioethanol production							
Sugar cane [a]	m^3/ton	5	122	10	137	m^2/ton	141.50
Diesel consumption [b]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Transport [c]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Ethylene production							
Internal fuel [d]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
External fuel [d]	m^3/GJ	0.12	-		0.12	m^2/GJ	0.01
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^2/GJ	9.27
Polymerization							
Internal fuel [d]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
External fuel [d]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^2/GJ	9.27

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016) .

b: Calculation is in Table 4

c: Transportation is using diesel truck

d: There is no further explanation of fuel type. It assumes the fuel is diesel.

e: Calculation of water footprint of electricity is in Table I.5 and calculation of land footprint of electricity is in Table I.6.

Since diesel is a product of crude oil, the water and land footprint of diesel can be calculated with the water and land footprint of crude oil considering the product and value fraction. The formulae to calculate water and land footprint of diesel can be seen in Table I.4. Table I.4 shows the values of water and land footprint of diesel. For transportation, the water footprint is the same as the water footprint for diesel. It is assumed that the transportation is using the diesel engine truck. Both internal and external fuel are assumed to use diesel fuel as well.

Table I.4. Calculation of water and land footprint of diesel

	Crude Oil	Diesel	Source
Product fraction	1	0.48	eia (2017a)
Price ($/barrel)	49.69	2.64	eia (2017a)
Water footprint	1.058[a]	0.12[b]	
Land footprint	0.11[c]	0.01[d]	

a: Water footprint is based on Hoekstra (2013)

b: Based on calculation; WF of diesel = (WF of crude oil × price diesel)/(price crude oil × product fraction diesel)

c: Based on Fritsche et al. (2017)

d: Based on calculation; LF of diesel = (LF of crude oil x price diesel)/(price crude oil x product fraction diesel)

Meanwhile, the water footprint of electricity is based on the calculation in Table I.5. The energy mix for electricity is assumed to be the same from the national electricity supply. The Brazilian national electricity supply data comes from Coltro et al. (2003). From that data, the percentage of Brazilian electricity supply is obtained. Each energy sources have their own range of water footprint values (Mekonnen et al., 2015). The water footprint of electricity for different energy sources are calculated from the average value of those ranges. The water footprint of electricity (m^3/GJ) is multiplied by the percentage of energy supply to calculate the water footprint of each energy sources. The percentage of energy supply is calculated from the ratio of energy input which is converted from the mass unit (kg) to energy unit (MJ). The conversion ratio can be seen from point d to i in the footnote below Table I.5. It is assumed that the water footprint of biomass is entirely green water footprint. On the other hand, all the water footprint of other energy sources are fully blue water footprint.

Table I.5. Calculation of water footprint of Brazilian electricity supply per GJ

	Unit	Input/GJ electricity [a]	Energy input in MJ	Percentage of energy supply	Water footprint (m^3/GJ)[b]	Water footprint (m^3)	
						Blue	Green
Energy input	GJ	1.584					
Provided by							
Biomass [c]	kg	4.87	87.66 [d]	5.8%	275	-	15.93
Coal	kg	12.84	376.31 [e]	20.4%	1.08	0.22	-
Natural gas	kg	0.76	37.24 [f]	2%	0.66	0.01	-
Oil	kg	1.21	50.66 [g]	3.5%	0.71	0.02	-
Water (thermal evaporated)	kg	231.44	523.05[h]	34.6%	-	0.23	-
Water (Hydropower)	m^3	116.32	511.81[i]	33.8%	421.15	143.76	-
Total						144.25	15.93

a: Source: Coltro et al. (2003)
b: Obtain from the average value of water footprint of electricity from Mekonnen et al. (2015)
c: Assume all water footprint of biomass is green water footprint
d : 1 kg biomass = 18 MJ (Smil, 1983) ; e)1 kg coal = 24 MJ (world-nuclear, 2017) ; f)1 kg natural gas = 39 MJ (world-nuclear, 2017) ; g) 1 kg oil = 44 MJ (world-nuclear, 2017) ; h)1 kg thermal evaporation = 2.26 MJ (Tuohy (2014) ; i)1 m^3 hydropower = 4.4 MJ (rounded from total energy input)

The land footprint of electricity is calculated using the same method as the water footprint. The land footprint for electricity generation is retrieved from Fritsche et al. (2017). The calculation can be seen in Table I.6.

Table I.6. Calculation of land footprint of Brazilian electricity supply per GJ

	Percentage	Land footprint (m^2/GJ) [a]	Land footprint (m^2)
Biomass	5.8%	138.89	8.04
Coal	20.4%	1.39	0.28
Natural gas	2%	0.06	0.00
Oil	3.5%	0.11	0.00
Water (thermal evaporated)	34.6%	0.00	0.00
Water (Hydropower)	33.8%	2.78	0.94
Total			9.27

a: Source: Fritsche et al. (2017)

Table I.7 shows the calculated result from the data in Table I.2 and Table I.3 above. The input product values in Table I.2 are multiplied by water and land footprint units of each product from Table I.3. For the sugar cane, water footprint is divided into blue, green, and grey components. Meanwhile, the energy and transportation are classified as blue and green water footprint. For water as input product, the used amount of water is directly added to the blue water footprint. The water and land footprint of diesel consumption, transportation, internal fuel, external fuel, and electricity are very small.

The water footprint for producing 1 kg of sugar cane based PE is 4.53 m^3 and the land footprint is 3.93 m^2. The water footprint is mainly for growing sugar cane (83%) and the rest is for production process and energy. Meanwhile, most of the land footprint (98%) of PE is allocated for growing the crop.

Table I.7. The water and land footprint of 1 kg sugar cane based PE

Input product	**Water footprint (m^3/kg PE)**				**Land footprint (m^2/kg PE)**
	Blue	Green	Grey	Total	
Bioethanol production					
Sugar cane	0.14	3.36	0.28	3.77	3.89
Water	0.05	-	-	0.05	-
Diesel consumption	0.00	-	-	0.00	0.00
Transport	0.00	-	-	0.00	0.00
Ethylene production					
Internal fuel	0.00	-	-	0.00	0.00
External fuel	0.00	-	-	0.00	0.00
Electricity	0.16	0.02	-	0.18	0.00
Polymerization					
Internal fuel	0.00	-	-	0.02	0.00
External fuel	0.00	-	-	0.01	0.00
Electricity	0.48	0.05	0.00	0.53	0.03
Total	**0.83**	**3.43**	**0.28**	**4.53**	**3.93**

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix II. Calculation of water and land footprint of Belgian sugar beet-based PE

The input products for sugar beet-based polyethylene (PE) production is shown in Table II.1. The first step of PE production by generating bioethanol from sugar beet in Belgium. The data is retrieved from Belboom and Léonard (2016). The second step is ethylene production. The last is polymerization of ethylene. Data from Borealis (2008) in Liptow and Tillman (2012), a Swedish PE producer are used. In Table II.1, the input products to produce PE are listed. These are raw data using different units of measurements.

Table II.1. Input products for producing sugar beet-based polyethylene

Process	Unit		Sources
Bioethanol production			
Sugar beet	t/t PE	23.92	Belboom and Léonard (2016)
Transportation	km	50.0	Belboom and Léonard (2016)
Electricity	kWh/t bioethanol	163.0	Belboom and Léonard (2016)
Heat	MJ/t bioethanol	6248.0	Belboom and Léonard (2016)
Ethylene production			
Steam	t/t ethylene	1.2	Belboom and Léonard (2016)
Electricity	Kwh /t ethylene	340.0	Belboom and Léonard (2016)
Heat	MJ / t ethylene	200.0	Belboom and Léonard (2016)
Polymerization			
Internal fuel supply	t/yr	1748.0	Borealis (2008)
External fuel supply	t/yr	1159.0	Borealis (2008)
Electricity	MJ/yr	1.5.x 10^9	Borealis (2008)

To simplify the data to be used in the further calculation, Table II.2 is made to show the list of products required to produce 1 kg of PE. The conversion ratio of each input products can be seen in the footnote below Table II.2.

Based on Liptow and Tillman (2012) and Tsiropoulos et al. (2014), 1 tonne PE is produced from 2,400 liter bioethanol and the density of bioethanol is 0.789 kg/liter. Based on these values, the electricity and heat consumption during bioethanol production for producing 1 kg of PE can be calculated.

The optimal distance from sugar beet plant to ethanol production is 50 km by using 32 tonnes truck capacity (the common industrial heavy truck capacity). Hence, the total distance from sugar beet plantation to the factory and back again to the plantation is 100 km. By using the same methodology as sugar cane based PE in Appendix I, the transportation energy for producing 1 kg of sugar beet PE can be obtained. The result can be seen in Table II.2.

During the polymerization process, fuel, and electricity are needed. There is no further explanation about the types of fuel that is used. It is assumed to be using diesel fuel. The available values for fuel and electricity are in ton per year for fuel and MJ per year for electricity. To convert these values to GJ per kg PE, energy content in diesel and capacity production per year are needed. From Nylund and

Erkkila (2005), the energy content of diesel is known to be 38 MJ per liter. The capacity production data is taken from Borealis (2008) which is 450,000 ton PE per year.

Table II.2. Input products to producing 1 kg sugar beet-based polyethylene

Input product	**Unit**	
Bioethanol production		
Sugar beet	ton	2.39 x 10^{-2}
Transportation	GJ	1.14 x 10^{-3} [a,b]
Electricity	GJ	1.78 x 10^{-3} [c]
Heat	GJ	1.18 X 10^{-2} [c]
Ethylene production		
Steam	m^3	1.21 x 10^{-3} [d]
Electricity	GJ	1.22 x 10^{-3} [d]
Heat	GJ	2.00 x 10^{-4} [d]
Polymerization		
Internal fuel	GJ	1.76 x 10^{-4} [b,e,f]
External fuel	GJ	1.17 x 10^{-4} [b,e,f]
Electricity	GJ	3.33 x 10^{-3} [f]

a: It is assumed that the transportation is using 32 tonnes diesel truck (common capacity truck for industrial). Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006).
b: Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).
c: Based on 1 ton PE is produced from 2,400 liter bioethanol and bioethanol density of 0.789 kg/l (Liptow and Tillman (2012); Tsiropoulos et al. (2014)).
d: Based on Terry (2012), 1 ton PE is produced from 1 ton ethylene.
e: Assume fuel is diesel. 1 ton of diesel equal to 1,192 liters (Hofstrand, 2008).
f: Based on Borealis (2008), polyethylene capacity production is 450,000 ton/year.

The water footprint and land footprint of material for producing PE are shown in Table II.3 below. The water footprint of sugar beet was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of sugar beet is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table II.3. Water and Land Footprint for producing sugar beet-based polyethylene

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bioethanol production							
Sugar beet [a]	m^3/ton	0.00	51.00	13.00	64.00	m^2/ton	122.30
Transportation [b]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.03
Ethylene production					0.00		
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.03
Polymerization					0.00	m^2/GJ	
Internal fuel supply [e]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
External fuel supply [e]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).
b: Transportation is using diesel truck.
c: Calculation of water footprint of electricity is in Table II.4 and calculation of land footprint of electricity is in Table II.5.
d: It is assumed 100% heat comes from natural gas.
e: There is no further explanation of fuel type. It assumes the fuel is diesel.

The water and land footprint of diesel can be seen in Table I.4 in Appendix I. For transportation, the water footprint is the same as the water footprint for diesel. It is assumed that the transportation is using diesel engine truck. Meanwhile, the water footprint of electricity is based on the calculation in Table II.4. The energy mix for electricity is assumed to be the same from the national electricity supply. The Belgium national electricity supply data comes from eia (2016). The water footprint of energy sources are obtained from the average value of water footprint of electricity from Mekonnen et al. (2015). The water footprint of electricity (m^3/GJ) is multiplied by the percentage of energy supply to calculate the water footprint of each energy sources. It is assumed that the water footprint of biomass is entirely green water footprint. On the other hand, all the water footprint of other energy sources are fully blue water footprint.

Table II.4. Calculation of water footprint of Belgium electricity supply

Energy sources	**Percentage of energy supply** [a]	**Water footprint (m^3/GJ)**[b]	**Water footprint (m^3)**	
			Blue	Green
	47.2	0.73	0.3	-
Natural gas	27	0.66	0.2	-
Biofuels and waste	7.9	275	-	21.73
Wind	6.5	0.01	0.0	-
Coal	6.2	1.09	0.1	-
Solar	4	1.15	0.0	-
Heat	0.5	0.66	0.0	-
Hydropower	0.4	425.15	1.7	-
Oil	0.3	0.70	0.0	-
Total			2.3	21.7

a: Source: IINAS (2017)

b: Obtained from the average value of water footprint of electricity from Mekonnen et al. (2015)

The land footprint of electricity is calculated using the same method as the water footprint. The land footprint for electricity sources are retrieved from IINAS (2017). The calculation can be seen in Table II.5.

Table II.5. Calculation of land footprint of Belgium electricity supply

Energy sources	**Percentage of energy supply**	**Land footprint** [a] **(m^2/GJ)**	**Land Footprint (m^2)**
Nuclear	47.2	0.28	0.13
Natural gas	27.0	0.03	0.01
Biofuels and waste	7.9	125.00	9.88
Wind	6.5	0.19	0.01
Coal	6.2	0.06	0.00
Solar	4.0	2.42	0.10
Heat	0.5	0.03	0.00
Hydropower	0.4	0.97	0.00
Oil	0.3	0.03	0.00

a: Source: Fritsche et al. (2017)

Table II.6 shows the calculated result from the data in Table II.2 and Table II.3 above. The input product values in Table II.2 are multiplied by water and land footprint units of each product from Table II.3. For the sugar beet, water footprint is divided into blue, green, and grey components. Meanwhile, the energy and transportation are classified as blue and green water footprint. For water as input product, the used amount of water is directly added to the total water footprint. The water and land footprint of diesel consumption, transportation, internal fuel, external fuel, and electricity are very small.

The water footprint for producing 1 kg of sugar beet-based PE is 1.69 m^3 and the land footprint is 2.99 m^2. The water footprint is mainly for growing sugar beet (91%) and the rest is for production process and energy. Meanwhile, most of the land footprint (98%) of PE is allocated for growing the crop.

Table II.6. The water and land footprint of 1 kg sugar beet-based PE

Input product	**Water footprint (m^3/kg PE)**				**Land footprint (m^2/kg PE)**
	Blue	Green	Grey	Total	
Ethanol production					
Sugar beet	-	1.22	0.31	1.53	2.93
Transportation	0.00	-	-	0.00	0.00
Electricity	0.00	0.04	-	0.04	0.02
Heat	0.01	-	-	0.01	0.00
Ethylene production					
Steam	0.00	-	-	0.00	-
Electricity	0.00	0.03	-	0.03	0.01
Heat	0.00	-	-	0.00	0.00
Polymerization					
Internal fuel supply	0.00	-	-	0.00	0.00
External fuel supply	0.00	-	-	0.00	0.00
Electricity	0.01	0.07	-	0.08	0.03
Total	0.02	1.36	0.31	1.69	2.99

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix III. Calculation of water and land footprint of Belgian wheat based PE

The input products for wheat-based polyethylene (PE) production is shown in Table III.1. The first step of PE production by generating bioethanol from wheat in Belgium. The data is retrieved from Belboom and Léonard (2016). The second step is ethylene production. The last is polymerization of ethylene. Data from Borealis (2008) in Liptow and Tillman (2012), a Swedish PE producer are used. In Table III.1, the input products to produce PE are listed. These are raw data using different units of measurements.

Table III.1. Input products for producing wheat based polyethylene

Process	Unit		Sources
Bioethanol production			
Wheat	t/t PE	6.84	Belboom and Léonard (2016)
Transportation	km	50.0	Belboom and Léonard (2016)
Electricity	kWh/t bioethanol	235.0	Belboom and Léonard (2016)
Heat	MJ/t bioethanol	1800.0	Belboom and Léonard (2016)
Ethylene production			
Steam	t/t ethylene	1.2	Belboom and Léonard (2016)
Electricity	Kwh /t ethylene	340.0	Belboom and Léonard (2016)
Heat	MJ / t ethylene	200.0	Belboom and Léonard (2016)
Polymerization			
Internal fuel supply	t/yr	1748.0	Borealis (2008)
External fuel supply	t/yr	1159.0	Borealis (2008)
Electricity	MJ/yr	1.5.x 10^{9}	Borealis (2008)

To simplify the data to be used in the further calculation, Table III.2 is made to show the list of products required to produce 1 kg of PE. The conversion ratio of each input products can be seen in the footnote below Table III.2. The methodology of calculation the input products to producing 1 kg wheat based PE is the same as previous appendix (sugar beet based PE).

Table III.2. Input products to producing 1 kg wheat based polyethylene

Input product	Unit	
Bioethanol production		
Wheat	ton	6.84 x 10^{-3}
Transportation	GJ	3.25 x 10^{-4} [a,b]
Electricity	GJ	2.57 x 10^{-3} [c]
Heat	GJ	3.41 X 10^{-3} [c]
Ethylene production		
Steam	m^{3}	1.21 x 10^{-3} [d]
Electricity	GJ	1.22 x 10^{-3} [d]
Heat	GJ	2.00 x 10^{-4} [d]
Polymerization		
Internal fuel	GJ	1.76 x 10 $^{-4}$ [b,e,f]
External fuel	GJ	1.17 x 10^{-4} [b,e,f]
Electricity	GJ	3.33 x 10 $^{-3}$ [f]

a: It is assumed that the transportation is using 32 tonne diesel truck (common capacity truck for industrial). Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006).

b: Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).

c: Based on 1 ton PE is produced from 2,400 liter bioethanol and bioethanol density of 0.789 kg/l (Liptow and Tillman (2012); Tsiropoulos et al. (2014)).

d: Based on Terry (2012), 1 ton PE is produced from 1 ton ethylene.

e: Assume fuel is diesel. 1 ton of diesel equal to 1,192 liters (Hofstrand, 2008).

f: Based on Borealis (2008), polyethylene capacity production is 450,000 ton/year.

The water footprint and land footprint of material for producing PE are shown in Table III.3 below. The water footprint of wheat was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of wheat is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

The water and land footprint of diesel can be seen in Table I.4 in Appendix I. For transportation, the water footprint is the same as the water footprint for diesel. It is assumed that the transportation is using diesel engine truck. Meanwhile, the water footprint of electricity is based on the calculation in Table II.4 in Appendix II. The land footprint calculation for electricity can be seen in Table II.5 in Appendix II.

Table III.3. Water and Land Footprint for producing wheat based polyethylene

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bioethanol production							
Wheat [a]	m^3/ton	0.00	403.00	181.00	584.00	m^2/ton	1062.37
Transportation [b]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.03
Ethylene production					0.00		
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.03
Polymerization					0.00	m^2/GJ	
Internal fuel supply [e]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
External fuel supply [e]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
Electricity [c]	m^3/GJ	2.34	21.73	-	24.07	m^2/GJ	10.13

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).
b: Transportation is using diesel truck.
c: Calculation of water footprint of electricity is in Table II.4 and calculation of land footprint of electricity is in Table II.5.
d: It is assumed 100% heat comes from natural gas.
e: There is no further explanation of fuel type. It assumes the fuel is diesel.

Table III.4 shows the calculated result from the data in Table III.2 and Table III.3 above. The input product values in Table III.2 are multiplied by water and land footprint units of each product from Table III.3. For the wheat, water footprint is divided into blue, green, and grey components. Meanwhile, the energy and transportation are classified as blue and green water footprint. For water as input product, the used amount of water is directly added to the blue water footprint. The water and land footprint of diesel consumption, transportation, internal fuel, external fuel, and electricity are very small.

The water footprint for producing 1 kg of wheat-based PE is 4.17 m^3 and the land footprint is 7.34 m^2. The water footprint is mainly for growing wheat (96%) and the rest is for production process and energy. Meanwhile, most of the land footprint (99%) of PE is allocated for growing the crop.

Table III.4. The water and land footprint of 1 kg wheat based PE

Input product	**Water footprint (m^3/kg PE)**				**Land footprint (m^2/kg PE)**
	Blue	Green	Grey	Total	
Ethanol production					
Sugar beet	-	2.76	1.24	3.99	7.27
Transportation	0.00	-	-	0.00	0.00
Electricty	0.01	0.06	-	0.06	0.03
Heat	0.00	-	-	0.00	0.00
Ethylene production					
Steam	0.00	-	-	0.00	-
Electricty	0.00	0.03	-	0.03	0.01
Heat	0.00	-	-	0.00	0.00
Polymerization					
Internal fuel supply	0.00	-	-	0.00	0.00
External fuel supply	0.00	-	-	0.00	0.00
Electricity	0.01	0.07	-	0.08	0.03
Total	0.02	2.91	1.24	4.17	7.34

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix IV. Calculation of water and land footprint of India molasses cane based PET

Polyethylene terephthalate (PET) is formed from terephthalic acid (PTA) and monoethylene glycol (MEG). PTA is derived from oil feedstock, meanwhile, MEG is produced from biomaterial which is molasses cane. Based on Papong et al. (2014), 1 kg PET is produced from 30% of MEG and 70% of PTA. The complete input products to make PET can be seen in Table IV.1.

Table IV.1. Input products for producing molasses cane based PET

Process	Unit		Sources
MEG	kg/kg PET	0.35	Papong et al. (2014)
PTA	kg/kg PET	0.87	Papong et al. (2014)
Electricity	kwh/kg PET	0.38	Papong et al. (2014)
Heat	MJ/kg PET	6.3	Papong et al. (2014)
Hydrous ethanol production			
Molasses cane	kg/kg ethanol	5.06	Tsiropoulos et al. (2014)
Water	m^3/kg ethanol	0.01	Tsiropoulos et al. (2014)
Transport	km	100	Soam et al. (2015)
Ethylene production			
Hydrous ethanol	kg/kg ethylene	1.74	Kochar et al. (1981)
Electricity	MJ/kg ethylene	1.60	Kochar et al. (1981)
MEG production			
Ethylene	kg/kg MEG	0.60	DPT (2001)
Electricity	kwh/kg MEG	0.47	DPT (2001)
Paraxylene production			
Heavy naphtha	kg/kg paraxylene	4.3	DPT (2001)
Electricity	Kwh/kg paraxylene	0.03	DPT (2001)
Cooling Water	m^3/kg paraxylene	0.26	DPT (2001)
PTA production			
Paraxylene	kg/kg PTA	0.66	Papong et al. (2014)
Water	kg/kg PTA	0.43	Papong et al. (2014)
Electricity	kWh/kg PTA	0.47	Papong et al. (2014)
Heat	MJ/kg PTA	3.93	Papong et al. (2014)

One kg of MEG is produced from 0.60 kg ethylene meanwhile 1 kg ethylene is produced from 1.74 kg hydrous ethanol and 1 kg hydrous ethanol is produced from 5.06 kg molasses cane. Based on these data, 1 kg of MEG is produced from 5.28 kg molasses cane. For water consumption, 0.01 m^3 water is needed per 1 kg of ethanol. So, to produce 1 kg of MEG, the calculation is (0.01 m^3 water/kg ethanol) x (yield ethanol to ethylene) x (ethylene to MEG) = 0.01 x 1.74 x 0.60 = 0.012 m^3 water/kg MEG. By using the same concept, the electricity for producing 1 kg of MEG can be calculated.

For transportation, the same concept like the previous appendix can be applied. The energy for transporting 1 kg MEG can be obtained by multiplying diesel needed for transporting molasses cane to factory and energy contained in diesel, it is then divided by the truck capacity in kg. It is known that 5.28 kg of molasses cane is needed to produce 1 kg of MEG. As a result, the transportation energy for producing 1 kg MEG equals to the energy for transporting 1 kg molasses cane multiplied by 5.28. The result can be seen in Table IV.2. For creating 1 kg of MEG, it needs 5.28 kg of molasses cane, 0.01 m^3 of water, 2.64 MJ of electricity and 1.34 MJ energy to transport cane to the factory (Table IV.2).

Table IV.2. Input products for producing 1 kg MEG

1 kg of MEG		
Molasses cane	ton/kg MEG	5.28×10^{-3}
Water	m^3/kg MEG	1.19×10^{-2}
Electricity	GJ/kg MEG	2.64×10^{-3}
Transport	GJ/kg MEG	1.34×10^{-4} [a]

a: It is using 32 tonnes capacity diesel truck. Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006). Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).

PTA is derived from paraxylene which is obtained from naphtha. For producing 1 kg of PTA, 2.84 kg of naphtha is needed. The water used in the process of making PTA is cooling water. It is assumed that 90% of cooling water is recycled since there is no further explanation about how much water is really used. The complete input products to make PTA is shown in Table IV.3.

Table IV.3. Input products for producing 1 kg PTA

1 kg pf PTA		
Heavy naphtha	ton/kg PTA	2.84×10^{-3}
Water	m^3/kg PTA	1.75×10^{-2} [a]
Electricity	GJ/kg PTA	1.77×10^{-3}
Heat	GJ kg PTA	3.93×10^{-3}

a: Assume 90% of cooling water in processing paraxylene is recycled.

The water footprint and land footprint of material for producing molasses cane based PET are shown in Table IV.4. The water footprint and the land footprint is calculated by considering the value and product fraction of molasses cane. In Table IV.5 below, the water footprint of Indian electricity supply is calculated. Meanwhile, the calculation of land footprint of Indian electricity supply is on Table IV.6.

Table IV.4. Water and Land footprint for producing molasses cane based PET

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Molasses [a,b]	m^3/ton	354	306	42	702	m^2/ton	369.35
Electricity [c]	m^3/GJ	64.10	6.88	-	188.86	m^2/GJ	4.84
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.06
Heavy naphtha [e]	m^3/ton	2.58	-	-	2.58	m^2/ton	0.11
Transport [f]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01

a: Water footprint is based on Mekonnen and Hoekstra (2011).

b: Based on calculation; LF of molasses cane = (LF sugar cane x value fraction/product fraction). LF sugar cane is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016). Value fraction and product fraction from Mekonnen and Hoekstra (2011) are 0.13 and 0.05, respectively.

c: Calculation of water footprint of electricity is in Table IV.5 and calculation of land footprint of electricity is in Table IV.6

d: It is assumed 100% heat comes from natural gas.

e: Water footprint is based on Gerbens-Leenes et al. (2018). The land footprint calculation of heavy naphtha is based on calculation; product fraction of naphtha 0.068 (Gerbens-Leenes et al., 2018); value fraction 0.07 (Gerbens-Leenes et al., 2018); LF of crude oil 0.11 (Fritsche et al., 2017).

f: Transportation is using diesel truck.

The water footprint of electricity is based on the calculation in Table IV.5. The energy mix for electricity is assumed to be the same from the national electricity supply. The Indian national electricity supply data comes from CEA (2017). Each energy sources have their own range of water footprint values (Mekonnen et al., 2015). The water footprint of electricity for different energy sources are calculated from the average value of those ranges. The water footprint of electricity (m^3/GJ) is multiplied by the percentage of energy supply to calculate the water footprint of each energy sources. It is assumed that the water footprint of biomass is entirely green water footprint. On the other hand, all the water footprint of other energy sources are fully blue water footprint.

Table IV.5. The water footprint calculation of Indian electricity supply

Energy sources	Percentage of energy supply [a]	Water footprint (m^3/GJ)[b]	Water footprint (m^3)	
			Blue	Green
Coal	59	1.09	0.64	-
Hydro	15	425.15	63.35	-
Gas	8	0.66	0.05	-
Wind	10	0.01	0.00	-
Nuclear	2	0.73	0.02	-
Solar	4	1.15	0.05	-
Biomass	3	275.00	-	6.88
Total			64.10	6.88

a : Source : CEA (2017)
b : Source : Mekonnen et al. (2015)

The land footprint of electricity is calculated using the same method as the water footprint. The land footprint for electricity generation is retrieved from Fritsche et al. (2017). The calculation can be seen in Table IV.6.

Table IV.6. The land footprint calculation of Indian electricity supply

Energy sources	Percentage of energy supply [a]	Land footprint (m^3/GJ) [b]	Land Footprint (m^3)
Coal	59%	1.39	0.82
Hydro	15%	2.78	0.41
Gas	8%	0.06	0.00
Wind	10%	0.28	0.03
Nuclear	2%	0.03	0.00
Solar	4%	2.78	0.11
Biomass	3%	138.89	3.47
Total			4.84

a: Source: CEA (2017)
b: Source: Fritsche et al. (2017)

Table IV.7 shows the calculated result from the data in Table IV.2 and Table IV.4 above. The input product values in Table IV.2 are multiplied by water and land footprint units of each product from Table IV.4 to get the water and land footprint value of MEG. Meanwhile, Table IV.8 shows the calculated result from input products in Table IV.3 multiplied by water and land footprint form Table IV.4.

Table IV.7. The water and land footprint calculation of 1 kg MEG

Input product	**Water footprint (m^3/kg MEG)**				**Land footprint (m^2/kg MEG)**
	Blue	Green	Grey	Total	
Molasses	1.87	1.62	0.22	3.71	1.95
Water	0.01	-	-	0.01	-
Electricity	0.17	0.02	-	0.19	0.01
Transport	0.00	-	-	0.00	0.00
Total	2.05	1.63	0.22	3.91	1.96

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Table IV.8. The water and land footprint calculation of 1 kg PTA

Input product	**Water footprint (m^3/kg PTA)**				**Land footprint (m^2/kg PTA)**
	Blue	Green	Grey	Total	
Heavy napta	0.01	-	-	0.01	0.00
Water	0.03	-	-	0.02	-
Electricity	0.11	0.01		0.12	0.01
Heat	0.00	-	-	0.00	0.00
Total	0.14	0.01	-	0.15	0.01

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

After knowing water and land footprint for MEG (Table IV.7) and PTA (Table IV.8), Table IV.9 is made. Table IV.9 shows water and land footprint of 1 kg PET. As mentioned in Table IV.1, it needs 0.35 kg MEG, 0.87 kg PTA, 0.38 kWh electricity and 6.3 MJ of heat to produce 1 kg of PET. For electricity and heat, water and land footprint values in Table IV.4 are used.

The water footprint for producing 1 kg of molasses cane based PET is 1.60 m^3 and the land footprint is 0.70 m^2. The water and the land footprint are small since it is only partially bio-based products (30% bio-based).

Table IV.9. The water and land footprint calculation of 1 kg molasses cane based PET

Input product	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
PTA	0.12	0.01	0.00	0.13	0.01
MEG	0.72	0.57	0.08	1.37	0.69
Electricity	0.09	0.01	-	0.10	0.01
Heat	0.00	-	-	0.00	0.00
Total	0.93	0.59	0.08	1.60	0.70

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix V. Calculation of water and land footprint of Brazilian sugar cane based PET

Polyethylene terephthalate (PET) is formed from 30% bio-based MEG and 70% oil feedstocks based PTA. The complete input product for making PET can be shown in Table V.1. The process of making PET is the same as in Table IV.1. The different path is hydrous ethanol production which uses sugar cane as bio-feedstock.

Table V.1. Input products for producing sugar cane based PET

Process	Unit		Sources
MEG	kg/kg PET	0.35	Papong et al. (2014)
PTA	kg/kg PET	0.87	Papong et al. (2014)
Electricity	kwh/kg PET	0.38	Papong et al. (2014)
Heat	MJ/kg PET	6.3	Papong et al. (2014)
Hydrous ethanol production			
Sugar cane	kg/kg ethanol	14.69	Tsiropoulos et al. (2014)
Water	m^3/kg ethanol	0.0247	Tsiropoulos et al. (2014)
Transport	km	21	Gonzales et al. (2010)
Ethylene production			
Hydrous ethanol	kg/kg ethylene	1.74	Kochar et al. (1981)
Electricity	MJ/kg ethylene	1.60	Kochar et al. (1981)
MEG production			
Ethylene	kg/kg MEG	0.60	DPT (2001)
Electricity	kwh/kg MEG	0.47	DPT (2001)
Paraxylene production			
Heavy naphtha	kg/kg paraxylene	4.3	DPT (2001)
Electricity	Kwh/kg paraxylene	0.03	DPT (2001)
Cooling Water	m^3/kg paraxylene	0.26	DPT (2001)
PTA production			
Paraxylene	kg/kg PTA	0.66	Papong et al. (2014)
Water	kg/kg PTA	0.43	Papong et al. (2014)
Electricity	kWh/kg PTA	0.47	Papong et al. (2014)
Heat	MJ/kg PTA	3.93	Papong et al. (2014)

Producing 1 kg of MEG, 15.6 kg sugar cane is used (see Table V.2). Meanwhile, the complete input products to make PTA is shown in Table IV.3 in Appendix IV since it has the same values as earlier.

Table V.2. Input products for producing 1 kg MEG

Input product	Unit	
Sugar cane	ton/kg MEG	1.56×10^{-2}
Water	m^3/kg MEG	2.58×10^{-2}
Electricity	GJ/kg MEG	2.64×10^{-3}
Transport	GJ/kg MEG	3.11×10^{-4} [a]

a: It is using 32 tonnes capacity diesel truck. Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006). Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).

The water footprint and land footprint of material for producing molasses cane based PET are shown in Table V.3. The water and land footprint of electricity and heat are based on the calculation in Appendix I since the original country of sugar cane is the same.

Table V.3. Water and Land footprint for producing sugar cane based PET

Input product	Water footprint					Land footprint	
	Unit	Blue	Green	Grey	Total	Unit	Total
Sugar cane [a,b]	m^3/ton	5.00	122.00	10.00	137.00	m^2/ton	141.50
Electricity [c]	m^3/GJ	144.25	15.93	-	160.18	m^2/GJ	9.27
Heat [d]	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.06
Heavy naphtha [e,f]	m^3/ton	2.58	-	-	2.58	m^2/ton	0.11
Transport [g]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01

a: Source: Mekonnen and Hoekstra (2011)
b: The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).
c: Calculation of water footprint of Brazilian electricity is in Table I.5 and calculation of land footprint of Brazilian electricity is in Table I.6. It is both in Appendix I.
d: It is assumed 100% heat comes from natural gas.
e: Water footprint is based on Gerbens-Leenes et al. (2018).
f: The land footprint calculation of heavy naphtha is based on calculation; product fraction of naphtha 0.068 (Gerbens-Leenes et al., 2018); value fraction 0.07 (Gerbens-Leenes et al., 2018); LF of crude oil 0.11 (Fritsche et al., 2017).
g: Transportation is using diesel truck.

Table V.4 shows the calculated result of water and land footprint of 1 kg MEG from the data in Table V.2 and Table V.3 above. The input product values in Table V.2 are multiplied by water and land footprint units of each product from Table V.3 to get the water and land footprint value of MEG. Meanwhile, Table V.5 shows the calculated result from input products in Table IV.3 in Appendix IV multiplied by water and land footprint form Table V.3.

Table V.4. The water and land footprint calculation of 1 kg MEG

Input product	Water footprint (m^3/kg MEG)				Land footprint (m^2/kg MEG)
	Blue	Green	Grey	Total	
Sugar cane	0.08	0.08	0.16	2.14	2.21
Water	0.03	-	-	0.03	-
Electricity	0.38	0.04	-	0.42	0.02
Transport	0.00	-	-	0.00	0.00
Total	2.31	0.12	0.16	2.59	2.23

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Table V.5. The water and land footprint calculation of 1 kg PTA

Input product	Water footprint (m^3/kg PTA)				Land footprint (m^2/kg PTA)
	Blue	Green	Grey	Total	
Heavy naphtha	0.01	-	-	0.01	0.00
Water	0.02	-	-	0.02	-
Electricity	0.25	0.02	-	0.27	0.02
Heat	0.00	-	-	0.00	0.00
Total	0.28	0.02	0.00	0.30	0.02

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

After knowing water and land footprint for MEG (Table V.4) and PTA (Table V.5), Table V.6 is made. Table V.6 shows water and land footprint of 1 kg PET. The water footprint for producing 1 kg of sugar cane based PET is 1.39 m^3 and the land footprint is 0.81 m^2. The water and the land footprint are small since it is only partially bio-based products (30% bio-based). Even MEG (bio-based product) contains only 30% of PET, the MEG's water and land footprint share 65% of PET's water footprint and 96% of total PET's land footprint.

Table V.6. The water and land footprint calculation of 1 kg sugar cane based PET

Input product	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
PTA	0.25	0.01	-	0.26	0.01
MEG	0.81	0.04	0.05	0.91	0.78
Electricity	0.20	0.02	-	0.22	0.01
Heat	0.00	-	-	0.00	0.00
Total	1.26	0.08	0.05	1.39	0.81

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix VI. Calculation of water and land footprint of Thailand cassava-based PLA

The input products for polylactic acid (PLA) production is shown in Table VI. 1. The first step of PLA production by making cassava starch from cassava roots. The data is retrieved from Papong et al. (2014), this study has gathered inventory data about life cycle assessment of bioplastic PLA production in Thailand. The second step is glucose production. There is no industrial data regarding glucose production from cassava starch, so data from a report on the financial and economic viability of bioplastics production in Thailand (Siriluk et al., 2014) and Renouf et al. (2008) are used. The last step is converting glucose to lactic acid to lactide and lastly to PLA. Data from Groot and Borén (2010) are used. In Table VI. 1, the input products to produce PLA are listed. These are raw data using different units of measurements.

Table VI. 1. Input products for producing cassava-based polylactic acid

Process	**Unit**		**Sources**
Cassava starch production stage			
Cassava roots	kg/kg starch	4.33	Papong et al. (2014)
Water	l/kg starch	18.65	Papong et al. (2014)
Fuel oil	MJ/kg starch	1.28	Papong et al. (2014)
Biogas	m^3/kg starch	0.03	Papong et al. (2014)
Electricity	kWh/kg starch	0.21	Papong et al. (2014)
Transport	km [a]	320.00	Papong et al. (2014)
Glucose production stage			
Electricity	kWh/kg glucose	0.14	Siriluk et al. (2014) and Renouf et al. (2008)
Fuel oil	l/kg glucose	0.01	Siriluk et al. (2014) and Renouf et al. (2008)
Lactic acid, lactide, PLA production			
Electricity	kWh/kg PLA	0.97	Groot and Borén (2010)
Steam	l/kg PLA	12.47	Groot and Borén (2010)

a: 32 tonnes truck transport: field to starch mills 50 km and 32 tonnes truck transport: starch mills to glucose plant 270 km (Papong et al., 2014).

Based on Groot and Borén (2010), yield cassava starch to glucose is 100% and glucose to PLA is 98%. Using these values, the input products in cassava starch and glucose production phase can be converted in per kg PLA. For fuel oil, it is assumed it is using diesel. For biogas, the energy contains in 1 m^3 of biogas is 22 MJ (Rohstoffe eV, 2008). For transportation, the same method as used as the previous appendixes. The energy for transporting 1 kg PLA can be obtained by multiplying diesel needed for transporting cassava roots to factory and energy contained in diesel, it is then divided by the truck capacity in kg. It is known that 4.42 kg of cassava roots is needed to produce 1 kg of PLA. As a result, the transportation energy for producing 1 kg PLA equals to the energy for transporting 1 kg molasses cane multiplied by 4.42. The complete calculation can be seen in Table VI. 2 below.

Table VI. 2. Input products to producing 1 kg cassava-based polylactic acid

Input product	**Unit**	
Cassava starch production stage		
Cassava roots [a]	ton/kg PLA	4.42 x 10^{-3}
Water [a]	m^3/kg PLA	1.90 x 10^{-2}
Fuel oil [a,b]	GJ/kg PLA	1.31 x 10^{-3}
Biogas [a,c]	GJ/kg PLA	6.73 x 10^{-4}
Electricity [a]	GJ/kg PLA	7.71 x 10^{-4}
Transport [d,e,f]	GJ/kg PLA	4.81 x 10^{-4}
Glucose production stage		
Electricity [a]	GJ/kg PLA	5.29 x 10^{-4}
Fuel oil [a,b]	GJ/kg PLA	2.60 x 10^{-4}
Lactic acid, lactide, PLA production		
Electricity	GJ/kg PLA	3.49 x 10^{-3}
Steam	m^3/kg PLA	1.25 x 10^{-2}

a: Yield cassava starch to glucose is 100% and glucose to PLA is 98% (Groot & Borén, 2010).
b: It is assumed that fuel oil is diesel.
c: 1 m^3 biogas contains 22 MJ energy (Rohstoffe eV, 2008)
d: Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006). Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).
e: 32 tonnes truck transport: field to starch mills 50 km and 32 tonnes truck transport: starch mills to glucose plant 270 km (Papong et al., 2014).
f: Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005).

The water footprint and land footprint of material for producing PLA are shown in Table VI. 3 below. The water footprint of cassava roots was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of cassava is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table VI. 3. Water and Land Footprint for producing cassava-based polylactic acid

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Cassava starch production stage							
Cassava roots [a]	m^3/ton	-	435.00	32.0	467.0	m^2/ton	449.3
Fuel oil [b]	m^3/GJ	0.1	-	-	0.1	m^2/GJ	0.11
Biogas [c]	m^3/GJ	36.0	43.0	-	79.0	m^2/GJ	138.89
Electricity [d]	m^3/GJ	15.6	11.6	-	27.1	m^2/GJ	6.26
Transportation [e]	m^3/GJ	0.1	-	-	0.1	m^2/GJ	0.01
Glucose production stage							
Electricity [d]	m^3/GJ	15.6	11.6	-	27.1	m^2/GJ	6.26
Fuel oil [b]	m^3/GJ	0.1	-	-	0.1	m^2/GJ	0.11
Lactic acid, lactide, PLA production							
Electricity [d]	m^3/GJ	15.6	11.6	-	27.1	m^2/GJ	6.26

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).
b: It is assumed that fuel oil is diesel.
c: Water footprint of biogas is based on Pacetti et al. (2015). The land footprint of biogas is based on Fritsche et al. (2017)
d: Calculation of water footprint of electricity is in Table VII.4 and calculation of land footprint of electricity is in Table VII.5.
e: Transportation is using diesel truck

Meanwhile, the water footprint of electricity is based on the calculation in Table VI. 4. The energy mix for electricity is assumed to be the same from the national electricity supply. The Thailand national electricity supply data comes from OECD/IEA (2016). From that data, the percentage of Thailand electricity supply is obtained. Each energy sources have their own range of water footprint value (Mekonnen et al., 2015). The water footprint of electricity for different energy sources are calculated from the average value of those ranges. The water footprint of electricity (m^3/GJ) is multiplied by the percentage of energy supply to calculate the water footprint of each energy sources.

Table VI. 4. Calculation of water footprint of Thailand electricity supply per GJ

	Percentage of energy supply [a]	**Water footprint (m^3/GJ)**[b]	**Water footprint (m^3)**	
			Blue	Green
Natural gas	71%	0.66	0.46	-
Coal	20%	1.09	0.22	-
Hydropower	4%	425.15	14.88	-
Biofuels and waste [c]	4%	275.00	-	11.55
Solar and wind	1%	0.58	0.00	-
Total			15.57	11.55

a: Source: OECD/IEA (2016)
b: Obtain from the average value of water footprint of electricity from Mekonnen et al. (2015)
c: Assume all water footprint of biomass is green water footprint

The land footprint of electricity is calculated using the same method as the water footprint. The land footprint for electricity generation is retrieved from Fritsche et al. (2017). The calculation can be seen in Table VI. 5.

Table VI. 5. Calculation of land footprint of Thailand electricity supply per GJ

	Percentage	**Land footprint (m^2/GJ)**[a]	**Land footprint (m^2)**
Biomass	5.8%	138.89	8.04
Natural gas	71%	0.06	0.04
Coal	20%	1.39	0.28
Hydropower	4%	2.78	0.10
Biofuels and waste	4%	138.89	5.83
Solar and wind	1%	1.53	0.01
Total			6.26

a: Source: Fritsche et al. (2017)

Table VI. 6 shows the calculated result from the data in Table VI. 2 and Table VI. 3 above. The input product values in Table VI. 2 are multiplied by water and land footprint units of each product from Table VI. 3. For the cassava roots, water footprint is divided into blue and grey components. Meanwhile, the energy and transportation are classified as blue and green water footprint. For water and steam as input product, the used amount of water is directly added to the total water footprint. The water footprint for producing 1 kg of cassava-based PLA is 2.28 m^3 and the land footprint is 2.11 m^2.

Table VI. 6. The water and land footprint of 1 kg cassava-based PLA

Input product	**Water footprint (m^3/kg PLA)**				**Land footprint (m^2/kg PLA)**
	Blue	Green	Grey	Total	
Cassava starch production stage					
Cassava roots	-	1.92	0.14	2.06	1.99
Water	0.02	-	-	0.02	-
Fuel oil	0.00	-	-	0.00	-
Biogas	0.02	0.03	-	0.05	0.09
Electricity	0.01	0.01	-	0.02	0.00
Transport	0.00	-	-	0.00	0.00
Glucose production stage					
Electricity	0.01	0.01	0.00	0.01	0.00
Fuel oil	0.00	-	-	0.00	0.00
Lactic acid, lactide, PLA production					
Electricity	0.05	0.04	-	0.09	0.02
Steam	0.01	-	-	0.01	-
Total	**0.13**	**2.01**	**0.14**	**2.28**	**2.11**

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix VII. Calculation of water and land footprint of USA corn-based PLA

The input products for polylactic acid (PLA) production is shown in Table VII. 1. The data is retrieved from Vink and Davies (2015) and Vink et al. (2007), a life cycle assessment study of PLA by NatureWorks. This study lists the input products for producing PLA as a whole without breaking it into each step of production. The production of 1 kg PLA uses the starch fraction of 1.53 kg corn starch from 2.67 kg corn (57.4% starch). Based on this study, it needs 64 MJ of energy to make 1 kg of PLA. The detail about primary energy input is in Table VII. 1. Energy for transportation of corn to corn wet mill is 0.4 MJ/kg PLA (Vink et al., 2003). The corn wet mill, as well as the lactic acid and PLA plant, are located on the same site, so no significant additional transport is required between those operations (Vink et al., 2003).

Table VII. 1. Input products to producing 1 kg corn starch-based polylactic acid

Input product	Unit	
Corn starch	ton	1.53×10^{-3}
Primary Energy Inputs		
Crude oil	GJ	1.95×10^{-3}
Oil sand	GJ	4.20×10^{-5}
Hard coal	GJ	8.01×10^{-3}
Lignite	GJ	6.09×10^{-4}
Natural gas	GJ	9.93×10^{-3}
Coalbed methane	GJ	1.56×10^{-3}
Shale gas	GJ	6.78×10^{-3}
Tight Gas	GJ	6.02×10^{-3}
Uranium	GJ	3.51×10^{-3}
Geothermal	GJ	1.19×10^{-4}
Solar	GJ	2.53×10^{-2}
Wind	GJ	4.72×10^{-4}
Water for production	m^3	1.36×10^{-2}
Transportation	GJ	4×10^{-4}

The water footprint and land footprint of material for producing PLA are shown in Table VII. 2 below. The water footprint of corn starch was taken from Mekonnen and Hoekstra (2011) with considering the product and value fraction of corn starch. Meanwhile, the land footprint of corn starch is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton) with considering the product and value fraction of corn starch. These data were taken from FAO (2016). The product and value fraction can be seen in the footnote below Table VII. 2.

For the water footprint of energy carries, data from Gerbens-Leenes et al. (2009) and Spang et al. (2014) are taken. For the land footprint of energy carries, data from Trainor et al. (2016) is taken. There is no study about the land footprint of energy carriers. The study in Trainor et al. (2016) is about the land footprint of electricity in the USA. It is assumed that energy to electricity conversion is 65%.

Table VII. 2. Water and Land Footprint for producing corn starch-based polylactic acid

Input product	**Water footprint**					**Land footprint** [f]	
	Unit	Blue	Green	Grey	Total	Unit	Total
Corn starch [a]	m^3/ton	110	909	307	1326	m^2/ton	1791
Energy sources							
Crude oil [b]	m^3/GJ	1.06	-	-	1.06	m^2/GJ	0.11
Oil sand [c]	m^3/GJ	0.114	-	-	0.114	m^2/GJ	0.11
Hard coal [b]	m^3/GJ	0.16	-	-	0.16	m^2/GJ	1.48
Lignite [d]	m^3/GJ	0.16	-	-	0.16	m^2/GJ	1.48
Natural gas [b]	m^3/GJ	0.11	-	-	0.11	m^2/GJ	0.18
Coalbed methane [e]	m^3/GJ	0.11	-	-	0.11	m^2/GJ	0.18
Shale gas [c]	m^3/GJ	0.017	-	-	0.017	m^2/GJ	0.18
Tight Gas [c]	m^3/GJ	0.11	-	-	0.11	m^2/GJ	0.18
Uranium [b]	m^3/GJ	0.09	-	-	0.09	m^2/GJ	0.02
Geothermal [c]	m^3/GJ	0.736	-	-	0.736	m^2/GJ	0.92
Solar [b]	m^3/GJ	0.27	-	-	0.27	m^2/GJ	2.71
Wind [b]	m^3/GJ	0	-	-	0	m^2/GJ	0.23
Transportation [g]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01

a: Based on calculation; WF/LF of corn starch = (WF/LF corn x value fraction/product fraction). WF of corn is based on Mekonnen and Hoekstra (2011). LF corn is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016). Value fraction from Mekonnen and Hoekstra (2011) is 1. Product fraction is 0.57 from Vink and Davies (2015).
b: Water footprint is based on Gerbens-Leenes et al. (2009)
c: Water footprint is based on Spang et al. (2014)
d: It is assumed that the water and land footprint for lignite are the same as coal
e: It is assumed that the water and land footprint for coalbed methane, tight gas is the same as natural gas
f: Source: Trainor et al. (2016) except for corn starch. It is assumed that energy to electricity conversion is 65%.
g: Transportation is using diesel truck.

Table VII. 3 shows the calculated result from the data in Table VII. 1 and Table VII. 2 above. The input product values in Table VII. 1 are multiplied by water and land footprint units of each product from Table VII. 2. For the corn starch, water footprint is divided into blue and grey components. Meanwhile, the energy is classified as blue water footprint. The water footprint for producing 1 kg of corn starch-based PLA is 2.06 m^3 and the land footprint is 2.83 m^2.

Table VII. 3. The water and land footprint of 1 kg corn starch-based PLA

Input product	**Water footprint (m^3/kg PLA)**				**Land footprint (m^2/kg PLA)**
	Blue	Green	Grey	Total	
Corn starch [a]	0.17	1.39	0.47	2.03	2.75
Energy sources				0.00	
Crude oil [b]	0.00	-	-	0.00	0.00
Oil sand [c]	0.00	-	-	0.00	0.00
Hard coal [b]	0.00	-	-	0.00	0.01
Lignite [d]	0.00	-	-	0.00	0.00
Natural gas [b]	0.00	-	-	0.00	0.00
Coalbed methane [e]	0.00	-	-	0.00	0.00
Shale gas [c]	0.00	-	-	0.00	0.00
Tight Gas [c]	0.00	-	-	0.00	0.00
Uranium [b]	0.00	-	-	0.00	0.00
Geothermal [c]	0.00	-	-	0.00	0.00
Solar [b]	0.01	-	-	0.01	0.07
Wind [b]	0.00	-	-	0.00	0.00
Water for production	0.01	-	-	0.01	0.00
Transportation	0.00	-	-	0.00	0.00
Total	0.19	1.39	0.47	2.06	2.83

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix VIII. Calculation of water and land footprint of 100% bio-based PET

Polyethylene terephthalate (PET) is formed from terephthalic acid (PTA) and monoethylene glycol (MEG). PTA is derived from oil feedstock, meanwhile, MEG is produced from biomaterial which is molasses cane. Currently, there is no industrial process to make 100% bio-based PET since PTA is derived from oil. A preliminary study to make bio-based PTA is done by Akanuma et al. (2014). Based on this study, there are three different biobased PTA pathways (1) muconic acid beginning with wheat stover, (2) isobutanol starting with corn, and (3) BTX beginning with poplar. The input products to make 100% bio-based PET can be seen in Table VIII. 1.

Table VIII. 1. Input products of 100% bio-based PET

Input products	**Unit**		**Sources**
Wheat/Corn/Poplar	kg/kg PET	4.41/3.25/5.05	Akanuma et al. (2014)
MEG	kg/kg PET	0.35	Papong et al. (2014)
Electricity	MJ/kg PET	1.37	Papong et al. (2014)
Heat	MJ/kg PET	6.3	Papong et al. (2014)

The water and land footprint for wheat, corn, poplar can be seen in Table VIII. 2. The water and the land footprint are using the global value from M. M. Mekonnen and Hoekstra (2011) and FAO (2016). For water footprint of poplar, it is obtained from average values of four nations but it did not make a distinction between green and blue component. So, it is assumed that it is a green component.

Table VIII. 2. The water and land footprint of wheat, corn, and poplar

Input products	**Water footprint (m^3/ton)**				**Land footprint (m^2/ton)**
	Blue	Green	Grey	Total	
Wheat [a,b]	342	1277	207	1826	2936
Corn [a,b]	82	947	194	1222	1773
Poplar [c]	-	794.5	-	794.5	2325 [d]

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the overall production of the crop (ton). These data were taken from FAO (2016) .
b: Water footprint is based on Gerbens-Leenes et al. (2009)
c: Source: Gerbens-Leenes et al. (2009). Average of 4 countries which are Netherlands, USA, Brazil, and Zimbabwe. There is no distinction between blue and green water footprint. It is assumed that 100% water footprint is a blue component.
d: Source : Dillen et al. (2013)

After knowing water and land footprint of wheat, corn, and poplar, the water and land footprint of 100% bio-based PET can be calculated. The energy and other products for producing bio-based PTA are neglected. The water and land footprint of bio-based PTA are only derived from biomaterial in this case wheat or corn or poplar.

The calculation of water and land footprint of PET is combined between bio-based PTA (wheat, corn, and poplar) and bio-based MEG (molasses cane, sugar cane). The water and land footprint of MEG, electricity, and heat are already calculated in Appendix IV for molasses cane based MEG and Appendix V for sugar cane based MEG.

From Table VIII. 3 to Table VIII. 8, the water and land footprint of 100% bio-based are calculated.

Table VIII. 3 The water and land footprint of wheat-molasses cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Wheat based PTA	1.51	5.63	0.91	8.05	12.95
Molasses cane based MEG	0.72	0.57	0.08	1.37	0.69
Electricity	0.09	0.01	0.00	0.10	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	2.32	6.21	0.99	9.52	13.65

Table VIII. 4. The water and land footprint of wheat-sugar cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Wheat based PTA	1.51	5.63	0.91	8.05	12.95
Sugar cane based MEG	0.17	0.68	0.05	0.91	0.78
Electricity	0.20	0.02	0.00	0.22	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	1.88	6.34	0.97	9.18	13.75

Table VIII. 5. The water and land footprint of corn-molasses cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Corn based PTA	0.26	3.08	0.63	3.97	5.76
Molasses cane based MEG	0.72	0.57	0.08	1.37	0.69
Electricity	0.09	0.01	0.00	0.10	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	1.07	3.66	0.71	5.44	6.46

Table VIII. 6. The water and land footprint of corn-sugar cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Corn based PTA	0.26	3.08	0.63	3.97	5.76
Sugar cane based MEG	0.17	0.68	0.05	0.91	0.78
Electricity	0.20	0.02	0.00	0.22	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	0.63	3.78	0.69	5.10	6.56

Table VIII. 7. The water and land footprint of poplar-molasses cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Poplar based PTA	0.00	4.01	0.00	4.01	11.74
Molasses cane based MEG	0.72	0.57	0.08	1.37	0.69
Electricity	0.09	0.01	0.00	0.10	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	0.81	4.59	0.08	5.48	12.44

Table VIII. 8. The water and land footprint of poplar-sugar cane based PET

Input products	**Water footprint (m^3/kg PET)**				**Land footprint (m^2/kg PET)**
	Blue	Green	Grey	Total	
Poplar based PTA	0.00	4.01	0.00	4.01	11.74
Sugar cane based MEG	0.17	0.68	0.05	0.91	0.78
Electricity	0.20	0.02	0.00	0.22	0.01
Heat	0.00	0.00	0.00	0.00	0.00
Total	0.37	4.72	0.06	5.14	12.54

Appendix IX. Calculation of water and land footprint of palm oil-corn starch PUR

The input products for polyurethane (PUR) production is shown in Table IX. 1. Two main ingredients of PUR are polyol and isocyanate. There are two primary isocyanates: toluene diisocyanates (TDI) and methylene diphenyl diisocyanate (MDI). TDI is used primarily in the production of flexible foams, meanwhile, MDI is used to produces a wide variety of rigid, flexible, semi-rigid, and thermoset foams. In this study, MDI is used to produce flexible foam of PUR.

In Table IX. 1, the input products for producing polyol is made. The polyol is made from bio glycerine, propanediol (PDO), Phthalic Anhydride (Pht), and Succinic acid (SA). Pht is derived from fossil feedstock. Meanwhile, bio glycerine is produced from palm oil. For PDO and SA, both are derived from corn starch. For transportation, 100 km is assumed to be the distance from plantation to the factory because there is no data about transportation crop products (palm and corn) to the factory. To simplify the data to be used in the further calculation, Table IX. 2 is made to show the list of products required to produce 1 kg of polyol.

Table IX. 1. Input products for producing 1 kg bio-based polyol

Input products	**Unit**		**Sources**
Bio Glycerine	kg/kg polyol	0.07	Garcia Gonzalez et al. (2017)
1,3-propanediol	kg/kg polyol	0.35	Garcia Gonzalez et al. (2017)
Phthalic Anhydride	kg/kg polyol	0.38	Garcia Gonzalez et al. (2017)
Succinic acid	kg/kg polyol	0.20	Garcia Gonzalez et al. (2017)
Bio Glycerine (Bio Gly)			
Palm oil	kg/kg bio gly	9.43	Jungbluth et al. (2007)
Electricity	kWh/kg bio gly	0.0041	Jungbluth et al. (2007)
Heat	MJ/kg bio gly	0.09	Jungbluth et al. (2007)
Water	kg/kg bio gly	0.0027	Jungbluth et al. (2007)
Transportation	km	100.00 [a]	Jungbluth et al. (2007)
1,3-propanediol (PDO)			
Corn Starch	kg/kg PDO	1.84	Urban and Bakshi (2009)
Electricity	MJ/kg PDO	2.60	Urban and Bakshi (2009)
Heat	MJ/kg PDO	23.40	Urban and Bakshi (2009)
Water	kg/kg PDO	1.07	Urban and Bakshi (2009)
Phthalic Anhydride (Pht)			
o-xylol	kg/kg Pht	0.95	Althaus et al. (2007)
Electricty	kWh/kg Pht	0.50	Althaus et al. (2007)
Heat	MJ/kg Pht	7.50	Althaus et al. (2007)
Transportation	km	100.00 [a]	Althaus et al. (2007)
Succinic acid			
Corn Starch	kg/kg SA	4.00	Verghese (2009)
Electricity	kWh/kg SA	2.33	Verghese (2009)
Water	kg/kg SA	30.90	Verghese (2009)
Transportation	km	100.00 [a]	Verghese (2009)

a: It is assumed the distance from plantation to the factory is 100 km.

Table IX. 2. Input products to producing 1 kg bio-based polyol

Input products	**Unit**	
Bio Glycerine (Bio Gly)		
Palm oil	ton	6.60 x 10^{-4}
Electricity	GJ	1.04 x 10^{-6}
Heat	GJ	6.29 x 10^{-6}
Water	m^3	1.86 x 10^{-7}
Transportation	GJ	6.27 x 10^{-5} [a]
1,3-propanediol (PDO)		
Corn Starch	ton	6.44 x 10^{-4}
Electricty	GJ	9.10 x 10^{-4}
Heat	GJ	8.19 x 10^{-3}
Water	m^3	3.75 x 10^{-4}
Transportation		6.12 x 10^{-5} [a]
Phthalic Anhydride (Pht)		
o-xylol	ton	3.61 x 10^{-4}
Electricty	GJ	6.84 x 10^{-4}
Heat	GJ	2.85 x 10^{-3}
Succinic acid		
Corn Starch	ton	8.00 x 10^{-4}
Electricity	GJ	1.68 x 10^{-3}
Water	m^3	6.18 x 10^{-3}
Transportation	GJ	7.60 x 10^{-5} [a]

a: Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006). Diesel contains 38 MJ energy per liter (Nylund & Erkkila, 2005). It is assumed that it is using 32 tonnes diesel truck.

The water footprint and land footprint of material for producing bio-based polyol are shown in Table IX. 3 below. For bio glycerine from palm oil, it is using Malaysia palm oil. The water footprint of palm oil was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of palm oil is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016). For electricity during bio glycerine process, data of Malaysian national grid mix is used. Meanwhile, for corn starch-based PDO and corn starch based SA, they are assumed from USA.

Meanwhile, the water footprint of electricity for bio glycerine production is based on the calculation in Table IX. 4. The energy mix for electricity is assumed to be the same from the Malaysia national electricity supply. It is assumed that the water footprint of biomass is entirely green water footprint. On the other hand, all the water footprint of other energy sources are fully blue water footprint. The land footprint of electricity is calculated using the same method as the water footprint. The land footprint for electricity generation is retrieved from Fritsche et al. (2017). Table IX. 5 shown the calculation of water and land footprint of electricity for PDO and SA production using the USA national grid mix.

Table IX. 3. Water and Land Footprint for producing bio-based polyol

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bio Glycerine (Bio Gly)							
Palm oil [a]	m^3/ton	-	824	34.00	858.00	m^2/ton	472.80
Electricity [b]	m^3/GJ	9.21	24.75	-	33.96	m^2/GJ	12.97
Heat	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.06
Transportation [c]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01
1,3-propanediol (PDO)							
Corn Starch	m^3/ton	110	990	307	1326.00	m^2/ton	1791.70
Electricty [d]	m^3/GJ	28.34	4.13	-	32.47	m^2/GJ	3.90
Heat	m^3/GJ	0.66	-	-	0.66	m^2/GJ	0.28
Phthalic Anhydride (Pht)	m^3/GJ	0.12				m^2/GJ	0.01
o-xylol							
Electricty [d]	m^3/ton	73.11	-	-	73.11	m^2/ton	3.12
Heat [e]	m^3/GJ	28.34	4.13	-	32.47	m^2/GJ	3.90
Transportation	m^3/GJ	0.45	-	-	0.45	m^2/GJ	0.56
Succinic acid							
Corn Starch	m^3/ton	110	909	307	1326.00	m^2/ton	1791.70
Electricity [b]	m^3/GJ	28.34	4.13	-	32.47	m^2/GJ	3.90
Transportation [c]	m^3/GJ	0.12	-	-	0.12	m^2/GJ	0.01

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).
b: Calculation of water footprint and land footprint of electricity is in Table X.4.
c: Transportation is using diesel truck.
d. Calculation of water and land footprint of electricity is in Table X.5.
e: Heat come from coal, light fuel, heavy oil, and natural gas. The calculation of water and land footprint can be seen in Table X.6.

Table IX. 4. Calculation of water and land footprint of Malaysia electricity supply per GJ

	Percentage of energy supply [a]	**Water footprint (m^3/GJ)**[b]	**Water footprint (m^3)**		**Land footprint (m^2/GJ)**[c]	**Land footprint (m^2)**
			Blue	Green		
Oil	34.0%	0.70	0.24	-	0.11	0.04
Natural gas	22.0%	0.66	0.14	-	0.06	0.01
Coal	26.0%	1.09	0.28	-	1.39	0.36
Nuclear	6.0%	0.73	0.04	-	0.03	0.00
Biomass/waste	9.0%	275.00	-	24.75	138.89	12.50
Hydro	2.0%	425.15	8.50		2.78	0.06
Total			**9.21**	**24.75**		**12.97**

a: Source: Tan et al. (2013)
b: Obtain from the average value of water footprint of electricity from Mekonnen et al. (2015)
c: Source: Fritsche et al. (2017)

Table IX. 5. Calculation of water and land footprint of USA electricity supply per GJ

	Percentage of energy supply[a]	**Water footprint (m^3/GJ)**[b]	**Water footprint (m^3)**		**Land footprint (m^2/GJ)**[c]	**Land footprint (m^2)**
			Blue	Green		
Natural gas	33.8%	0.66	0.22		0.28	0.09
Coal	30.4%	1.09	0.33		0.17	0.05
Nuclear	19.7%	0.73	0.14		0.03	0.01
Wind	5.6%	0.01	0.00		0.36	0.02
Hydropower	6.5%	425.15	27.63		4.69	0.31
Solar	0.9%	1.15	0.01		5.36	0.05
Biomass	1.5%	275.00		4.13	225.00	3.38
Etc	1.6%					
Total			**28.34**	**4.13**		**3.90**

a: Source: eia (2017b)

b: Obtain from the average value of water footprint of electricity from Mekonnen et al. (2015)

c: Source: Trainor et al. (2016)

For heat in Pht production, the energy comes from coal, light fuel, heavy fuel, and natural gas. The water and land footprint of heat can be seen in Table IX. 6.

Table IX. 6. Calculation of water and land footprint of heat

	Percentage [a]	**Water footprint (m^3/GJ)**	**Water footprint (m^3)**	**Land footprint (m^2/GJ)** [d]	**Land footprint (m^2)**
			Blue		
Coal	31.1%	0.16 [b]	0.05	1.48	0.46
Light fuel	4.1%	2.61 [c]	0.11	0.11	0.00
Heavy fuel	18.3%	1.34 [c]	0.25	0.06	0.01
Natural gas	46.5%	0.11 [b]	0.05	0.18	0.08
Total			**0.45**		**0.56**

a: Source: Althaus et al. (2007)

b: Source: Gerbens-Leenes et al. (2009)

c: Source: Gerbens-Leenes et al. (2018)

d: From own calculation. LF of coal and natural gas from Trainor et al. (2016) with taking into account energy to electricity efficiency is 65%. Light fuel and heavy fuel from calculation = (LF crude oil x value fraction / product fraction). Product and value fraction is obtained from Gerbens-Leenes et al. (2018).

Table IX. 7 shows the calculated result from the data in Table IX. 2 and

Table IX. 3 above. The input product values in Table IX. 2 are multiplied by water and land footprint units of each product from Table IX. 3. For the palm oil and cornstarch, water footprint is divided into blue, green, and grey components. Meanwhile, the energy and transportation are classified as blue and green water footprint. For water as input product, the used amount of water is directly added to the total water footprint. The water footprint for producing 1 kg of palm oil PUR is 2.63 m^3 and the land footprint is 2.92 m^2.

Table IX. 7. The water and land footprint of 1 kg bio-based polyol

Input product	**Water footprint (m^3/kg polyol)**				**Land footprint (m^2/kg polyol)**
	Blue	Green	Grey	Total	
Bio Glycerine (Bio Gly)					
Palm oil	-	0.54	0.02	0.57	0.31
Electricity	0.00	0.00	-	0.00	0.00
Heat	0.00	-	-	0.00	0.00
Water	0.00	-	-	0.00	-
Transportation	0.00	-	-	0.00	0.00
1,3-propanediol (PDO)					
Corn Starch	0.07	0.59	0.20	0.85	1.15
Electricty	0.03	0.00	-	0.03	0.00
Heat	0.01	-	-	0.01	0.00
Water	0.00	-	-	0.00	-
Transportation	0.00	-	-	0.00	0.00
Phthalic Anhydride (Pht)					
o-xylol	0.03	-	-	0.03	0.00
Electricty	0.02	0.00	-	0.02	0.00
Heat	0.00	-	-	0.00	0.00
Succinic acid					
Corn Starch	0.09	0.73	0.25	1.06	1.43
Electricity	0.05	0.01	-	0.05	0.01
Water	0.01	-	-	0.01	-
Transportation	0.00	-	-	0.00	0.00
Total	**0.29**	**1.87**	**0.47**	**2.63**	**2.92**

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

For producing MDI, the accounted input products are energy and water. The data is obtained from the eco-profile of TDI and MDI from PlasticsEurope (2012). The water and land footprint of input products of producing MDI are in Table IX. 8.

Table IX. 8. Input products to producing 1 kg MDI (PlasticsEurope, 2012)

Input products	**Unit**	
Crude oil	GJ	1.70.E-02
Gas	GJ	2.62.E-02
Coal	GJ	2.87.E-03
Nuclear	GJ	3.40.E-03
Water for processing	m^3	3.00.E-03
Water for cooling	m^3	1.90.E-03

Based on and Table IX. 8, is made. The input product values in Table IX. 7 are multiplied by water and land footprint units of each product from Table IX. 8. The water footprint of producing 1 kg MDI is 0.03 m3, meanwhile, the land footprint is 0.01 m2.

Table IX. 9. Water and Land Footprint for producing MDI

Input product	**Water footprint**[a]					**Land footprint**[b]	
	Unit	Blue	Green	Grey	Total	Unit	Total
Crude oil	m^3/GJ	1.06	-	-	1.06	m^2/GJ	0.11
Gas	m^3/GJ	0.11	-	-	0.11	m^2/GJ	0.18
Coal	m^3/GJ	0.16	-	-	0.16	m^2/GJ	1.48
Nuclear	m^3/GJ	0.10	-	-	0.10	m^2/GJ	0.02

a: Source: Gerbens-Leenes et al. (2018)

b: LF of electricity from Trainor et al. (2016). LF of energy is calculated from LF of electricity divided by energy to electricity efficiency. Energy to electricity efficiency is 65%.

Table IX. 10. Water and Land Footprint for producing 1 kg MDI

Input product	**Water footprint (m^3/kg MDI)**				**Land footprint (m^2/kg MDI)**
	Blue	Green	Grey	Total	
Crude oil	0.02	-	-	0.02	0.00
Gas	0.00	-	-	0.00	0.00
Coal	0.00	-	-	0.00	0.00
Nuclear	0.00	-	-	0.00	0.00
Water	0.00	-	-	0.00	0.00
Total	0.03	-	-	0.03	0.01

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

After knowing water and land footprint of polyol and MDI, the water and land footprint of PUR can be calculated. The result can be seen in Table IX. 11.

Table IX. 11. Water and land footprint for producing 1 kg palm oil-corn starch-based PUR

Input product		**Water footprint (m^3/kg PUR)**				**Land footprint (m^2/kg PUR)**
		Blue	Green	Grey	Total	
Polyol	60%	0.17	1.12	0.28	1.58	1.75
MDI	40%	0.01	-	0.00	0.01	0.00
Total		0.19	1.12	0.28	1.59	1.75

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix X. Calculation of water and land footprint of sugar cane based PP

The input products for polypropylene (PP) production is shown in Table X. 1. The first step of PP production by generating bioethanol from sugar cane in Brazil. The data is retrieved from Braskem company, a leading producer of PE from Brazilian sugar cane. The second step is ethylene production. There is no industrial data regarding ethylene production, so data from Kochar et al. (1981) in Liptow and Tillman (2012) are used. The last is propylene production and polymerization. In Table I. 1, the input products to produce PP are listed. These are raw data using different units of measurements. To simplify the data to be used in the further calculation, Table X. 2 is made.

Table X. 1. Input products for producing sugar cane based polypropylene

Process	**Unit**		**Sources**
Bioethanol production			
Sugar cane	t/t bioethanol	15	Terry (2012)
Water	m^3/t bioethanol	24.7	Tsiropoulos et al. (2014)
Diesel consumption	MJ/t bioethanol	217.0	Liptow and Tillman (2012)
Transportation	km	21	Gonzales et al. (2010)
Ethylene production			
Internal fuel	kJ/kg ethylene	3736.0	Kochar et al. (1981)
External fuel	kJ/kg ethylene	1675.0	Kochar et al. (1981)
Electricity	kJ/kg ethylene	1116.0	Kochar et al. (1981)
Propylene production, polymerization			
Electricity	MJ/kg PP	1.2	Worrell et al. (2000)

Table X. 2. Input products to producing 1 kg sugar cane based polypropylene

Input product	**Unit**	
Bioethanol production		
Sugar cane	ton	3.61 x 10^{-2} [a,c]
Water	m^3	1.13 x 10^{-1} [a,c]
Diesel consumption	GJ	9.89 x 10^{-4} [a,c]
Transportation	GJ	7.20 X 10^{-4} [a,b,c]
Ethylene production		
Internal fuel	GJ	4.75 x 10^{-3} [c]
External fuel	GJ	2.13 x 10^{-3} [c]
Electricity	GJ	1.42 x 10^{-3} [c]
Propylene production, polymerization		
Electricity	GJ	1.20 x 10^{-3}

a: Based on 1 ton ethylene is produced from 2,400 liter bioethanol and bioethanol density of 0.789 kg/l (Liptow and Tillman (2012); Tsiropoulos et al. (2014))

b: The transportation is using 32 tonne diesel truck. Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006).

c: 1 kg PP is produced from 1.27 kg ethylene Kikuchi et al. (2017); Selke (1994).

The water footprint and land footprint of material for producing PP are shown in Table X. 3 below. The water footprint of sugar cane was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of sugar cane is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table X. 3. Water and Land Footprint for producing sugar cane based polypropylene

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bioethanol production							
Sugar cane [a]	m^3/ton	5	122	10	137	m^3/ton	141.50
Diesel consumption [b]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
Transport [c]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
Ethylene production							
Internal fuel [d]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
External fuel [d]	m^3/GJ	0.12	-		0.12	m^3/GJ	0.01
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^3/GJ	9.27
Propylene production, Polymerization							
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^3/GJ	9.27

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

b: Calculation is in Table I.4 in Appendix 1.

c: Transportation is using diesel truck.

d: There is no further explanation of fuel type. It assumes the fuel is diesel.

e: Calculation of water footprint of electricity is in Appendix 1 Table I.5 and calculation of land footprint of electricity is in Table I.6.

The water footprint for producing 1 kg sugar cane based PP is 5.42 m^3 and the land footprint is 5.13 m^2. The water footprint is mainly for growing sugar cane (91%) and the rest is for production process and energy. Meanwhile, most of the land footprint (99%) of PP is allocated for growing the crop.

Table X. 4. The water and land footprint of 1 kg sugar cane based PP

Input product	**Water footprint (m^3/kg PP)**				**Land footprint (m^2/kg PP)**
	Blue	Green	Grey	Total	
Bioethanol production					
Sugar cane	0.18	4.40	0.36	4.94	5.11
Water	0.06	-	-	0.06	-
Diesel consumption	0.00	-	-	0.00	0.00
Transport	0.00	-	-	0.00	0.00
Ethylene production					
Internal fuel	0.00	-	-	0.00	0.00
External fuel	0.00	-	-	0.00	0.00
Electricity	0.20	0.02	-	0.23	0.01
Propylene production, Polymerization					
Electricity	0.17	0.02	-	0.19	0.01
Total	**0.62**	**4.44**	**0.36**	**5.42**	**5.13**

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix XI. Calculation of water and land footprint of sugar cane based PVC

The input products for polyvinyl chloride (PVC) production is shown in Table XI. 1. The first step of PP production by generating bioethanol from sugar cane in Brazil. The data is retrieved from Braskem company, a leading producer of PE from Brazilian sugar cane. The second step is ethylene production. There is no industrial data regarding ethylene production, so data from Kochar et al. (1981) in Liptow and Tillman (2012) are used. The third is chlorine production which is an energy-intensive product. The last is vinyl chloride monomer (VCM) production and polymerization. In Table I. 1, the input products to produce PVC are listed. These are raw data using different units of measurements. To simplify the data to be used in the further calculation, Table XI. 2 is made.

Table XI. 1. Input products for producing sugar cane based polyvinyl chloride

Process	**Unit**		**Sources**
Bioethanol production			
Sugar cane	t/t bioethanol	15	Terry (2012)
Water	m^3/t bioethanol	24.7	Tsiropoulos et al. (2014)
Diesel consumption	MJ/t bioethanol	217.0	Liptow and Tillman (2012)
Transportation	km	21	Gonzales et al. (2010)
Ethylene production			
Internal fuel	kJ/kg ethylene	3736.0	Kochar et al. (1981)
External fuel	kJ/kg ethylene	1675.0	Kochar et al. (1981)
Electricity	kJ/kg ethylene	1116.0	Kochar et al. (1981)
Chlorine production			
Electricity	MJ/kg chlorine	9.72	Ayers (1997)
Steam	Kg/kg chlorine	0.89	Ayers (1997)
VCM production, polymerization			
Electricity	kwh/kg PVC	0.33	Tötsch and Gaensslen (1992)
Water	kg/kg PVC	6.78	Tötsch and Gaensslen (1992)
Steam	kg/kg PVC	0.43	Tötsch and Gaensslen (1992)

Table XI. 2. Input products to producing 1 kg sugar cane based polyvinyl chloride

Input product	**Unit**	
Bioethanol production		
Sugar cane	ton	1.30 x 10^{-2} [a,b]
Water	m^3	2.15 x 10^{-2} [a,b]
Diesel consumption	GJ	1.89 x 10^{-4} [a,b]
Transportation	GJ	2.60 x 10^{-4} [a,b,d]
Ethylene production		
Internal fuel	GJ	1.71 x 10^{-3} [b]
External fuel	GJ	7.69 x 10^{-4} [b]
Electricity	GJ	5.12 x 10^{-4} [b]
Chlorine production		
Electricity	GJ	5.64 x 10^{-3} [c]
Steam	m^3	5.16 x 10^{-4} [c]
VCM production, polymerization		
Electricity	GJ	1.18 x 10^{-3}
Water	m^3	6.78 x 10^{-3}
Steam	m^3	4.30 x 10^{-4}

a: Based on 1 ton ethylene is produced from 2,400 liter bioethanol and bioethanol density of 0.789 kg/l (Liptow and Tillman (2012); Tsiropoulos et al. (2014)).

b: 1 kg PVC is produced from 0.459 kg ethylene Tötsch and Gaensslen (1992)

c: 1 kg PVC is produced from 0.58 kg chlorine Tötsch and Gaensslen (1992)

d: The transportation is using 32 tonnes diesel truck. Full loaded diesel truck needs 50 liters per 100 km meanwhile empty loaded truck needs 30 liters per 100 km (Mårtensson, 2006).

The water footprint and land footprint of material for producing PVC are shown in Table XI. 3 below. The water footprint of sugar cane was taken from Mekonnen and Hoekstra (2011). Meanwhile, the land footprint of sugar cane is obtained by dividing the total crop area harvested (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

Table XI. 3. Water and Land Footprint for producing sugar cane based polyvinyl chloride

Input product	**Water footprint**					**Land footprint**	
	Unit	Blue	Green	Grey	Total	Unit	Total
Bioethanol production							
Sugar cane [a]	m^3/ton	5	122	10	137	m^3/ton	141.50
Diesel consumption [b]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
Transport [c]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
Ethylene production							
Internal fuel [d]	m^3/GJ	0.12	-	-	0.12	m^3/GJ	0.01
External fuel [d]	m^3/GJ	0.12	-		0.12	m^3/GJ	0.01
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^3/GJ	9.27
Chlorine production							
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^3/GJ	9.27
VCM production, Polymerization							
Electricity [e]	m^3/GJ	144.25	15.93	-	160.18	m^3/GJ	9.27

a: Water footprint is based on Mekonnen and Hoekstra (2011). The land footprint is calculated by dividing the total area harvested of the crop (ha) and the total production of the crop (ton). These data were taken from FAO (2016).

b: Calculation is in Table I.4 in Appendix 1.

c: Transportation is using diesel truck

d: There is no further explanation of fuel type. It assumes the fuel is diesel.

e: Calculation of water footprint of electricity is in Appendix 1 Table I.5 and calculation of land footprint of electricity is in Table I.6.

The water footprint for producing 1 kg of sugar cane based PVC is 3.01 m^3 and the land footprint is 1.92 m^2. The water footprint is mainly for growing sugar cane and electricity in chlorine production phase. Meanwhile, most of the land footprint (96%) of PVC is allocated for growing the crop.

Table XI. 4. The water and land footprint of 1 kg sugar cane based PVC

Input product	**Water footprint (m^3/kg PP)**				**Land footprint (m^2/kg PP)**
	Blue	Green	Grey	Total	
Bioethanol production					
Sugar cane	0.07	1.59	0.13	1.79	1.84
Water	0.02	-	-	0.02	-
Diesel consumption	0.02	-	-	0.02	0.00
Transport	0.00	-	-	0.00	0.00
Ethylene production					
Internal fuel	0.00	-	-	0.00	0.00
External fuel	0.00	-	-	0.00	0.00
Electricity	0.07	0.01	-	0.08	0.00
Chlorine production					
Electricity	0.81	0.09	-	0.90	0.05
Steam	0.00	0.00	-	0.00	-
VCM production, Polymerization					
Electricity	0.17	0.02	-	0.19	0.01
Water	0.01	-	-	0.01	-
Steam	0.00	-	-	0.00	-
Total	**1.17**	**1.71**	**0.13**	**3.01**	**1.92**

Note :(-) means there is no water and land footprint
(0.00) means there is water or land footprint, but really small

Appendix XII. Result of calculation water and land footprint if complete change from fossil-based plastics to bio-based plastics using different scenarios

From Table XII. 1 to Table XII. 9, the result of calculation water and land footprint if the complete move from fossil-based plastics to bio-based plastics using different scenarios are presented. Table XII. 1 to Table XII. 3 are using 'high' value scenario and using three different recycling rate. Table XII. 4 to Table XII. 6 are using 'average' value scenario meanwhile Table XII. 7 to Table XII. 9 are using 'low' value scenario.

Table XII. 1. The water and land footprint if complete shift to bioplastics using 'high' value scenario and 10% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	6.41.E+10	2.65.E+11	2.13.E+10	3.51.E+11	5.69.E+11
PP	19.21	61.87	3.44.E+10	2.47.E+11	2.01.E+10	3.02.E+11	2.86.E+11
PVC	13.37	43.04	4.55.E+10	6.61.E+10	5.05.E+09	1.17.E+11	7.42.E+10
PET	5.85	18.83	3.93.E+10	1.05.E+11	1.68.E+10	1.61.E+11	2.33.E+11
PS & EPS*	5.85	18.83	3.14.E+09	1.90.E+10	4.74.E+09	2.69.E+10	2.97.E+10
PUR	5.01	16.14	1.90.E+09	2.91.E+10	2.05.E+09	3.31.E+10	4.11.E+10
Other	23.98	77.21	1.61.E+11	4.32.E+11	6.88.E+10	6.62.E+11	9.55.E+11
Total	100	322	3.49.E+11	1.16.E+12	1.39.E+11	1.65.E+12	2.19.E+12

*PS & EPS is assumed to be substituted by PLA

Table XII. 2. The water and land footprint if complete shift to bioplastics using 'high' value scenario and 36% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	4.56E+10	1.89E+11	1.52E+10	2.49E+11	4.04E+11
PP	19.21	61.87	2.45E+10	1.76E+11	1.43E+10	2.15E+11	2.03E+11
PVC	13.37	43.04	3.23E+10	4.70E+10	3.59E+09	8.30E+10	5.28E+10
PET	5.85	18.83	2.79E+10	7.63E+10	1.17E+10	1.11E+11	1.66E+11
PS & EPS*	5.85	18.83	1.57E+09	2.42E+10	1.70E+09	2.75E+10	3.41E+10
PUR	5.01	16.14	1.92E+09	1.16E+10	2.89E+09	1.64E+10	1.81E+10
Other	23.98	77.21	1.15E+11	3.13E+11	4.78E+10	4.54E+11	6.79E+11
Total	100	322	2.48E+11	8.37E+11	9.71E+10	1.16E+12	1.56E+12

*PS & EPS is assumed to be substituted by PLA

Table XII. 3. The water and land footprint if complete shift to bioplastics using 'high' value scenario and 62% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	2.70.E+10	1.12.E+11	9.00.E+09	1.48.E+11	2.40.E+11
PP	19.21	61.87	1.45.E+10	1.04.E+11	8.48.E+09	1.28.E+11	1.21.E+11
PVC	13.37	43.04	1.92.E+10	2.79.E+10	2.13.E+09	4.93.E+10	3.13.E+10
PET	5.85	18.83	1.66.E+10	4.45.E+10	7.09.E+09	6.81.E+10	9.84.E+10
PS & EPS*	5.85	18.83	9.34.E+08	1.44.E+10	1.01.E+09	1.63.E+10	2.03.E+10
PUR	5.01	16.14	1.14.E+09	6.88.E+09	1.71.E+09	9.73.E+09	1.08.E+10
Other	23.98	77.21	6.80.E+10	1.82.E+11	2.91.E+10	2.79.E+11	4.03.E+11
Total	100	322	1.47.E+11	4.92.E+11	5.85.E+10	6.98.E+11	9.25.E+11

*PS & EPS is assumed to be substituted by PLA

Table XII. 4. The water and land footprint if complete shift to bioplastics using 'average' value scenario and 10% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	2.25.E+10	1.99.E+11	4.71.E+10	2.68.E+11	3.68.E+11
PP	19.21	61.87	3.44.E+10	2.47.E+11	2.01.E+10	3.02.E+11	2.86.E+11
PVC	13.37	43.04	4.55.E+10	6.61.E+10	5.05.E+09	1.17.E+11	7.42.E+10
PET	5.85	18.83	1.83.E+10	6.48.E+10	7.67.E+09	9.08.E+10	1.42.E+11
PS & EPS*	5.85	18.83	2.76.E+09	2.88.E+10	5.18.E+09	3.67.E+10	2.97.E+10
PUR	5.01	16.14	2.69.E+09	1.63.E+10	4.06.E+09	2.30.E+10	3.59.E+10
Other	23.98	77.21	5.13.E+10	2.13.E+11	2.96.E+10	2.94.E+11	4.12.E+11
Total	100.00	322	1.77.E+11	8.35.E+11	1.19.E+11	1.13.E+12	1.35.E+12

*PS & EPS is assumed to be substituted by PLA

Table XII. 5. The water and land footprint if complete shift to bioplastics using 'average' value scenario and 36% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	1.60.E+10	1.41.E+11	3.35.E+10	1.91.E+11	2.62.E+11
PP	19.21	61.87	2.45.E+10	1.76.E+11	1.43.E+10	2.15.E+11	2.03.E+11
PVC	13.37	43.04	3.23.E+10	4.70.E+10	3.59.E+09	8.30.E+10	5.28.E+10
PET	5.85	18.83	1.30.E+10	4.61.E+10	5.45.E+09	6.46.E+10	1.01.E+11
PS & EPS*	5.85	18.83	1.96.E+09	2.05.E+10	3.69.E+09	2.61.E+10	2.98.E+10
PUR	5.01	16.14	1.92.E+09	1.16.E+10	2.89.E+09	1.64.E+10	1.81.E+10
Other	23.98	77.21	3.65.E+10	1.51.E+11	2.11.E+10	2.09.E+11	2.93.E+11
Total	100	322	1.26.E+11	5.94.E+11	8.45.E+10	8.04.E+11	9.60.E+11

*PS & EPS is assumed to be substituted by PLA

Table XII. 6. The water and land footprint if complete shift to bioplastics using 'average' value scenario and 62% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	9.50.E+09	8.39.E+10	1.99.E+10	1.13.E+11	1.56.E+11
PP	19.21	61.87	1.45.E+10	1.04.E+11	8.48.E+09	1.28.E+11	1.21.E+11
PVC	13.37	43.04	1.92.E+10	2.79.E+10	2.13.E+09	4.93.E+10	3.13.E+10
PET	5.85	18.83	7.72.E+09	2.74.E+10	3.24.E+09	3.83.E+10	5.98.E+10
PS & EPS*	5.85	18.83	1.16.E+09	1.22.E+10	2.19.E+09	1.44.E+10	1.77.E+10
PUR	5.01	16.14	1.14.E+09	6.88.E+09	1.71.E+09	9.73.E+09	1.08.E+10
Other	23.98	77.21	2.17.E+10	8.98.E+10	1.25.E+10	1.23.E+11	1.74.E+11
Total	100	322	7.49.E+10	3.53.E+11	5.02.E+10	4.76.E+11	5.70.E+11

*PS & EPS is assumed to be substituted by PLA

Table XII. 7. The water and land footprint if complete shift to bioplastics using 'low' value scenario and 10% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	1.87.E+09	1.05.E+11	2.41.E+10	1.31.E+11	2.32.E+11
PP	19.21	61.87	3.44.E+10	2.47.E+11	2.01.E+10	3.02.E+11	3.97.E+11
PVC	13.37	43.04	4.55.E+10	6.61.E+10	5.05.E+09	1.17.E+11	1.48.E+11
PET	5.85	18.83	1.05.E+10	1.22.E+10	9.26.E+08	2.35.E+10	5.44.E+10
PS & EPS*	5.85	18.83	3.30.E+09	2.36.E+10	7.97.E+09	3.49.E+10	1.63.E+11
PUR	5.01	16.14	2.69.E+09	1.63.E+10	4.06.E+09	2.30.E+10	1.63.E+11
Other	23.98	77.21	4.29.E+10	4.99.E+10	3.80.E+09	9.65.E+10	5.44.E+10
Total	100.00	322.00	1.41.E+11	5.21.E+11	6.60.E+10	7.28.E+11	1.21.E+12

*PS & EPS is assumed to be substituted by PLA

Table XII. 8. The water and land footprint if complete shift to bioplastics using 'low' value scenario and 36% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	1.33E+09	7.48E+10	1.71E+10	9.33E+10	1.65E+11
PP	19.21	61.87	2.45E+10	1.76E+11	1.43E+10	2.15E+11	2.03E+11
PVC	13.37	43.04	3.23E+10	4.70E+10	3.59E+09	8.30E+10	5.28E+10
PET	5.85	18.83	7.43E+09	8.65E+09	6.59E+08	1.67E+10	8.46E+09
PS & EPS*	5.85	18.83	2.35E+09	1.68E+10	5.67E+09	2.48E+10	2.54E+10
PUR	5.01	16.14	1.92E+09	1.16E+10	2.89E+09	1.64E+10	2.18E+10
Other	23.98	77.21	3.05E+10	3.55E+10	2.70E+09	6.86E+10	3.47E+10
Total	100	322	1.00E+11	3.70E+11	4.69E+10	5.18E+11	5.11E+11

*PS & EPS is assumed to be substituted by PLA

Table XII. 9. The water and land footprint if complete shift to bioplastics using 'low' value scenario and 62% recycling rate

Plastic material demand by 2015	**Percentage**	**Demand in million tonnes**	**Water footprint (m^3)**				**Land footprint (m^2)**
			Blue	Green	Grey	Total	
PE	26.73	86.08	7.90.E+08	4.44.E+10	1.02.E+10	5.54.E+10	9.78.E+10
PP	19.21	61.87	1.45.E+10	1.04.E+11	8.48.E+09	1.28.E+11	1.21.E+11
PVC	13.37	43.04	1.92.E+10	2.79.E+10	2.13.E+09	4.93.E+10	3.13.E+10
PET	5.85	18.83	4.41.E+09	5.14.E+09	3.91.E+08	9.94.E+09	5.02.E+09
PS & EPS*	5.85	18.83	1.39.E+09	9.97.E+09	3.37.E+09	1.47.E+10	1.51.E+10
PUR	5.01	16.14	1.14.E+09	6.88.E+09	1.71.E+09	9.73.E+09	1.29.E+10
Other	23.98	77.21	1.81.E+10	2.11.E+10	1.60.E+09	4.08.E+10	2.06.E+10
Total	100	322	5.96.E+10	2.20.E+11	2.79.E+10	3.07.E+11	3.03.E+11

*PS & EPS is assumed to be substituted by PLA