Master's thesis in Sustainable Biotechnology

Comparative Life Cycle Assessment of two bio-based plastics and polystyrene used for token manufacturing

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Abstract

b-token, a plastic token manufacturing company, aims to reduce its environmental footprint by replacing fossil-fuel based plastics with alternatives made from renewable and biodegradable resources. Therefore, two bio-based plastics, Solanyl® and Arboform® were selected as these are comparable to polystyrene in terms of mechanical and physical properties. To assist b-token in their future decision-making regarding sustainability strategies, this study aims to measure and identify both environmental benefits and trade-offs of Solanyl® and Arboform® in comparison to polystyrene. Hence, a cradle-to-gate assessment was conducted to quantify the environmental impact of all three plastics.

It was shown that the bio-based plastics could decrease the global warming potential and fossil resource scarcity potential by approximately 40% and 67% respectively, which is likely a result of the biological feedstocks used for Solanyl® and Arboform® resin production. Nevertheless, higher potential impacts were found for land use, eutrophication and fine particulate matter formation, which are primarily caused by agricultural activities and fuel combustion. However, when further considering the end-of-life options, it is though that Solanyl® and Arboform® are more desirable as compositing and mechanical recycling are both possible.

Differences in potential impacts were found comparing just Solanyl® and Arboform®. Indeed, Solanyl® has a more significant potential impact on water use, marine eutrophication and fine particulate matter whereas Arboform® has a more significant potential on land use and freshwater eutrophication. These findings also indicate potential hotspots. It was also found that the composition of both bio-based plastics influences the environmental impact significantly. Hence, there is room for future optimization by focusing on the hotspots and defining the optimum composition.

During this study, high potential impacts were obtained for the toxicity. It is thought that underlying background data, along with the value choices, resulted in overestimated potential toxicity. Hence, further research regarding the toxic impact is recommended in order to determine the absolute impact.

List of abbreviations

BP	-	Biodegradable bioplastic
CR	-	Chemical recycling
CH_4	-	Methane
EPS	-	Expanded polystyrene
GHG	-	Greenhouse gas
H	-	Hierarchist
H_2O	-	Water vapour
LCA	-	Life Cycle Assessment
LCI	-	Life Cycle Inventory
LCIA	-	Life Cycle Impact Assessment
MR	-	Mechanical recycling
NBP	-	Non-biodegradable plastics
OR	-	Organic recycling
PA	-	Polyamide
PC	-	Polycarbonate
PET	-	Polyethene terephthalate
PLA	-	Poly lactic acid
PS	-	Polystyrene
RF	-	Renewable feedstock
TPS	-	Thermo plastic starch
tkm	-	Tonne kilometre
WMR	-	Waste management route

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1. Introduction

Shortly after the discovery of plastics and its benefits, they were adopted in almost all industries. The widespread use of plastic over the years resulted in a massive number of plastics being manufactured and sold. The cumulative amount of plastics produced over the years surpassed eight billion metric tons in 2018. Unfortunately, synthetic plastics give rise to multiple disadvantages that are less tangible compared to the endless benefits encountered in a person's everyday life (Ritchie and Roser, 2018).

Synthetic plastics cause severe environmental damages that present risks to everyone. The production of plastics requires energy-intensive processes generating considerable greenhouse gas emissions. The increasing accumulation of these gases in the atmosphere induces global warming, a phenomenon where the average atmospheric temperature increases. The rising global temperature triggers changes in the climatic system that safeguards the liveable conditions; hence poses a threat to all living organisms on this planet. Besides, the production of synthetic plastics relies entirely on fossil resources which are available and accessible in limited volumes on this planet. Increasing demand for those finite resources will eventually result in growing geopolitical and economic instability. Finally, post-consumer plastics cause severe environmental problems at their end-of-life stage. Globally, governments fail to accommodate the tremendous consumption of plastics with according waste management systems. Over the years, mismanaged plastic invaded the environment bringing damage to the ecosystems and human health (Andrady, 2015; Ritchie and Roser, 2018).

Fortunately, many public and private organisations around the globe are working on innovative solutions to address these problems by both reinventing waste management routes and re-engineering plastics. An example of a company seeking to reduce their environmental footprint is b-token, a Belgian company manufacturing and selling about 100 tons of plastic tokens annually. These tokens are used at events and festivals where they can be considered as a local currency. Seeing events or festivals generally take place one or a few days, these tokens only have a short life-time. As a result, these plastic become waste rapidly. Therefore, b-token is developing new strategies to become more sustainable and future-proof.

One of b-token's strategies is rethinking their plastic product by integrating alternative plastic resins. Indeed, b-token works with plastics, made from agricultural products and industrial by-products as feedstocks, to replace the polystyrene resins, in order to reduce the environmental impact of their tokens. Both bio-based plastics express similar thermoplastic processing properties while benefitting from biodegradable functionality. These bio-based plastics are named Solanyl® and Arboform®.

Renewable and biodegradable materials are generally accepted to be environmentally superior compared to their fossil counterparts. Nevertheless, it is still critical to investigate the real environmental benefits and trade-offs of the selected alternatives in comparison to the plastic they substitute. Life Cycle Assessment is the most commonly used to assess and simulate the environmental performance of products and services (La Rosa et al., 2013). An LCA includes multiples stages starting by modelling of a life cycle inventory by collecting and calculating all material, energy and emission data followed by the life cycle impact analysis to evaluate the impact of the life cycle inventory and finally the interpretation of the results (Vink et al., 2003). Within this study, a cradle-to-resin analysis is conducted to compare the environmental performance of Solanyl®, Arboform® and polystyrene. The life cycle inventories for one kg of resins of Solanyl® and Arboform® are built separately in order to compare the environmental impacts. In order to bring the results in context, the life cycle impact results of polystyrene, will be analysed and compared simultaneously.

2. Research question and report structure

2.1 Research questions

The purpose of this report is to indicate which plastic out of the proposed plastics is more environmentally advantageous for b-token. This is done by conducting a cradle-to-resin study where the production processes of Solanyl® and Arboform® are simulated using the SimaPro software in order to determine the estimated environmental impact. The obtained impact results are compared to the potential impact results of Polystyrene (PS), which will be simulated using the life cycle inventory data provided by the global database Ecoinvent 3.5.

The main research question is as follows:

Are Solanyl® and Arboform® resins performing better compared to PS resins from an environmental perspective?

The sub-questions that are answered in order to respond to the main answer are:

1) *What are the estimated environmental benefits of the bio-based alternatives compared to PS?*
2) *What are the estimated environmental trade-offs of the bio-based alternatives compared to PS?*
3) *What bio-based alternative is estimated to be environmentally superior?*

2.2 Report structure

This report starts with a simple introduction to enlighten the reader about the theme of the project and the researched topic followed by the research question and sub-questions. These questioned will be answered throughout the report. The background is then presented, entailing more information regarding the problem formulation and the technological solutions that can contribute to solving the general problem. The background also describes the chosen resin types and the tool used to conduct a comparison between the types of resins.

The second part of the report is focused on the analysis. It begins with the describing the goal and scope of the analysis. After that, the LCI is composed for each type of resins. Assumptions, reasonings, inputs and outputs are mentioned for every aspect of the LCI. Then, the LCIA is conducted where the environmental impacts of the resins are analysed and compared based on the LCI. Here the results for all analysed impact categories are presented and shortly described. The impact results for each type of resin are presented simultaneously to enable a better comparison.

After that, a sensitivity analysis is conducted. Here multiple scenarios are tested in order to quantify the influence these uncertainties have on the outcomes. The last part is the interpretation/discussion section. Here the essential findings and uncertainties are summarised followed by a discussion of the results which are linked back to certain aspects mentioned in the background in order to determine the superior alternative resin. Based on the essential findings and the discussion, recommendations and conclusions are constructed.

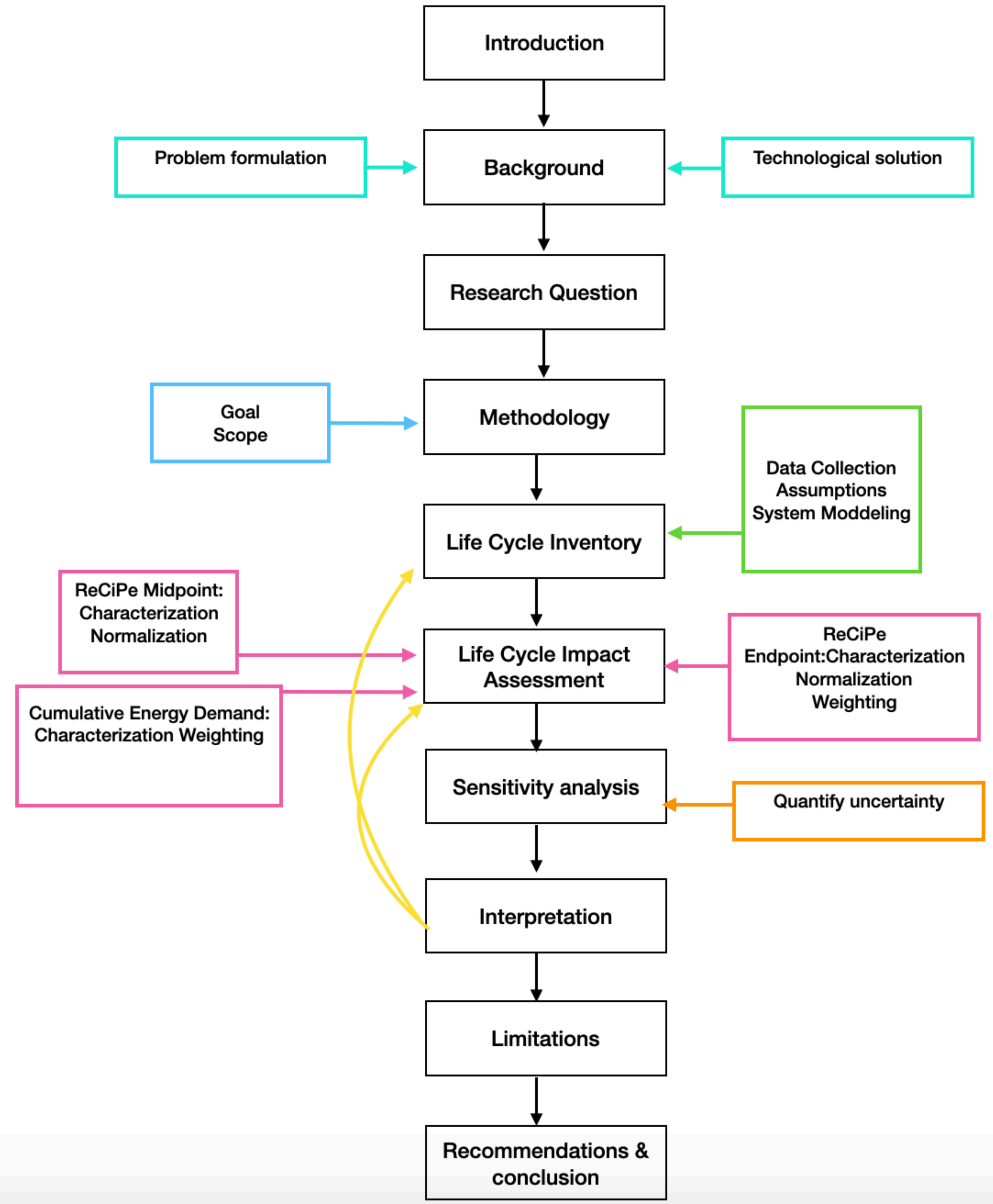

Figure 1: Schematic representation of the report structure

3. Background

This section entails background information regarding the stud. It starts with plastics and their related sustainability considerations. Waste management and renewable feedstocks are then introduced and described, as these are considered solutions to the environmental impacts caused by synthetic plastics.

3.1 Plastics

The carbon-rich composition of fossil fuels like petroleum drove researchers to look into new applications in order to exploit them, resulting in the discovery of the first synthetic plastics (Science History Institute, 2020). SP are long-chained linear macromolecules made by bounding multiple monomers into one long chain of repeating units (Andrady, 2015). This structure allows SP to express outstanding mechanical and physical properties such as strength, low-weight, UV and chemical resistance and flexibility among many others. The maturity of the technology and the inexpensive raw materials stimulate low pricing of plastics (Andrady, 2015). The combination of these factors resulted in plastic being considered as nothing less than wonder materials sold at about 0.5$/kg (Sutton, 2020; Plasticker, 2020).

Consequently, more than 80 thousand SP formulations were made commercially available, resulting in the adoption of plastic in quasi all industries extending from automobile and construction to medical, textile and packaging applications (Andrady, 2015; Lisicins et al., 2015). As a result, plastics are to be used in tremendous capacities, surpassing 360 million metric tons (MMT) annually nowadays. Continuous growth in global population numbers and middle-income families, coupled with the business-as-usual, will most likely cause global plastic consumption to double by 2040 (Zero waste Europe, 2019).

Synthetic plastics are produced through a polymerisation process where at least two monomers are coupled through chemical reactions triggered by the addition of heat, pressure and catalytic substance (Shrivastava, 2018). The variety of polymerisation technologies is wide. Nevertheless, they are grouped into two main categories. First, addition polymerisation that converts monomers into active radicals and links them together into polymers (Encyclopedia Britannica, 2020; Andrady, 2015). Second, condensation polymerisation where monomers are linked into polymers through the release of water or methanol (Andrady, 2015).

Depending on the monomers and polymerisation process, a tremendous range of synthetic plastics can be produced. While they can all be processed under high temperatures, there is one fundamental property that results in plastics being categorised into two groups: thermoplastics and thermosets. The main physical difference relies on the fact that thermoplastics can undergo the melt-and-shape process multiple times whereas thermosets can only be melted and shaped once and will then remain under solid-state even when the temperature increases (Modor Plastics, 2020). This is because thermosets, like epoxy or phenol-formaldehyde, are formed by mixing one or multiple components with one or more comonomers, molecules with multiple reactive groups, to create a chemical bond by cross-linking components (Sastri, 2014). Hence, a highly complex structure is created that provides some excellent properties like mechanical strength, the ability to remain stable under increasing temperatures and resistance to solvents (Madhav, Singh and Jaiswar, 2019).

In contrast, thermoplastics are not formed by chemical bonding. As a result, the chemical reaction is reversible. Thermoplastics can thus be moulded and shaped without affecting the physical and mechanical qualities almost endlessly due to the simple structure of the macromolecules consisting of independent and neutral molecules connected by van der Waals forces. These weak electrostatic forces facilitate polymer disruption under heating conditions, causing a melting effect (Mayer, 2018; Singh, 2016).

3.1.1 Polystyrene

From b-token's perspective, a particular interest rises towards PS, thermoplastic polymer used as a feedstock to produce their tokens. b-token uses general-purpose polystyrene (GPPS) is an aromatic plastics. GPPS is a rigid plastic that benefits from stability under a wide range of temperatures and offers high mechanical strength (Mohanty and Chulsung, 2015).

Apart from GPPS, there are different grades or types of PS that are commercially available. The most commonly used, is expanded polystyrene (EPS), which is also referred to as Styrofoam. EPS has a lower density compared to GPPS which is obtained through a supplementary step that adds heat and a blowing agent. The main advantage of EPS compared to other plastics is its very light weight and isolating properties (Madehow.com, 2020). However, in the context of b-token and their respective processes, the focus will be concentrated on GPPS (will be referred to as PS).

PS is formed by free-radical polymerisation, a type of addition polymerisation. During the polymerisation, process monomers are attached to a free radical, forming an active chain-end that in turn, becomes a free-radical again (Choi and Rudin, 2013). The monomer, styrene, is made by dehydrogenising the intermediate hydrocarbon ethylbenzene which is derived from ethylene and benzene through a catalytic alkylation reaction (Icis, 2009-B). Styrene is an organic compound that is entirely derived from fossil fuels as ethylene is produced through a steam cracking process of ethane, a natural gas component, and benzene is derived from crude oil through distillation and catalytic reforming processes (Icis, 2009-A; Icis, 2010). A simplified overview is represented schematically in the flow chart (Figure 2).

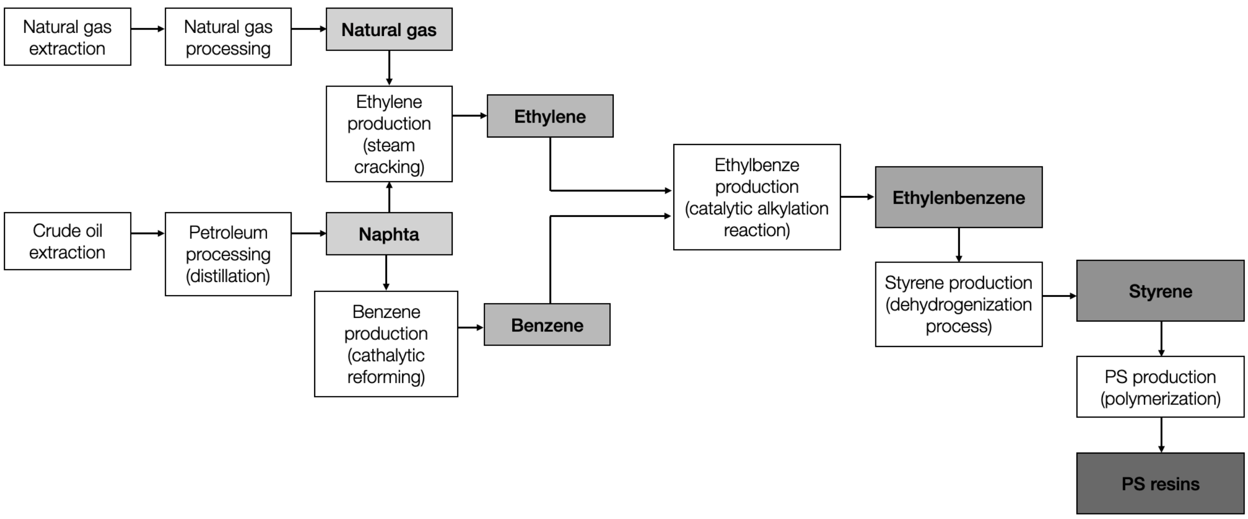

Figure 2: Simplified flow chart representing the manufacturing processes for PS. (Adapted from Feraldi and Cashman (2011) and Andrady (2015))

3.2 Environmental trade-offs of petroleum-derived plastics

Plastic production has grown exponentially over the past 70 years, reflecting its enormous popularity. Plastics offer undoubtedly extraordinary benefits for society as we know it today. The use of plastics in medical applications, food packaging and transport among others have arguably immensely contributed to the development of public health and economic growth. Nevertheless, the same production of plastic over the last 70 years simultaneously led to environmental issues affecting people and nature globally.

3.2.1 Post-consumer waste

First, enhanced use of plastics results inevitably in increasing post-consumer disposal of plastics. In 2016, the global number of post-consumer plastic surpassed 275 MMT (Ritchie and Roser, 2018). Within the same year, 335 MMT of synthetic plastics were produced. Hence, 80% was already disposed within less than a year, from which only one fifth was recycled. Another 25% was incinerated while the remaining share was discarded without proper treatment on landfills (Plasticseurope, 2019).

Mismanaged waste has direct adverse effects on landscape aesthetics, public health and ecosystems (Ritchie and Roser, 2018). Experts estimate that more than 8 MMT of plastics are discarded in the oceans every year, posing a threat to marine life through suffocation, entanglement and ingestion as well as damaging the aesthetic value of coastal regions (IUCN, 2020). Moreover, mismanaged plastic waste will eventually start to degrade. Biological degradation, which is desirable, takes up hundreds of year due to the recalcitrant nature of petroleum-based plastics (Andrady, 2015). As a consequent, synthetic plastics remain intact as long as forever on a human time-scale. Meanwhile, water and abiotic factors like UV radiation and movement interfere with plastics inducing hydrolysis and photodegradation (Sharma and Chatterjee, 2017). These make plastic disappear visibly. Unfortunately, the plastics are reduced to micro-plastics. These pieces of plastic are undetectable by the human eye, yet they pose both an ecological and health risk (Andrady, 2015). Microorganisms, such as zooplankton, ingest MPs causing bioaccumulation throughout the trophic levels up to the highest levels such as humans. Ingestion of MPs is described to be harmful to human and animal health, by interfering with the endocrine system, causing cancers and leading to infertility (Sharma and Chatterjee, 2017; IUCN, 2020).

3.2.2 Human-induced climate change

The earth's climate system is an interactive and highly complex mechanism maintained by an inter-complex equilibrium of natural cycles. These are influenced by five main elements or spheres, which are the atmosphere, biosphere, cryosphere, hydrosphere and lithosphere (Folland et al., 2001A). All spheres are inter-related and are thus all affected when changes occur, causing a disequilibrium to the climate system (Kellogg and Shware, 2019).

The atmosphere is particularly sensitive to changes. Its composition, which under normal conditions, is ideal for life as we witness on this planet today, consists of nitrogen (78.1%)[1], O_2 (20.9%) and argon

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[1] Percentages represent the volume mixing ratios

(0.93%) as well as trace gases such as CO_2, methane (CH_4), nitrous oxide (N_2O), water vapour (H_2O) and ozone (O_3) (Folland et al., 2001). Although theses trace gases only make up less than one per cent of the atmosphere, they have a powerful influence on the climate system. These gases trap energy in the atmosphere by absorbing and re-emitting infrared radiation, causing a heating or greenhouse effect (Rasmussen and Khalil, 1986; Folland et al., 2001). Hence, the higher the concentration of GHG, the lesser solar radiation that can escape out of the atmosphere, thus increasing the planet's surface temperature (Schneider, 1989). It is for this reason that these gases are referred to as greenhouse gases (GHG) (Folland et al., 2001).

Industrialisation and automatisation of processes, driven by fossil energy carriers, resulted in vast increases of these GHG and particularly CO_2. Atmospheric CO_2 concentrations have already grown 30% since the beginning of the industrial revolution, i.e. the start of fossil fuel combustion (Folland et al., 2001A). Since the demand for energy still outgrows the installed renewable and low-carbon energy capacity, CO_2 emissions will most likely not cease to increase in the near future. Consequently, increasing temperatures are measured worldwide. On average, the Earth's temperature increased with 1°C over the past century (United Nations, 2015).

Plastics also contribute considerably to this global threat. A recent study by Zheng and Suh (2019) claims that plastics are responsible for almost 4% of the total emissions today. The expected continuous growth of plastics in the foreseeable future will result in plastic contributing as much as 15% to the global GHG emissions (Zheng and Suh, 2019). These numbers indicate that plastics are significant contributors to human-induced climate change and are thereby pose a threat to the global commitment to keep the temperature increase below 1.5°C by 2100 (United Nations, 2015).

3.2.3 Depletion of finite resources

Fossil fuels are hydrocarbons that have accumulated over millions of years originating from decaying animal and plant residues. Although these are abundantly present on the earth, they are still physically limited. Besides, certain geographical circumstances can render oil or gas extraction technologically of economically unviable, thereby reinforcing the restricted availability. As a result, if the rate of extraction outpaces the rate of replenishing, a depletion of these finite resources could arise (Zheng and Suh, 2019). At present, 99% of plastics are derived from petrochemical feedstocks, using about 614 million tons of oil equivalent (Mtoe), which is nearly equal to the supply to all non-OECD countries in the Americas combined (Höök and Tang, 2013; IEA, 2019). These numbers are expected to grow enormously since market analysts forecast global plastic demand to reach 1244 MMT in 30 years from now (World economic forum, 2016). Seeing that fossil fuels are the primary feedstock, experts question if supply will continue to meet the demand or if shortages will arise (Höök and Tang, 2013).

3.3 Solutions

Continuously growing population size coupled to the global increase in income and rise of the middle class is boosting global consumption rate of finite resources (Höök and Tang, 2013). At current rates, further generations could be compromised in well-being and prosperity due to depletion of valuable resources, unstable climate conditions and devasted ecosystems caused by the current anthropogenic impacts on the earth. It is therefore of utmost importance to stimulate sustainable development, in order to safeguard future generations in terms of natural resources and ecosystems services, so that they can profit from equal prosperity, well-being and economic growth as do present generations. Therefore, continuous growing demand for plastics rises the quest to increase the diffusion of more environmentally desirable solutions that can eliminate the health and environmental hazards while providing similar societal benefits (Zheng and Suh, 2019; Vink et al., 2003)

3.3.1 Waste management routes

The waste management pyramid is a tool created to indicate more desirable waste management routes (WMR) in order to adopt a more sustainable approach to manage waste (represented in Figure 3) (Environment Protection Authority, 2017). The disposal of waste without treatment, including landfilling, littering and incineration without energy recovery, is considered the least desirable WMR as it is considered the most environmentally damaging. A superior WMR is incineration-based energy recovery, as the embodied energy of plastics can be recovered and converted into electricity. This technology offers a solution to the accumulation of waste while earning some "carbon credits" (74kg CO_2-eq/t_{waste}) by recovering energy (Clerens and Thuau, 2020). Carbon credits here are considered as the amount of carbon that is saved by recovering energy rather than producing it directly from fossil resources. Nonetheless, this WMR is still considered environmentally inferior compared to recycling as it devaluates the materials and stimulates a false sense of responsibility that results in discouragement of waste-reduction initiatives (UNEP, 2018). Recycling, including composting, is considered a more desirable WMR, due to its contribution to a closed-loop material flow and the circular economy (CE). Ultimately, the directions for utmost sustainable actions are to reuse and ultimately reduce the consumption of products to avoid waste effectively. These two options are reliant on fundamental changes in lifestyle behaviour and are considered complementary to technological solutions such as recycling and composting.

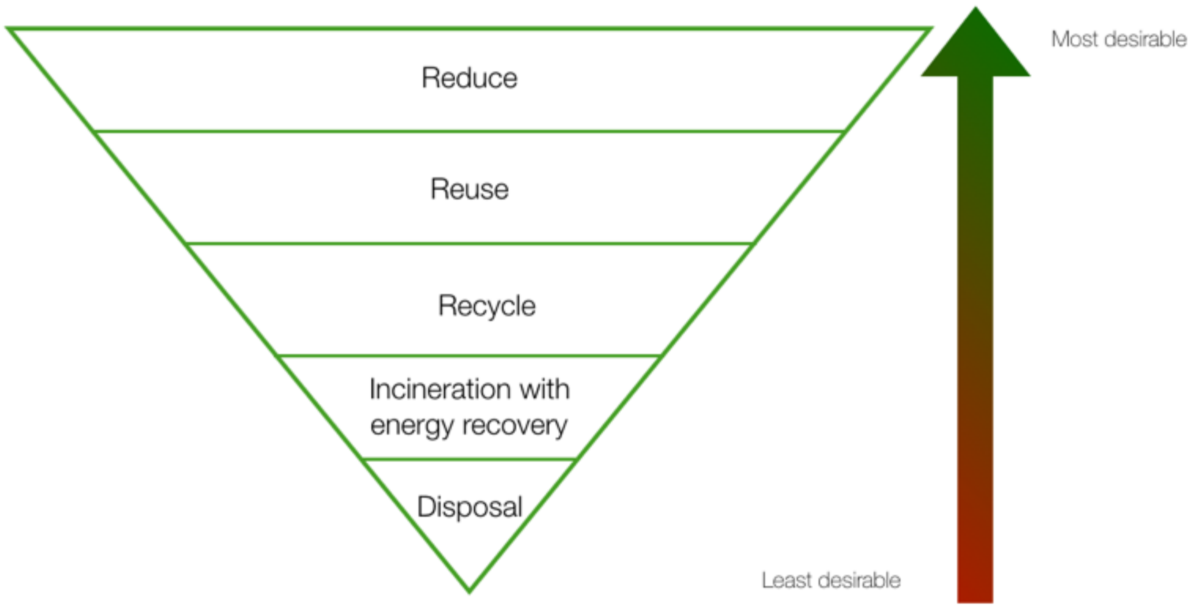

Figure 3: Waste management hierarchy. Indicating the most desirable waste management routes. Adapted from Environment Protection Authority (2017).

Recycling

Recycling is thought to be a major technological solution to ensure resources are valued and maintained within the economy by being converted into value-added products. Furthermore, recycling of plastics also offers a solution to avoid mismanaged waste being discarded and enables to reduce the carbon footprint of the plastic industry. At present 67MMT CO_2-eq are avoided by recycling (Zheng and Suh, 2019). Recycling strategies can be grouped into three main categories, namely mechanical, chemical and organic recycling.

Mechanical recycling (MR) is a process where materials are converted into new raw materials without altering the chemical composition (European Bioplastics, 2015). MR consists of four main steps: sorting, removal of dirt and specific contaminants, grinding and granulation. MR is highly established for a variety of conventional plastics, such as PET. However, there are still challenges around this technology. First, the degradation of plastics either during the recycling process or use phase due to UV radiation, shear stress or hydrolysis reduces the quality. Therefore, MR cannot be considered as an endless solution. Second, contaminants present in the polymer matrix or material can affect the effectiveness of the recycling process (Ragaert, Delva and Van Geem, 2017).

Chemical recycling (CR) is a different recycling strategy where polymers are depolymerised into monomers that can serve as secondary petrochemical feedstocks for (value-added) chemicals. Multiple well-established techniques such as glycolysis and pyrolysis can be used for CR. Particular advantages of CR are the facts that it can be used to recycle certain plastic products that have not yet been successfully mechanically recycled such as multilayer packages. Moreover, CR is less sensitive to some (organic) contaminants compared to MR. It is suggested that CR and MR are complementary to one another (Ragaert, Delva and Van Geem, 2017).

Organic recycling (OR) or composting are the decomposing of organic wastes such food rests, garden waste and certified biodegradable products or packages into smaller organic components or nutrients that were present in the waste such as carbon (C), nitrogen (N), phosphorus (P) and sulphur (S) under a set of certain conditions. These can be recirculated to value-added activities like fertilisers or bio-energy, hence contributing to a bio-based circular economy (Polprasert and Koottatep, 2007). OR can either be done under aerobic conditions as (industrial) composting or by anaerobic digestion (AD) (European Bioplastics, 2020). One of the main challenges for OR is the requirement for an efficient waste collection system that enables the separate collection of compostable waste, which requires governmentally regulated waste policies and waste management services (European Bioplastics, 2020; Defra, 2011).

3.3.2 Feedstocks – uncoupling plastics from petrochemical feedstocks

Another strategy described to reduce the environmental footprint of plastics is by shifting towards renewable feedstocks (RFs) in order to disconnect SPs from petrochemical feedstocks (Zheng and Suh, 2019). RFs are derived from natural sources such as forest or agriculture and used as carbon sources for a variety of applications like chemicals, plastics, pharmaceuticals and fuels that can substitute the petrochemical-derived alternatives (Bozell, 2008). RFs are distinguished from fossil feedstocks by the fact that they can replenish themselves over a relatively short period of time under natural conditions. Plants grow through photosynthesis processes where solar energy and CO_2 are converted into glucose used to sustain and stimulate the plant's growth (Bozell, 2008; Plavanescu et al., 2016). Ideally, RFs or biomass are converted into products which, when disposed of correctly, will eventually decompose back into CO_2 and other components (Figure 4) (Plavanescu et al., 2016). Processing biomass into a product consists of two main stages: converting and separating the biomass into chemical building blocks like starch or cellulose and converting the building blocks in products (Bozell, 2008).

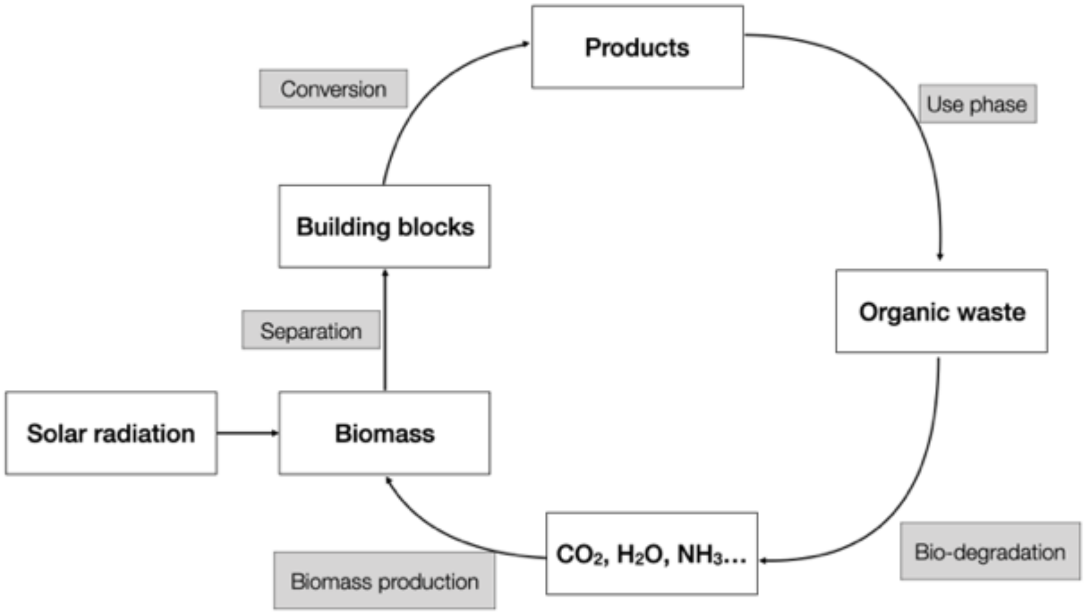

Figure 4: The self-replenishing cycle of biomass used for industrial applications. Adapted from Bozell (2008).

Transitioning to a bio-based economy by replacing fossil resources by biomass for fuel and chemical production offers many advantages. First of all, it enables CO_2 sequestering and recycling, thereby stimulating climate change mitigation (Bozell, 2008). The global biomass production capacity is quasi infinitive and widely spread (Melero, Iglesias and Garcia, 2012). Expanding RF refineries worldwide reduces the human dependence on finite fossil reserves while reducing global geopolitical instability caused by the unequal disparity of fossil reserves (Bozell, 2008). Furthermore, local availability of RFs contributes to local economies while stimulating the development of new industries and skills. The ability to convert existing refineries into biorefineries could help to avoid job losses in the petrochemical industry (Melero, Iglesias and Garcias, 2012).

Nevertheless, there are still many challenges encountered by the biorefinery industry. Bio-based production processes require alternative routes and building blocks. Developing the required knowledge and skills to do so demands high investments in both financial and intellectual capital (Melero, Iglesias and Garcia, 2012). Moreover, some processes remain inferior in efficiency compared to alternative petroleum-based processes. Especially regarding the downstream processes, some challenges arise with obtaining both high purity and cost-effectiveness (Harmsen, Hackmann and Bos, 2014). Besides, bio-based raw materials are challenged economically by the highly competitive fossil fuel prices (Us.spindices, 2020). Finally, some question the true environmental advantages of biomass, as it does contribute to adverse environmental externalities such as damage to ecosystems, land transformation, eutrophication, ecotoxicity among others (Viesturs and Melece, 2014; La Rosa et al., 2013).

RFs are classified into three main categories based on their source of origin. These are first, second and third-generation biomass. The fundamental element at the basis of this classification is the fact that a crop can be used for food applications or not. Processing food crops in non-food applications can conflict with food supply. Therefore, it is considered unethical to use food for non-food applications like fuel production (Lee and Lavoie, 2013). Table 1 represents an overview of these categories as well as examples of feedstock and their respective advantages and disadvantages.

Table 1: Overview of first, second and third-generation feedstocks.

First-generation biomass (Edible crops)				
Feedstocks	*Examples*	*Advantages*	*Disadvantages*	*References*
Dedicated biomass crops	Sugar cane, rapeseed, soybean, palm, sunflower, corn	Rich in sugar, developed and well-understood conversion processes, relatively easy separation processes	Land-use changes, intensification of agriculture, use of arable land, conflicts with food supply, loss of biodiversity, decrease in soil quality, enhanced eutrophication	Melero, Iglesias and Garcia (2012); Energy.gov (n.d.); Viesturs and Melece (2014); Lee and Lavoie (2013)
Second generation (non-edible crops or (industrial) residues)				
Feedstocks	*Examples*	*Advantages*	*Disadvantages*	*References*
Lignocellulosic biomass	Hemp, flax, switchgrass	No competition with food supply, reuse of waste or agricultural/forestry by-products,	More complex separation and conversion processes, more recalcitrant behaviour, use of arable land	Adhikari, Nam and Chakraborty (2018); Lee and Lavoie (2013)
Agricultural residues	Sugar cane bagasse, leaves, wheat straw,			
Forestry residues	Branches, leaves, bark			
Source-sorted organic fractioned municipal waste	Copenhagen's source-sorted organic municipal waste			
Activated sludge	Sludge from local wastewater treatment facilities			
Third generation (algal biomass)				
Feedstocks	*Examples*	*Advantages*	*Disadvantages*	*References*
(Micro)algae	Scenedesmsus sp., Spirulina sp.,	Use of non-arable land, no competition with food production, use of non-potable water is possible	Energy return of on investment is debated, risk of water pollution, Contamination risks reduce economic security, high capital investments	Zhu, Huo and Qin (2014)

3.3.2.1 Bio-based plastics

In recent years, many developments have been made to develop and broaden the portfolio of bio-based plastics. A wide variety of chemical and biological pathways are discovered to produce biopolymers that possess similar mechanical and processing properties as the petrochemical alternatives (Harmsen, Hackmann and Bos, 2014). Bio-based plastics are grouped into two classes: biodegradable (BP) and non-biodegradable bioplastics (NBP) (European Bioplastics, 2015). Figure 5 represents a schematic overview of various commercialised biopolymers.

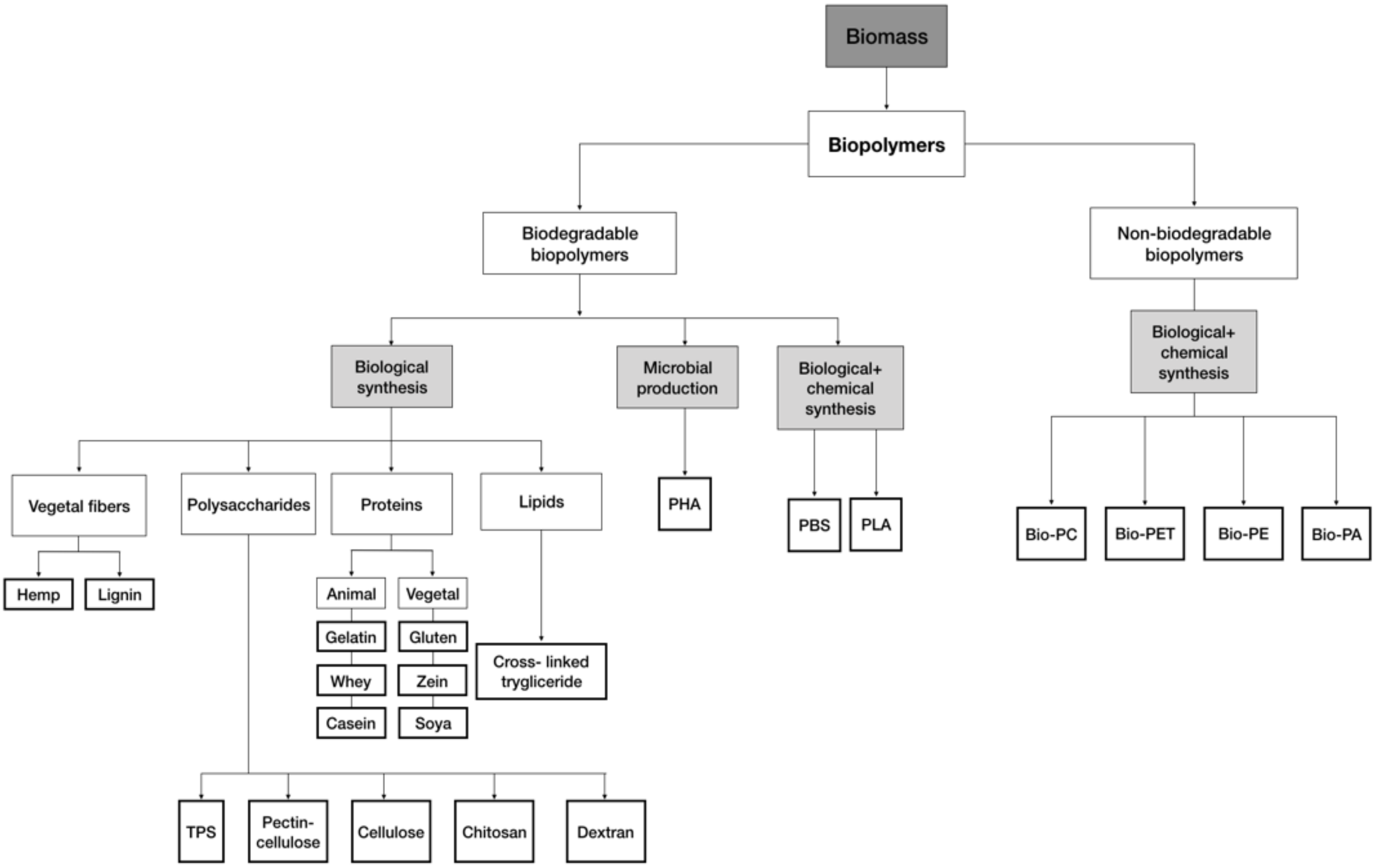

Figure 5: Schematic overview of polymers derived from biological feedstocks. (Thermoplastic starch (TPS), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), polylactic acid (PLA), polycarbonate (PC), polyethene terephthalate (PET), polyethene (PE) and Polyamide (PA)). Adapted from Khan et al. (2017) and Bioplastics guide (2020).

Non-biodegradable bioplastics

Some among the most commercialised conventional plastics such as PE and PET have received bio-based counterparts. These are commonly synthesised by a combination of biological conversion processes like fermentation to produce intermediate acids or building blocks which are eventually converted into polymers by catalytic reactions (Harmsen, Hackmann and Bos, 2014). Examples of NBP are bio-PC, Bio-PET, Bio-PE and Bio-PA. The most preferable WMR for NBP is mechanical recycling (European Bioplastics, 2015).

Biodegradable bioplastics

On the other hand, the majority of commercialised biopolymers are biodegradable and can thus be degraded by microorganisms. Based on the synthesis pathways, BPs are divided into three groups. First, polymers that are naturally synthesised in plants, algae and animals like fibres, polysaccharides, lipids and proteins. They are either used alone or mixed with other polymers to achieve desirable properties for further applications. Especially for packaging, these are considered good alternatives (Khan et al., 2017). The second group are polymers synthesised in microorganisms named polyhydroxyalkanoates (PHAs). These are polymer granules synthesised intracellularly by a variety of bacteria and microalgae for carbon (energy) storage. These can be chemically extracted and used for commercial applications (Jain et al., 2010). The third group are chemically synthesised polymers. These are obtained by polymerising acids, like lactic acid or succinic acid, obtained through fermentation processes (Khan et al., 2017).

3.4 Bio-based plastics for b-token

Within the context of this project, the focus will be narrowed on two biodegradable bioplastics as b-token has expressed its desire to include thermoplastic materials that profit from both a biological origin and possess biodegradability. These are two fully commercialised and suitable bio-based materials, namely Solanyl® and Arboform®.

3.4.1 Solanyl®

Solanyl® is a starch-based biopolymer patented and commercially produced by a Dutch company named Rodenburg Biopolymer. Solanyl is designed and created to substitute a variety of petroleum-derived thermoplastics, like PS. Rodenburg Biopolymer offers a variety of Solanyl® variants that can be tailored to specific application purposes such as moulds and films. General-purpose Solanyl® granules are created for injection moulding processing of commodity goods. It consists of wastewater reclaimed starch, PLA additives (Table 2) (Broeren et al., 2014). These are chemically modified and homogenously blended by reactive extrusion in a two-screw extruder in order to generate the resins (Moad, 2011; personal communication with Rodenburg Biopolymer).

Table 2: Composition general-purpose Solanyl® for processing by injection moulding. Adapted from Broeren et al. (2014). NOTE: In this project, the general-purpose Solanyl® variant created for injection moulding processing will be considered and analysed as the specific variant used by b-token is under trade secret and detailed information regarding composition could not be obtained (personal communication with Rodenburg Biopolymer).

Composites	Origin	Percentage (%)
Reclaimed starch	Industrial residue	25
PLA	Agriculture	43
Additives	Petrochemical	32

<u>Wastewater reclaimed starch</u>

Starch for polymer application is described to be a very promising alternative to fossil fuels due to its widespread availability, low-cost and environmental advantages like biodegradability. Starches are extracted from various food crops like potatoes, wheat, maise, rice and cassava (Khan et al., 2017, Broeren et al., 2017). In order to avoid conflicts with ethical debates on whether food crops should be used for non-food applications and reduce the environmental impact of Solanyl®, Rodenburg Biopolymers uses wastewater reclaimed starch from local potato processing facilities.

Native potato starch is a macromolecule consisting of amylose and amylopectin, which are connected by strong hydrogen-bonds. Native starch has a brittle and hydrophilic nature with low thermal stability, hence limiting the technical possibilities (Khan et al., 2017; Moad, 2011). By disrupting native starch through the addition of water, shear and heat, thermoplastic starch (TPS) is obtained. TPS behaves quite similar to some petrochemical polymers and can be used for commercial thermoplastic applications such as commodity goods or packaging (Khan et al., 2017; Zhang, Rempel and Liu, 2014).

Technical processing of TPS can be negatively impacted by chemical and physical reactions such as crystallisation, gelatinisation and retrogradation among others. Hence, to obtain more desirable properties as well as to fulfil market needs, TPS is often combined with another or multiple (bio)polymers like PS, PET, PP or PLA among many (Khan et al., 2017).

PLA

In the case of Solanyl®, polylactic acid (PLA) is blended in. PLA is another highly promising bio-based polymers due to its biodegradable functionality, strength and processing properties. Unfortunately, PLA is not yet as cost-effective as other polymers, hindering its competitiveness on the market. Hence, blending PLA with low-cost polymers such as starch can enhance the adoption of PLA blends for market applications (Du, Li and Zeng, n.d.).

PLA is produced from lactic acid mixtures which are obtained through fermentation of sugars. The lactic acid mixture is converted into lactide through a two-step process consisting of condensation followed by catalytic conversion. Finally, ring-opening polymerisation, a type of addition polymerisation targeting cyclic monomers, is used to generate the desired PLA resins (Vink et al., 2003).

Additives

In order to achieve desired processing properties as well as good adhesions between TPS and PLA polymers, additives are added to the polymer composite. Two types of additives are proven to be very effective. First, a group of additives that have a minimal molecule size allowing them to integrate very effectively into the three-dimensional polymer networks, these include glycerol, sorbitol, water and xylitol. Second, small-sized molecules containing an amide functional group (-CONH-), like formamide and urea, are effective plasticisers and compatibilisers for starch applications (Zhang, Rempel and Liu, 2014).

The precise additive used in Solanyl® resins is confidential and could not be disclosed by Rodenburg Biopolymers. Considering that additives almost represent a third of the total composition, it must somehow be represented in order to determine the environmental impact of Solanyl® as a material compared to its petrochemical counterpart. Hence, one of the most prominently described additives for TPS blends, i.e. glycerol, is included as an additive (Zhang, Rempel and Liu, 2014; Khan et al., 2017).

3.4.2 Arboform ®

Arboform® is a bio-based polymer composite commercially produced by the German company Tecnaro. As it is composed of wood-derived components for 90% while expressing thermoplastic behaviour, it is often referred to as liquid wood (Table 3). Arboform® resins are manufactured mechanically by mixing and tamping the components in a compounder under the absence of heat. The mechanical and technical properties include moderate thermal stability, little shrinkage, high rigidity, biodegradable functionality with wood-like aesthetics.

Table 3: Composition of Arboform® for injection moulding processing. Retrieved from Hu (2002).

Composites	Origin	Percentage (%)
Kraft lignin	Industrial residue	30
Hemp fibre	Agriculture	60
PLA	Agriculture	10

Lignin

Lignin is naturally found in all plants, both wood and non-wood. The complex structure of lignin reinforces the plant's strength and rigidity. Lignin can account up to even more than 35% of the plant's weight, resulting in lignin to be highly abundant and available. Annually, large numbers of lignin are extracted by plant and wood processing industries such as Kraft pulping, soda-anthraquinone pulping, sulphite pulping among others. The paper industry alone generates about 50 million tons annually (Chen, 2015; Bernier, Lavigne and Robidoux, 2012; Hu, 2002). Unfortunately, its complex composition causes lignin to be considered as a by-product with little to no commercial potential. At present, it is mostly reused as a low-value energy source through combustion to generate heat which is recirculated into the pulping process. Nevertheless, lignin offers many benefits from an environmental perspective for green chemical and polymer applications (Bernier, Lavigne and Robidoux, 2012). For example, including lignin into polymer composites is an excellent strategy to valorise lignin while promoting product sustainability and responsibility. Arboform® is an example of a bio-based composite that includes lignin as one of its main components (Hu, 2002).

Within Arboform® composites Tecnaro aims to integrate about ten sources of lignin. However, the exact sources and types are unknown within this project as Tecnaro was not able to share this information. Considering Kraft pulping accounts for approximately 85% of all lignin extracted by industrial processes, lignin used for Arboform® production is assumed to be Kraft lignin (Chen, 2015). Kraft pulping is a method to produce pulp from coniferous wood. During this process, wood is digested and washed, resulting in the dissolvement of lignin in black liquor. Subsequently, the lignin is extracted through a multistep process, including precipitation using liquid CO_2, filtration and washing (Chen, 2015; Bernier, Lavigne and Robidoux, 2012). Obtained Kraft lignin can readily be used for polymer applications without prior chemical treatment (Bernier, Lavigne and Robidoux, 2012).

Hemp

Arboform® composites consist of 60% from hemp fibres (Hu et al., 2002). Hemp fibres are separated from the herbaceous hemp plant *Cannabis sativa*. Hemp is an annual plant that can supply high yields (7-20t/ha) under a wide range of climates and soil compositions (Barth and Carus, 2015; González-García et al., 2010; Zampori, Dotelli and Vernelli, 2013). Cultivation of hemp requires multiple operations such as ploughing, harrowing, fertilisation, sowing, threshing, cutting, windrowing and baling (Zampori, Dotelli and Vernelli, 2013). As natural predators for hemp are somewhat limited, the addition of pesticides can be avoided (González-García et al., 2010). Regions with a minimum annual rainfall between 400 and 900mm allow hemp to be cultivated in the absence of irrigation practices (González-García et al., 2010; Amaducci and Gusovius, 2010). After harvesting, a scutching process is used to separate hemp fibres from the woody core. The fibre content in hemp varies between 20 and 33% (González-García et al., 2010; Zampori, Dotelli and Vernelli, 2013). Interest for hemp fibre is growing due to the numerous possible industrial applications and the described potential environmental benefits such as renewability and bio-degradability. As a result, the hemp fibre market is growing continuously. In particular, market growth is driven by applications in polymer, automotive, construction and thermal insulation industries.

PLA

In order to achieve enhanced thermoplastic properties, Tecnaro uses polymers as additives. According to Hu et al. (2002), PLA is often used as an additive in Arboform®. Hence, PLA will be included to simulate and analyse the environmental impact. (For more information, please see PLA under 3.4.1)

3.5 Life Cycle Assessment – a tool to quantify environmental trade-offs

Bio-based materials are often described to be a better alternative to reduce the environmental impacts of products and goods. Nevertheless, their extraction, production and end-of-life also require processing inputs such as energy, land and materials which can result in specific negative impacts on the environment (Viesturs and Melece, 2014; Broeren et al., 2017). Hence, to be able to identify the genuine environmental advantage of bio-based plastics compared to their well-established petroleum-based counterpart serving the same societal function, it is of high relevance to investigate their life cycle to quantify their impact.

At present, there are multiple tools available to investigate material and energy flows as well as socio-ecological and techno-economic analysing methods aiming to quantify the environmental impact of product and activities. Life Cycle Assessment (LCA) is one of the most, if not the utmost, used method to analyse and quantify environmental trade-offs and benefits of products. During an LCA study, life cycle activities are investigated in order to determine potential environmental impacts as a result of the life cycle activities (Vink et al., 2003). Results obtained by an LCA should however not be considered as a prediction of the environmental impact, but as the potential impact imposed on the environment by a specific activity. The results do also not represent any relation with global guidelines or safety references (Hauschild, Rosenbaum and Olsen, 2018).

An LCA analysis is an iterative process comprising four main stages which are established by the International Organization of Standardization ISO14040:2006/ ISO14044:2008 (Figure 6Figure 5). These seek to set up guidelines to ensure LCA results are consistent and reliable (La Rosa et al., 2013).

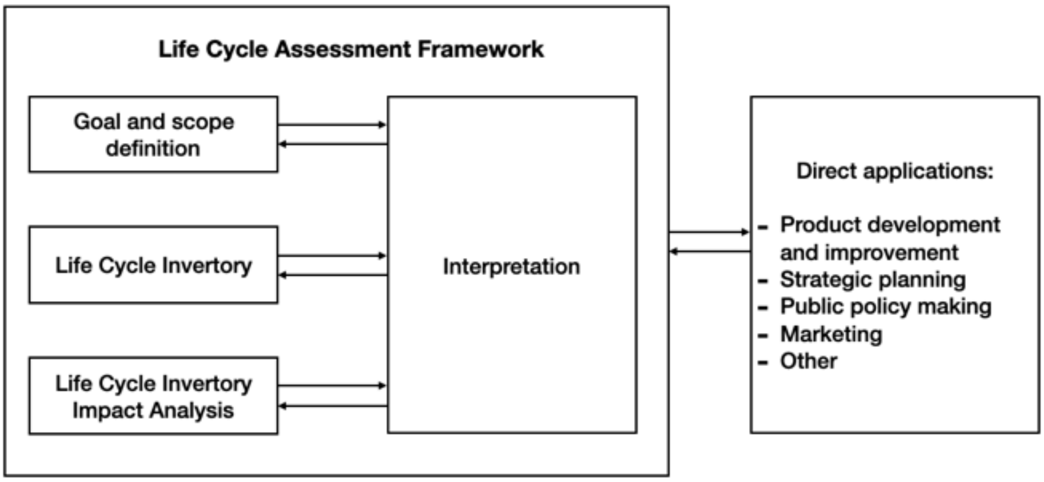

Figure 6: Stages of a Life Cycle Assessment. Adapted from Vink et al. (2003).

During the first stage, the Goal and Scope of the assessment are defined, which includes a general description of the project and system analyses. In order to compare different products that serve the same purpose, a functional unit must be defined, serving as a reference in terms of quantity for the studied products, 1kg of Solanyl® granules for example. This stage also includes establishing the system boundaries, reporting the activities that are integrated into the analysis. Ideally, LCA takes into account the entire life cycle, starting at the extraction of raw materials and ending at the disposal stage. Nevertheless, it is also possible to focus more on specific stages of the life cycle such as the production of products (cradle-to-gate) or resins (cradle-to resin)study (Figure 7) (Vink et al., 2003; La Rosa et al., 2013).

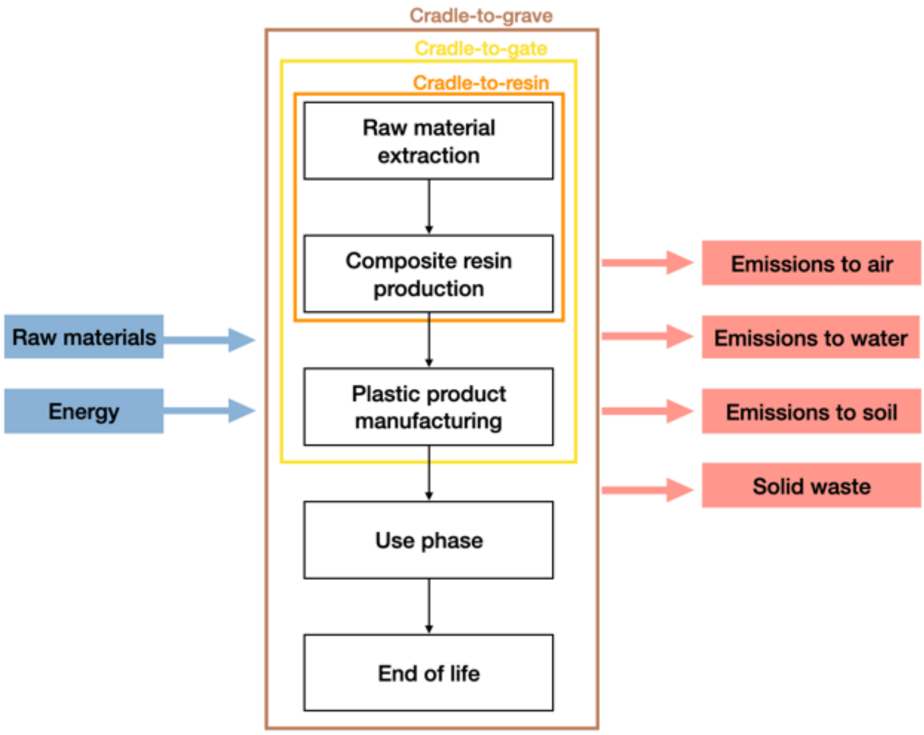

Figure 7: Simplified flow chart of the life cycle activities of plastic products. Cradle-to-grave (borwn) indicates the entire life cycle starting with extraction of raw materials and ending at the end-of-life of a certain product; Cradle-to-gate (yellow) indicates the life cycle activities required to produce a certain product; Cradle-to-resin indicates the life cycle activities that are required to produce resins or granules of plastics (Vink et al., 2003).

The second stage consists of developing a Life Cycle Inventory (LCI) in order to determine all inputs and outputs between the techno-and biosphere by performing data collection and data calculation on both energy and mass balances as well as environmental interventions that take place within the system boundaries (Figure 7). Life-cycle activities may generate multiple outputs, i.e. multi-functional processes, in such cases the environmental impact must be allocated proportionally to the outputs. The ISO standards (ISO 14040:2006/14044:2008) suggest, if possible, to allocate environmental burdens based on physical properties such as mass or energy input. If this is not possible, it is suggested to allocate the environmental burdens based on economic values (Vink et al., 2003; Zampori, Dotelli and Vernelli, 2013).

The third stage consists of the Life Cycle Impact Assessment (LCIA) which quantifies the potential environmental impact of the activities occurring within the systems boundaries using the data collected in the LCI. These results are assembled and classified to one or multiple environmental indicators such as climate change, ecotoxicity, acidification and eutrophication among others, in order to determine and compare the environmental impact of the studies life-cycle activities. The selection of impact categories, comprising the environmental indicators, is a mandatory process according to the ISO standards. In addition to classification, it is also compulsory to conduct a characterisation step. Here a characterisation factor, representing a standard unit such as CO_2-eq for example, is used to calculate the contribution of a process to the impact category. Furthermore, three optional steps can be performed within the LCIA: normalisation, grouping and weighing.

The fourth stage is the interpretation of the LCA results in order to identify opportunities to enhance a product's sustainability throughout the life-cycle activities. Recommendations can be established based on the interpretation of the results.

4. Goal and scope

This study will entail two main deliverables: the LCI and the LCIA (European Commission, 2010). First, the LCI reports the energy and material flow as well as the emissions and solid waste considered in the impact analysis for the production of the resins. The LCI also includes all the consulted data sources and reasoning behind calculated data. Second, the LCIA which translates the LCI into quantitative results for environmental impacts which are interpreted subsequently. In order to produce the LCI and LCIA, a goal and scope must be defined. This section will provide more information regarding the goal and the scope.

The goal describes the aim of the analysis along with specified conditions for the use of this project are reported. Afterwards, the scope of the study is reported, which includes details about the system boundaries and functional unit, data quality, allocation procedures and impact methodologies(European Commission, 2010).

4.1 Goal

The goal of this project is to conduct a cradle-to-resin analysis of Solanyl® and Arboform® in order to compare them with PS in terms of environmental performance. Therefore, the study includes the life-cycle activities related to the extraction of raw materials, manufacturing of materials and manufacturing of the composite resin as well as all required transportation activities. The objectives of the analysis are to identify the environmental benefits and trade-offs of the materials, which will be used to compare the Solanyl®, Arboform® and PS.

4.1.1 Commissioner and influential actors to this study

This study is commissioned by b-token, a company producing plastic tokens and other festival gadgets. They are in charge of multiple processes such as procuring materials such as thermoplastic resins and energy, mould the resins into the desired shape and sell the products. Other relevant parties that influence the study are the suppliers for the resins and other raw materials, especially Rodenburg Biopolymers and Tecnaro. Considering, the fact that this study is developed as part of a master's thesis project, supervisors and teaching assistants supervising and supporting the execution of this study are considered relevant influencing parties.

4.1.2 Indented audience

The commissioner of this study is b-token. Therefore, the intended audience of this study is the internal audience of b-token, meaning the company and its employees. Seeing the study makes part of a master's thesis project at Aalborg University, supervisors and teaching assistants are also considered part of the indented audience.

A second external party must critically review projects conducted for comparative purposes before being published according to the ISO standards 14040:2006. Hence, this report cannot be disclosed to a broader public than the indented audience mentioned above without being reviewed externally.

4.1.3 Applications and use of cradle-to-resin results

b-token is currently on an ambitious journey to become a sustainable company. The impact results described within this report are compared against the conventional alternative PS. Based on these findings, some recommendations are proposed. This cradle-to-resin study is intended to serve as a guideline for b-token in order to improve the environmental performance of their products by improving their product development and make strategic choices. Hence, it is intended to provide micro-level decision support (European Commission, 2010).

4.1.4 Assumptions and limitations

The chosen methodology combined with the made assumptions yields certain limitations to the usability and transferability of the results. In order to be as transparent as possible, all technical assumptions made throughout this study are mentioned in the according system modelling section in chapter 5.2.

4.2 Scope

In order to carry out the LCI and LCIA, the product system must be defined. Detailed information regarding the defined product system and impact methodology is provided below.

4.2.1 Functional unit

The functional unit serves as a reference unit to compare the different studied products or materials that intentionally share the same purpose or function. The functional unit in this study is defined as the production of one kg of resins, meaning that one kg of Arboform® resins and one kg of Solanyl® are analysed. The obtained results can then be compared to the indicative LCI and LCIA results of one kg of PS resins obtained directly from the Ecoinvent databases provided by SimaPro.

As a specific functional unit, indicating both quality and quantity can be defined in this study, a reference flow is not require (European Commission, 2010).

4.2.2 System boundaries

The system boundaries indicate all the life-cycle activities studied. All essential processes are determined in order to represent the cradle-to-resin life cycle correctly and map all impacts on the biosphere correctly. These can be summarised into:

1) Resource extraction or cultivation,
2) Transportation of resources to processing facilities,
3) Processing of resources into "intermediate polymers",
4) Transport intermediate products to the central resin production site,
5) Compounding of intermediate polymers into composite resins.

Since this is a comparative study, more precise details on the system boundaries of the studied composites are provided below.

Specific system boundaries for the cradle-to-resin study of Solanyl®

Figure 8 represents a simplified overview of the life cycle activities that are included in the LCI study. These include the following:

1) *Reclaimed starch:* Processing of starch-rich wastewater to achieve reclaimed starch, all energy and materials required for transport and evaporation are included. The cut-off rule is applied to reclaimed starch, meaning all environmental burdens are allocated to the primary product while the recyclable material is considered burden-free. This is done because it is assumed that potato cultivation and processing is driven and will be so in the foreseeable future by the demand for potato products and not starch wastewater (Broeren et al., 2017).
2) *PLA production*: All materials and energy used for crop growing, PLA production and transport are included.
3) *Glycerol:* The inventory data begins with the extraction of all raw materials and energy production in order to produce glycerol. Transport from the production site to the central location is included.
4) *Extrusion:* The extrusion process heats and mixes the components into homogeneous resins.

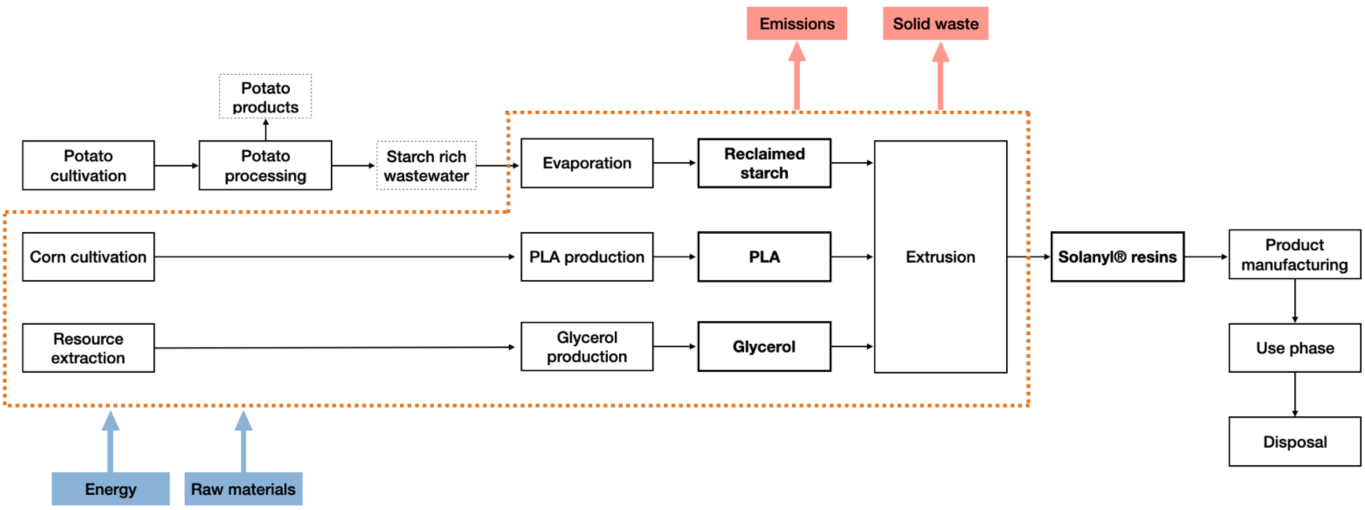

Figure 8: Simplified flow chart of the life cycle activities of Solanyl®. The orange dotted lines indicate the activities included in the systems boundaries. Adapted from Broeren et al. (2017)

Specific system boundaries for the cradle-to-resin study of Arboform®

Figure 9 represents a simplified overview of the life cycle activities that are included in the LCI study. These include the following:

1) *Lignin:* Processing of lignin-rich black liquor obtained from pulp processing to gain lignin. The cut-off rule is applied to lignin as it is assumed that the demand for wood and pulp products is driven and will be so in the foreseeable future by the demand for paper and not for lignin.
2) *PLA production:* All materials and energy used for crop growing, PLA production and transport are included.
3) *Hemp fibre production:* All materials and energy used for hemp cultivation, processing and transport are included.

4) *Compounding:* The compounding process that tamps and mixes the components into homogeneous resins.

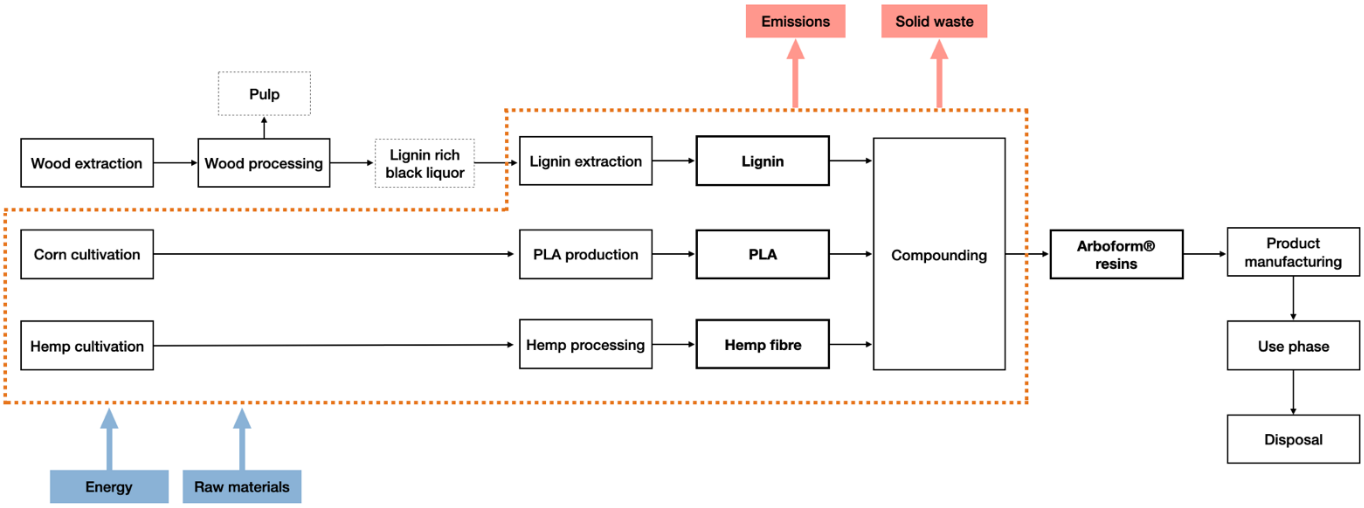

Figure 9: Simplified flow chart of the life cycle activities of Arboform®. The orange dotted lines indicate the life-cycle activities included in the systems boundaries. Adapted from Broeren et al. (2017)

<u>*Specific system boundaries for the cradle-to-resin study of PS*</u>

Figure 10 represents a simplified overview of the life cycle activities that are included in the LCI study. These include the following:

1) *Fossil fuel extraction:* Extraction of oil and gas, including transportation to processing plants.
2) *Oil refinery:* Processing oil and gas into intermediate products or monomers.
3) *Polymerisation:* Polymerising the monomers into polymers and compounding the polymers into resins.

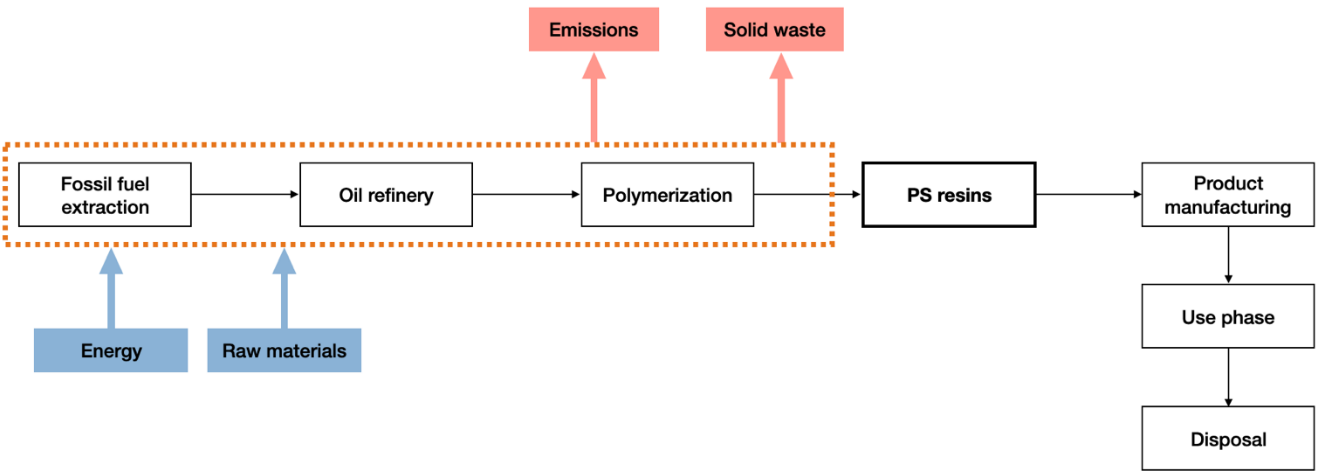

Figure 10: Simplified flow chart of the life cycle activities of PS resins. The orange dotted lines indicate the life-cycle activities included in the systems boundaries. Adapted from Broeren et al. (2017)

4.2.3 Allocation of impacts in multi-functional processes

Some included processes are multi-functional, meaning they have multiple outputs. In such cases, the allocation is preferably done in respect to physical properties as suggested by ISO 14040:2006. Therefore, in this study allocation of environmental burdens is done based on mass composition.

4.2.4 Data sources and data quality

In order to generate a complete and representative study, a variety of data derived from multiples types of sources is included. Therefore, it is essential to consider the data quality as it reflects the accuracy, completeness, precision and representativeness of the created inventory (European Commission, 2010). Primary datasets, provided by the developer or operator, are often preferred for product-specific unit processes. Nevertheless, secondary datasets provided by peer-reviewed scientific journals and databases such as Ecoinvent 3.5 are very valuable to provide missing or uncertain data. Moreover, as these datasets have been reviewed before, it facilitates the review process, which is considered an advantage (European Commission, 2010).

In this study, primary data is used when available. This is mainly for Solanyl® at the central point of production (compounding). Data regarding the extraction of raw materials, manufacturing of components and transport is retrieved from secondary databases (literature and Ecoinvent 3.5) which are selected to match geographical, temporal and technological aspects as much as possible. However, it is not always possible to find data for all required inputs, so certain assumptions are made where necessary.

4.2.5 Biogenic carbon uptake and product carbon footprint

Biogenic carbon is referred to when discussing atmospheric CO_2 removed during the biomass growth and cultivation phase (Broeren et al., 2017). The ISO standards regarding product carbon footprint state that biogenic carbon removal must be mentioned in the study (ISO 14067:2018). Especially since this is a cradle-to-resin study biogenic carbon uptake should be mentioned as it is of relevance for future applications within the value chain (ISO 14067:2018). Therefore both gross GHG emissions (CO_2 equivalent) as well as net GHG emissions are reported.

4.2.6 Life Cycle Inventory Impact Assessment – Impact categories

In order to assess the LCI, two methods have been selected: ReCiPe and Cumulative Energy Demand. These are selected as together they provide a broad range of impact categories that can be analysed.

ReCiPe

First, the Global ReCiPe (2016) methodology is used to analyse the life cycle impact in this study. This methodology offers different perspectives to analyse the impact based on societal paradigms of human behaviour. In this study, it is chosen to work with the hierarchist (H) perspective since it considers the most common policies and principles of human behaviour (PRé, 2019). ReCiPe investigates 18 impact categories at midpoint or problem-oriented level. The obtained scores are characterised to standard units representing the contribution of the bioplastics or PS to the impact categories. After that, the scores are normalised to a reference value. Both internal and external baselines are used to normalise the impact results.

The ReCiPe methodology enables to harmonise the midpoint scores into endpoint scores representing the potential damage caused to human health, ecosystems and resources. These results are likewise characterised and normalised. In addition, a weighting step is conducted in order to allow a better comparison. These results should be consulted with a careful eye as the result can be biased due to the applied weighting factors (ISO 14040:2006).

An overview of all impact categories along with their characterisation factors included in ReCiPe is provided in Table 21 in appendix A. Although all impact categories are of importance when studying the environmental impact, some are identified as immediately relevant in this study.

Global warming potential is considered one of the most relevant categories as bio-based plastics are described as an effective strategy to reduce GHG emissions caused by plastic production and processing (Zheng and Suh, 2019). Fossil resource scarcity is identified as relevant as bio-plastics could decouple plastics from fossil fuels. However, it is essential to investigate if the reliance on finite resources is not shifted from fossil resources to mineral resources such as phosphate rock, used to manufacture phosphate fertilisers, which is classified as critical raw material by the European Commission in 2014 (European Commission, 2014). Land use and transformation are considered of much relevance, as mentioned by Broeren et al. (2017) because increased land use and transformation are important trade-offs of bio-based plastics.

Likewise, water use is considered of high relevance since bio-based plastics could be responsible for up to 18% of the global water consumption, according to Putri (2018). Eutrophication in both marine and freshwater bodies is also identified as immediately relevant since badly-managed fertiliser use results in fertiliser leachate, affecting the nutrient balance. The excess of nutrients stimulates excessive growth of algae that damages the ecosystem (Broeren et al., 2017). Those fertilisers also interact with the soil components resulting in acidification. For this reason, terrestrial acidification is directly identified as relevant. Industrial processes and products release and emit substances that can act as stressors on ecosystems and therefore be environmentally hazardous (National Research Council, 2014). Considering this, ecotoxicity, may it be to terrestrial, marine or freshwater ecosystems, is identified as highly relevant. Finally, these environmental stressors may also be hazardous to human health. Consequently, both carcinogenic and non-carcinogenic toxicity are identified as important impact categories in this study (National Research Council, 2014).

Cumulative energy demand

Cumulative Energy Demand (CED) is a methodology that enables the calculation of both direct and indirect energy sources used to manufacture a product. Since non-renewable energy derived from fossil resources is often reported to be a significant contributor to the environmental impact of a product, analysing the energy demand and energy sources used to produce the products of interest is assumed to be relevant (Huijbregts et al., 2010). CED is used as a secondary and complementary methodology to investigate and compare the environmental performance of the studied plastics.

4.2.7 Sensitivity analysis

In order to quantify the influence certain uncertainties or assumptions have on the results, a sensitivity analysis is conducted. Here different scenarios are simulated in order to determine the difference in obtained results, which are represented as percentages.

It is considered that a change of 20% or more indicates that the uncertainty imposes a significant influence on the impact category in question. In addition, if the average change is more than 15%, then is considered that the uncertainty imposes a significant influence on the entire analysis.

4.2.8 Requirements

Specific requirements for comparative assertions

In order to enable comparison between two or more cradle-to-resin studies, they must be conducted in a similar manner. Hence, the must have the same functional unit and system boundaries that entails similar life cycle activities. Then, the allocation method and data quality must be similar as well. Finally, the same database and LCAI methodologies must be used (Vink and Davies, 2014; ISO 14040 :2006).

Need for critical review

As mentioned in 4.1.2, this study is intended for internal use only. Therefore, a critical review is no requirement. Must b-token decide to disclose this study publicly, an external review will be required (ISO 14040:2006/ISO 14044:2008).

5. Life cycle inventory

The following chapter entails details and reasoning behind the data collection and LCI. The production processes of both bio-based plastics will be discussed separately in different sub-sections.

5.1 Data collection

Defining all data inputs required to calculate the LCI correctly and accurately requires data collection processes. Where possible primary sources are used, otherwise peer-reviewed literature and the database Ecoinvent 3.5 are used to collect the data for all processes. Due to the variation of sources used for the process units, some questions regarding quality might arise. Therefore all data types and quality for each unit process are summarised in Table 22 in appendix B.

5.2 System modelling

In this section, each modelled process is explained shortly. Specific data included in the study and the reasoning behind it are mentioned as well.

At first, each component/process Solanyl® is described. Then idem is done for Arboform®. At last, the selected inventory data for PS is mentioned, which is intended for comparing Solanyl® and Arboform® later on. In appendix D, an overview of all selected inventory data is presented for each type of resin.

5.2.1 System overview – Solanyl®

This section will entail detailed information regarding the processes to produce the components as well as the process required to manufacture Solanyl® granules. Table 4 represents an overview of the assumptions made which are explained in detail. An overview of all inputs selected and inserted in SimaPro to simulate the production and analyse the environmental performance is presented in Table 29 in appendix D.1.

Table 4: Overview of assumptions made to model and simulate the production of Solanyl® resins.

Components	Assumptions
Solanyl	1) The composition is as mentioned in 3.4.1, 2) Biogenic carbon content is 67% (Broeren et al., 2017), 3) Material losses during compounding are neglectable (Broeren et al., 2017), 4) Electricity for extrusion processes is 0.54 kWh/kg (Kent, 2018), 5) Electricity used for the extrusion process is assumed to be of medium voltage.
Starch	1) The demand for potato products drives potato cultivation and processing. Therefore, environmental impacts related to these processes are allocated to potato products and not to starch wastewater (Broeren et al., 2017), 2) Potato cultivation and processing will remain to be driven by the demand for potato products in the foreseeable future (Broeren et al., 2017), 3) Evaporation of water has a 40% efficiency rate (Broeren et al., 2017), 4) Evaporated water is released to the atmosphere, 5) Biogenic carbon uptake is 1.63 kg $CO_2/kg_{[starch]}$ (Stoichiometrically derived from chemical formula $C_6H_{10}O_5$),

	6) Transport distance is estimated to be 50 km by truck (local suppliers – confirmed by Rodenburg Biopolymers).
PLA	1) PLA production system can be compared to the PLA production system described by Natureworks (Vink and Davies, 2015) 2) Biogenic carbon uptake is 1.83 kg $CO2/kg_{[PLA]}$ (Vink and Davies, 2015), 3) Transport of PLA for Rodenburg Biopolymers is estimated to be 192 km (supplier: Natureworks; Truck: lorry 7.5-16tons [euro4]), 4) Transport of PLA for Tecnaro is estimated to be 319 km by truck (supplier: Biotec; Truck: lorry 7.5-16tons [euro4]).
Glycerol	1) Glycerol is used as an additive (3.4.1), 2) Glycerine is similar to Glycerol (Ecoinvent 3.5).

Starch

Starch used for Solanyl® is reclaimed starch obtained from potato processing facilities. These facilities slice potatoes to produce potato products like fries which generates starch-rich wastewater as a by-product. The wastewater contains approximately 2.5% dry solids of starch, which is in turn concentrated to 40% moisture content through centrifugation. Thereafter, the reclaimed starch (60% dry solids) is transported to the central plant, Rodenburg Biopolymers, where it is further concentrated to 18% moisture content through evaporation, which is the final state before being mixed with the other components (Broeren et al., 2017).

Inputs *(All inputs and outputs are for one kg of reclaimed starch)*

All impacts related to the cultivation and processing of potatoes are considered outside the system boundaries and are thus cut-off. Likewise, the impacts related to the centrifugation step as it is considered part of the wastewater treatment process required before discharging the wastewater at the potato processing plant (Broeren et al., 2017). In order to obtain an 18% moisture content evaporation of water is done. Here it is assumed that there is a 40% efficiency rate and that natural gas is used as an energy source to generate the heat. Therefore, for every kg of reclaimed starch, 2.36 MJ heat is included in this unit (Broeren et al., 2017). This unit is provided by the database Ecoinvent 3.5. The average transport distance of the reclaimed starch is estimated to be 50 km (onternal communication with Rodenburg Biopolymers). Therefore, 0.08 tonne kilometre (tkm) by truck (>32 metric ton, EUR 4), provided by the database Ecoinvent 3.5, is included in this unit process (Table 29 in appendix D.1.).

Outputs

The evaporated water is assumed to be released into the atmosphere. Therefore air emissions of 220 g of water vapour are included in this unit process. The selected unit in Ecoinvent 3.5 provides all other outputs, including both emissions and solid wastes, related to the production of heat. The emissions and wastes related to the transport process are likewise provided by Ecoinvent 3.5 (Table 29 in appendix D.1.).

PLA

Natureworks, PLA manufacturer in the Netherlands, provides a highly detailed eco-profile regarding the production of PLA which is also available in Ecoinvent 3.5. The eco-profile is based on the PLA production of Cargill Dow. Seeing Natureworks also produces and sells PLA in the Netherlands, the eco-profile is adapted to fit global studies. The eco-profile provides all the inputs and outputs related to the five process units required to manufacture PLA resins: Cultivation of corn, transport to PLA factory, corn processing to obtain starch and conversion to dextrose, fermentation of dextrose in lactic acid, process to convert lactic acid into lactide prepolymers and finally polymerisation of lactide prepolymers into PLA granules (represented in Figure 11). Furthermore, the eco-profile provides all inputs and according output related to the operating supplies or chemicals. It is therefore assumed that this eco-profile provides all necessary data and is reliable to integrate into this study. No further calculations are made to generate data around PLA production.

Inputs

As mentioned above, all inventory data for this unit process are included in the PLA unit provided by Natureworks in Ecoinvent 3.5. Only, the transport from Natureworks to the central plant is included separately. The average transport of the PLA resins from their manufacturing site to the central plant is assumed to be 192 km, which is the distance from Natureworks to Rodenburg Biopolymers. In SimaPro, an input of 0.08 tkm by truck (7.5-16 metric tons, EUR4) is included (Table 29 in appendix D.1.).

Outputs

All related outputs to PLA production are included in the selected unit. Therefore, no further emissions are included. Likewise, all outputs caused by the transport process are included in the selected unit in the database Ecoinvent 3.5 (Table 29 in appendix D.1.).

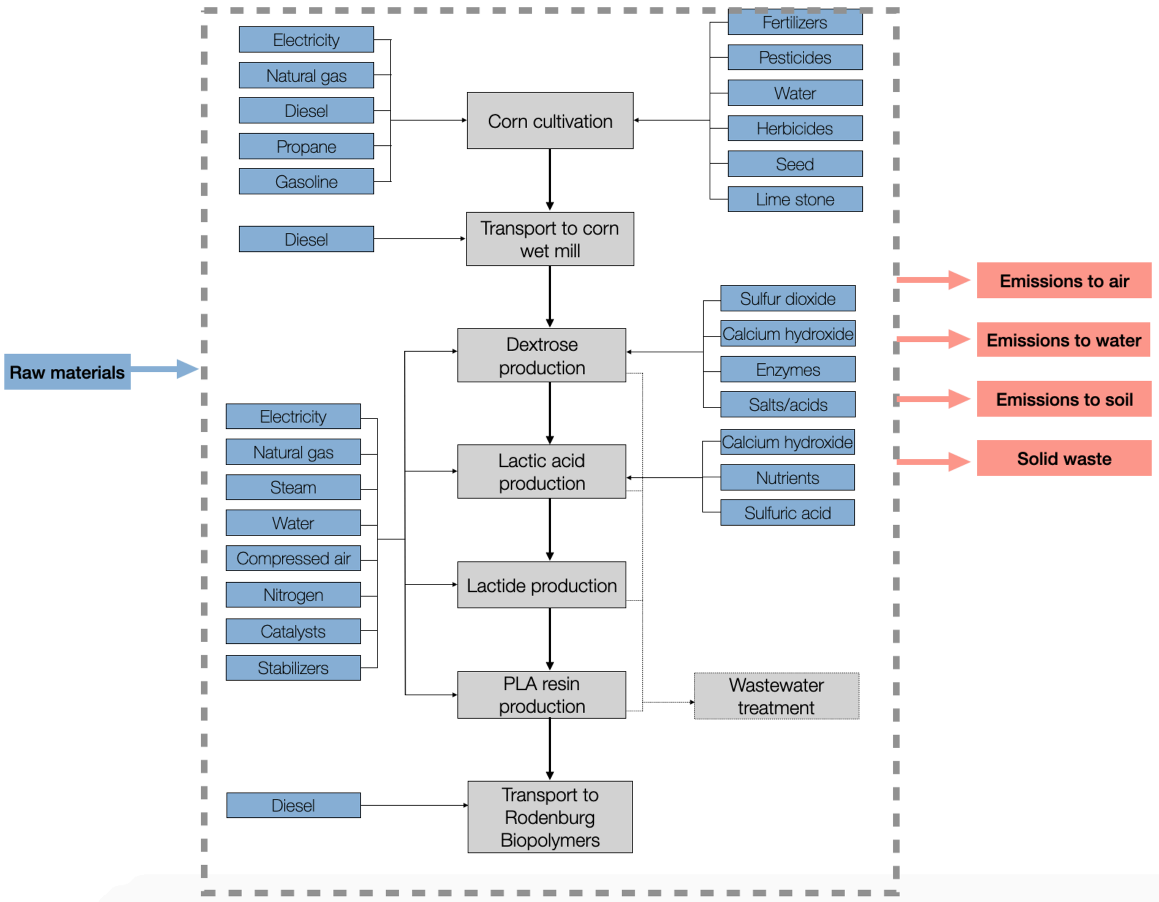

Figure 11: Flow diagram of all process units included in the PLA eco-profile provided by Natureworks. Adapted from (Vink and Davies, 2015)

Glycerol
The inventory data for glycerol is entirely provided by Ecoinvent 3.5. It includes all the inputs and outputs according to the activities to produce glycerol in the European Union. Average transportations distances to central locations in Europe are included. No additional transportation process is included.

Extrusion
When all components are supplied to the central plant, they are compounded in an extruder. The extruder mixes the components homogeneously under heat and shear conditions and cuts the mixture into resins. The electricity consumption required for this process is provided by Kent (2018) and is 0.54 kWh, including both electricity for the extrusions process as well as electricity required for site-conditioning (lightning, heating and cooling, among others).

Inputs
In Ecoinvent 3.5, the inventory data for medium voltage electricity from the Dutch specific energy mix is selected. Here the amount is set to 0.54 kWh (Table 29 in appendix D.1.).

Outputs
Emissions and wastes as a result of the electricity production and delivery are included in the life cycle inventory data selected in Ecoinvent 3.5 (Table 29 in appendix D.1.).

5.2.2 System overview – Arboform®

This section will entail detailed information regarding the processes to produce the components as well as the process required to manufacture Arboform® granules. Table 5 represents an overview of all assumptions made. An overview of all inputs selected and inserted in Simapro is presented in Table 30 in appendix D.2.

Table 5: Overview of assumptions made to model and simulate the production of Arboform® resins.

Components	Assumptions
Arboform®	1) The composition is as mentioned in 3.4.2. 2) Biogenic carbon content is 53.6% (calculated from mass composition and biogenic carbon uptakes), 3) Material losses during compounding are neglectable (Broeren et al., 2017), 4) No pre-treatment of components (lignin and hemp) are required before mechanical compounding, 5) Energy for compounding processes is 0.53kWh/kg (Kent, 2018).
Hemp	1) Cultivation production is 13 ton/hectare (Zampori, Dotelli and Vernelli, 2013), 2) Composition is 75% woody core, 20% fibre and 5% dust (Zampori, Dotelli and Vernelli, 2013), 3) Biogenic carbon uptake is 1.83 kg $CO_2/kg_{[hemp]}$ (Zampori, Dotelli and Vernelli, 2013), 4) Transport distance is estimated to be 107 km by truck (supplier: Bafa Neu GmBh; Truck: lorry 7.5-16tons [euro4]), 5) No pesticides are required for hemp cultivation (González-García et al., 2010), 6) Fertiliser emissions are based on general assumptions without considering site-specific factors such as soil composition, slope, water contents etc. (Stoessel et al. 2012), 7) Environmental impact of seeds is estimated to be 4.85% of the impact of hemp cultivation (Van Eynde, 2015)

	8) During the retting process, 10% of the stem (woody core) is digested (Van der Werf and Turunen, 2008), 9) The woody core contains 0.0095% N (Liu, 2013).
Lignin	1) Kraft lignin is used, 2) Processing of soft-and hardwoods will remain to be driven by the demand for paper and other pulp applications in the foreseeable future (Bernier, Lavigne and Robidoux, 2012), 3) Biogenic carbon uptake is 2.3 kg/kg$_{[lignin]}$ (Bernier, Lavigne and Robidoux, 2012), 4) Transport distance is estimated to be 106 km by truck (supplier: Stora Enso; Truck: lorry 7.5-16tons [euro4]), 5) For every kg of lignin extracted three kg of pulp are produced (Bernier, Lavigne and Robidoux, 2012), 6) Electricity used for filtration is medium voltage from German energy mix in 2014.
PLA	1) PLA production system can be compared to the PLA production system described by Natureworks (Vink and Davies, 2015), 2) Biogenic carbon uptake is 1.83 kg CO2/kg$_{[PLA]}$ (Vink and Davies, 2015), 3) Transport of PLA for Tecnaro is estimated to be 319 km by truck (supplier: Biotec; Truck: lorry 7.5-16tons [euro4]).

Lignin

Lignin in this study is assumed to be derived from the Kraft pulping industry where it is considered a by-product with little value. As it is assumed that demand for wood processing will continue to be driven by the demand for paper and other pulp applications and not for the demand for lignin, only impacts related to the extraction of lignin are included in this study. More specifically, this means the lignin-specific processes are included, whereas pulp-specific processes are ignored. Impacts related to common processes are allocated proportionally to lignin or pulp by physical relationships (Figure 12) (Bernier, Lavigne and Robidoux, 2012). The lignin-extraction happens through an acidification process of the lignin-rich black-liquor, generated by digesting and washing wood, by adding CO_2. Lignin present in the black-liquor is then precipitated. Acidification of the mixtures causes a release of H_2S which is in turn neutralised by NaOH in a scrubber. The H_2S scrubber is part of the pulp mill installation. Therefore only the NaOH used to neutralise the H_2S is allocated to the lignin extraction process. The precipitated mixture is filtered, separating the lignin from black liquor. The lignin is then washed with water and H_2SO_4 and dried producing lignin that can readily be used for polymer applications (Bernier, Lavigne and Robidoux, 2012) while the lignin-depleted black liquor is recirculated to the multi-effect boilers where steam is used to evaporate water in order to concentrate the black liquor in multiple stages.

Consequently, the concentrated black liquor enters the recovery boiler, which is used to recover certain valuable chemicals, leaving the boiler as smelt, and generate energy (, n.d.). The emissions caused by the recovery boiler are allocated to the extraction of lignin (Industrial Emissions Directive 2010/75/EU, 2015). The wastewater generated after the washing step is treated with $CaCO_3$ to neutralise any H_2SO_4 present. As wastewater treatment is part of the pulping process, only the required $CaCO_3$ is allocated to this study. It is assumed that woody plants take up 2.3kg of biogenic CO_2 to accumulate one kg of lignin (Bernier, Lavigne and Robidoux, 2012).

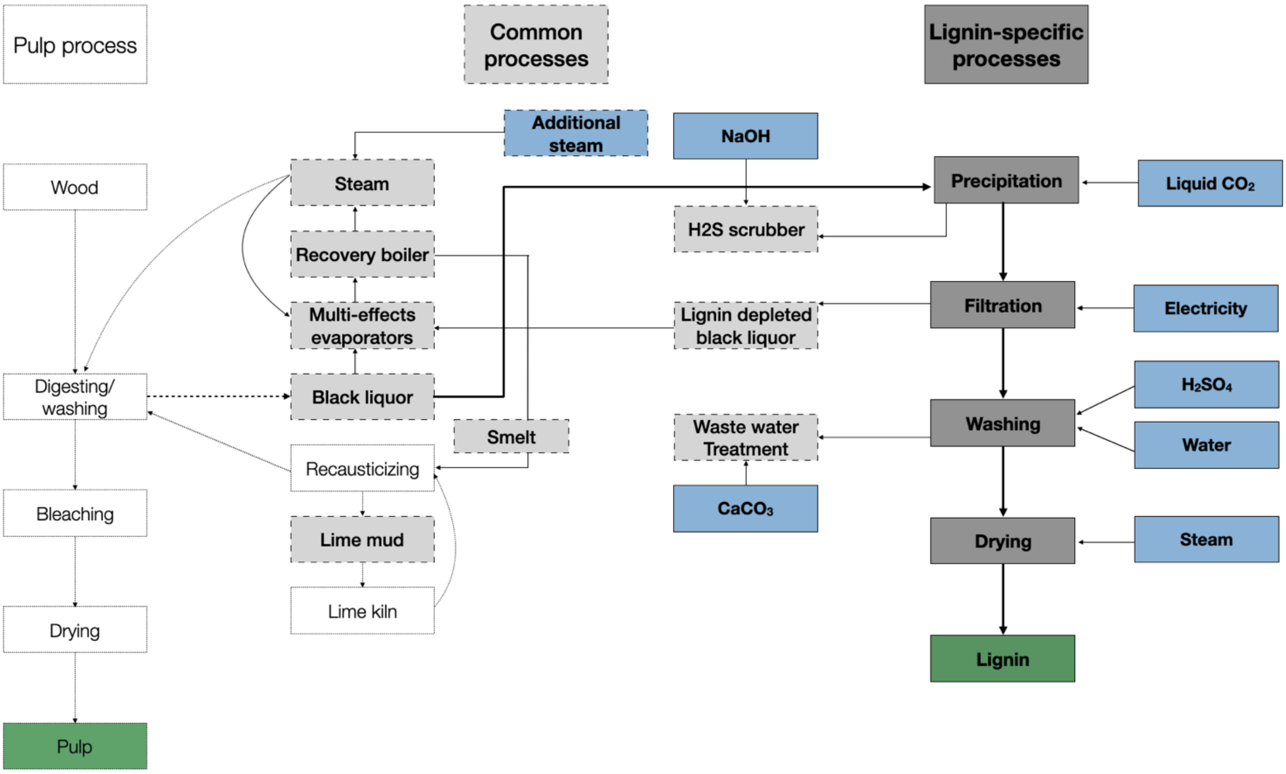

Figure 12: Simplified flow diagram representing the pulp mill processes, including the lignin extraction process. The white cases represent pulp-specific processes, the light-grey cases represent processes that are common to both, the dark-grey cases represent the lignin-specific processes, blue cases represented chemical input and green cases represent end products. Adapted from Bernier, Lavigne and Robidoux (2012).

Inputs *(All inputs and outputs are for one kg of lignin)*

Traditionally, lignin-rich black liquor is burned to produce steam which is supplied to pulp-specific processes. As lignin is extracted, steam production reduces substantially. In order to substitute the created shortage of steam, additional steam is generated using natural gas. Therefore, 31.5MJ of natural gas is included (Bernier, Lavigne and Robidoux, 2012). 0.30 kg of liquid CO_2 is included to precipitate lignin. The filtration step requires 0.010kWh, which is added from the German energy mix (medium voltage). The water and H_2SO_4 required for washing the lignin filtrate are 4.85kg and 0.230kg, respectively. Neutralising the H_2S, caused by acidifying the black liquor, demands 0.107kg NaOH. To neutralised the excess H_2SO_4 in wastewater 0.230kg $CaCO_3$ is supplied (Bernier, Lavigne and Robidoux, 2012). Finally, the average travel distance between a German Kraft pulp factory close to Tecnaro is included, which is calculated to be 0.03tkm. Finally, Bernier, Lavigne and Robidoux (2012) suggest that all chemicals required for the extraction travel on average 500km, for which an additional 0.43tkm by truck (16-32 metric tons, EUR4) is included. The biogenic CO_2 uptake is set to 2.3kg as input from nature. All mentioned inventory data are selected in Ecoinvent 3.5 (Table 30 in appendix D.2).

Outputs

The emissions and waste as a result of inventory data selected in Ecoinvent 3.5 including natural gas, liquid CO_2, H_2SO_4, NaOH, $CaCO_3$, tap water, electricity and transportations are provided by Ecoinvent 3.5 and are not further edited. However, the emissions to air as a result of the recovery boiler are estimated and included. These are 300g CO_2, 2.49g particulates (undefined), 4.08g NO_2 and 0.6g H_2S.

The reasoning and references behind the calculations are represented in Table 23 in appendix C.1. (an Overview is represented in Table 30 in appendix D.2).

Hemp fibre

Cultivation of hemp starts with preparing the soil, which includes ploughing to turn over the soils and harrowing to prepare the seedbed. Then, the prepared seedbed is supplied with fertilisers. They are added to the soil to enhance its fertility in order to stimulate the plant's growth. Thereafter, hemp seeds are dispersed over the seedbed, which is referred to as sowing (Zampori, Dotelli and Vernelli, 2013). The seeds need to be cultivated before and require a quite similar process as the hemp plant.

Hemp cultivation often begins in April with sowing taking place at the end of the month. Harvesting starts the midst of August (González-García et al., 2010). Harvesting is conducted through a combination of threshing and cutting. Afterwards, the hemp is segregated in windrows on the field to let it dew-ret and sun-dry for twenty days. Dew-retting is done to partially digest the woody core by microorganisms which facilitates the fibre extraction process. When optimal moisture content (approximately 12%) is obtained, the fibres are entirely extracted through a scutching process (González-García et al., 2010; Amaducci and Gusovius, 2010). The fibres are then baled and loaded into a truck and transported to Tecnaro for further processing. During the cultivation of hemp, no herbicides or pesticides are the supplied as hemp is quite robust against pests. No water irrigation is necessary as hemp can grow under rainfed conditions (Zampori, Dotelli and Vernelli, 2013; González-García et al., 2010; Amaducci and Gusovius, 2010). It is assumed that every ton of hemp fibre sequesters 1.83ton of CO_2 (Figure 13) (Zampori, Dotelli and Vernelli, 2013).

Inputs *(All inputs and outputs for Hemp fibre are calculated for one ton of **hemp fibre**)*

The agricultural activities are conducted by the help of a tractor with process-specific equipment attached. Based on the specific demand for all processes, the total on-farm fuel use is set to 33.5kg diesel per ton of hemp fibre production (reasoning Table 24, appendix C.2.). In addition to fuel, construction of the agricultural machinery used for this unit process is included. The value is derived from González-García et al. (2010) and set to 15.36kg. For fertilisation, it is assumed that fertilisers from mineral sources are used. The selected fertilisers are potassium chloride, ammonium nitrate and phosphate. The quantities of the fertilisers are likewise derived from González-García et al. (2010) and set to 83kg, 56kg and 43kg respectively. In addition, the average travel distance for the fertilisers of 330km or 60.4tkm is included by truck (7.5-16 metric tons; EUR4) González-García et al. (2010). The production of one tonne of hemp fibre requires 0.385ha of agricultural land under the assumption that one ha yields 13tons of hemp. After retting and sun-drying, the scutching process takes place, which separates the fibres. This process consumes 336kWh of electricity (medium voltage), which is selected to match with German energy mix in Ecoinvent 3.5. It is assumed that the hemp is provided by Bafa, one of the largest hemp producers in Europe, which is located 107km away from Tecnaro. Therefore, 0.06tkm by truck (7.5-16metic tons, EUR4) is included in the unit process. Finally, biogenic CO_2 uptake during the plant growth is set to 1.83tonnes as input from nature. All inventory data are selected in Ecoinvent 3.5.

As there is no inventory data available for hemp seed in Ecoinvent 3.5 for hemp seeds, the impacts are calculated based on the impacts of the hemp production, as both cultivation processes are similar (Table 26, appendix C.4.) (Van Eynde, 2015; González-García et al., 2010). Processes excluded here are scutching and dew-retting.

Outputs

All emissions and waste generated by both the construction and dismantling of the used agricultural machinery, the production and transportation of diesel, the production of the fertilisers, production and consumption of electricity and transportation processes are determined by Ecoinvent 3.5.

Air missions as a result of diesel combustion to power agricultural machinery are calculated based on emissions factors provided by Nemecek and Kägi (2007) which are represented in Table 25 in appendix C.3. Emissions caused by the usage of N and P fertilisers on the agricultural land are likewise calculated based on emissions factors and constant values, these are represented in Table 27 in appendix C.5. (Hutchings, Webb and Amon, 2013; Van Eynde, 2015; Stoessel et al., 2012). Air emissions generated by the digestion of organic material during the dew-retting process are similarly calculated based on N emission factors, represented in Table 28 in appendix C.5.

All emissions and waste as a result of seed production are determined through a similar approach as done for hemp fibre production.

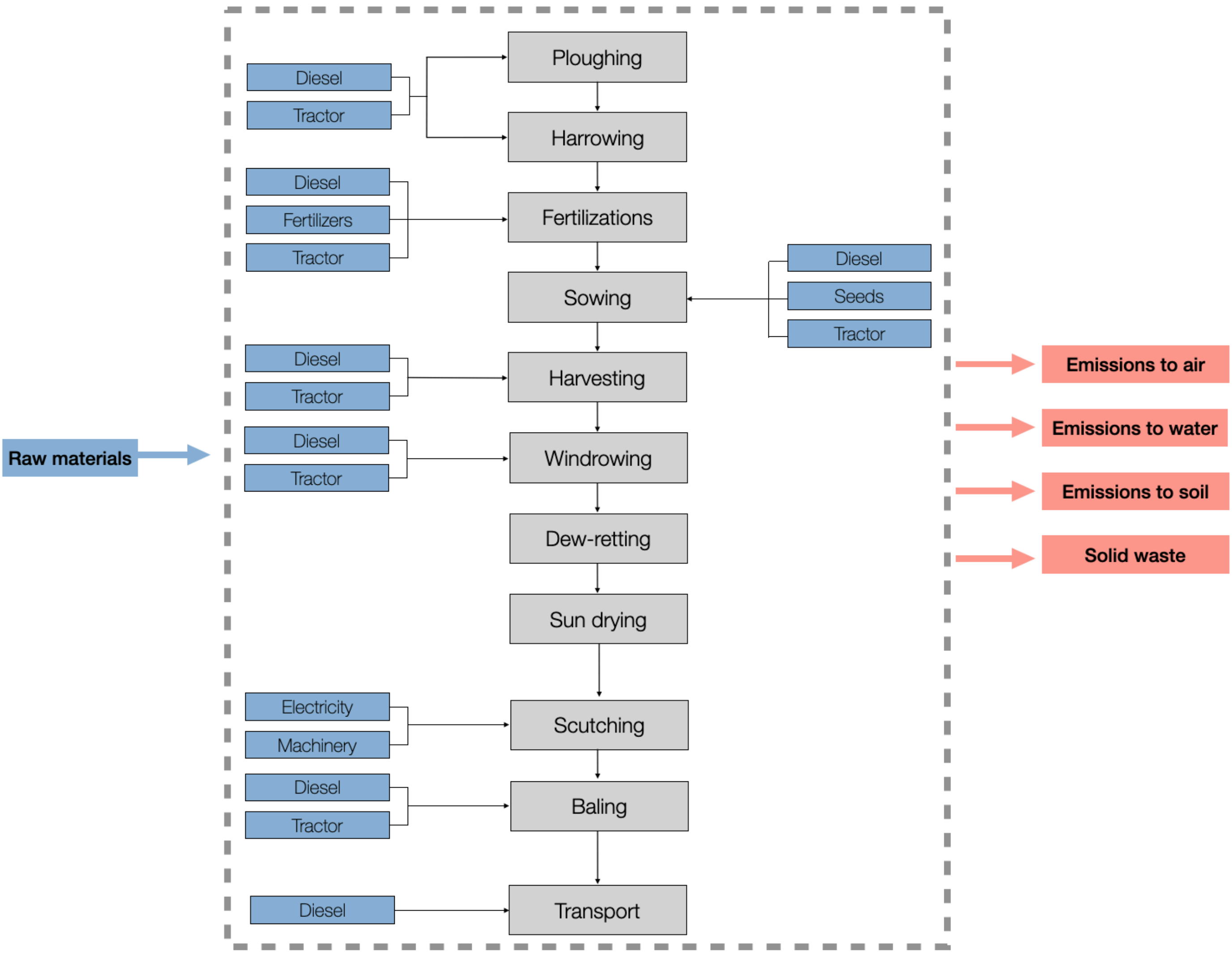

Figure 13: Flow diagram representing the unit processes included to produce one ton of hemp fibre.

PLA

The provider for PLA is assumed to be the same as for Solanyl®. The only difference is the distance the PLA resins are transported. The average travel distance is calculated to be 319km, which is the distance between Natureworks and Tecnaro. Therefore, 0.00319tkm by truck (16-32metric tons, EUR4) is included in this process unit.

Production of Arboform® resins

Similarly to the extrusion process of Solanyl® resins, Arboform are mechanically compounded into homogeneous resins. The electricity requirement is estimated to be 0.54 kWh which includes site-conditioning (Kent, 2018).

Inputs

Electricity for the compounding process is included as medium voltage electricity from the German energy mix. This input is selected in Ecoinvent 3.5.

Outputs

Emissions and wastes due to electricity production and delivery are included in the selected units in Ecoinvent 3.5.

5.2.3 Polystyrene

In order to bring the obtained LCAI results into context, they are compared to the environmental impacts caused by producing one kg of PS resins. Ecoinvent 3.5 provides a complete set with all life cycle inventory data regarding the production of PS resins starting at the extraction of raw materials, monomer production and polymerisation to produce PS as well as transportation. Therefore, this is selected as an input. All according outputs are provided as well by the selected life cycle inventory data.

6. Life cycle inventory impact assessment

This study investigates the environmental performance of two bio-based resins and compares it with the currently used alternative PS. The cradle-to-resin study is simulated using SimaPro 9.0. The environmental impacts are calculated using two methodologies: ReCiPe (2016) at midpoint and endpoint level and Cumulative Energy Demand.

The following chapter represents and describes the obtained impact results. The results for each type of resin are represented in parallel for each impact category to enable direct comparison between both bio-based alternatives and PS.

6.1 LCIA using ReCiPe methodology

This section displays and describes the results obtained using the ReCiPe methodology in SimaPro in order to compare the impacts caused by producing one kg of resins of Solanyl®, Arboform® and PS.

6.1.1 6.1.1 Gross and net GHG

The ReCiPe methodology calculates the contribution to climate change (GWP) caused by the emissions of GHG. Table 6 represents the characterised gross and net GHG emissions (CO_2-eq) caused by producing one kg of resins of Solanyl®, Arboform® or PS. The net GHG emissions are obtained by deducting the gross GHG by the potential CO_2 uptake during photosynthetic growth. The obtained results indicate that the bio-based alternatives have a considerably lower gross GWP compared to the petrochemical alternative. In addition, if potential biogenic carbon uptakes are considered, the net GWP of one kg of Solanyl® and Arboform® is reduced even more in comparison with PS.

Table 6: Gross and net GHG emissions caused by producing one kg of resins of the studied plastics.

	Solanyl resins	**Arboform resins**	**PS resins**
Gross GHG (kg CO2-eq)	2.567	2.105	3.935
Net GHG (kg CO2-eq)	1.372	0.1336	3.935

6.1.2 Relative contribution to impact categories per component present in the Solanyl® and Arboform® composites

Figure 14 (A&B) represent the proportional contribution per component or process (extrusion/compounding) for both Solanyl® and Arboform® resin production. The graph indicates that for Solanyl® production for all impact categories, both PLA and glycerol are the dominant contributors to all impact categories. PLA production contributes over 50% to global warming, ionising radiation, fine particulate matter, ozone formation, freshwater eutrophication, freshwater and marine toxicity, human non-carcinogenic toxicity, mineral and fossil resource scarcity and even more than 75% to water consumption. Glycerol contributes more than 50% to stratospheric ozone depletion, marine eutrophication and land use.

In contrast, the contribution of all component processes to the impact categories is more dispersed for Arboform® resins. Here hemp fibre accounts for about 90% to stratospheric ozone depletion and more than 50% to ozone formation, terrestrial acidification, land use and mineral resource scarcity, whereas PLA accounts mainly for water use and marine eutrophication. Kraft lignin is the major contributor to global warming and fossil resource scarcity while the compounding process contributes about 50% to ionising radiation and freshwater eutrophication.

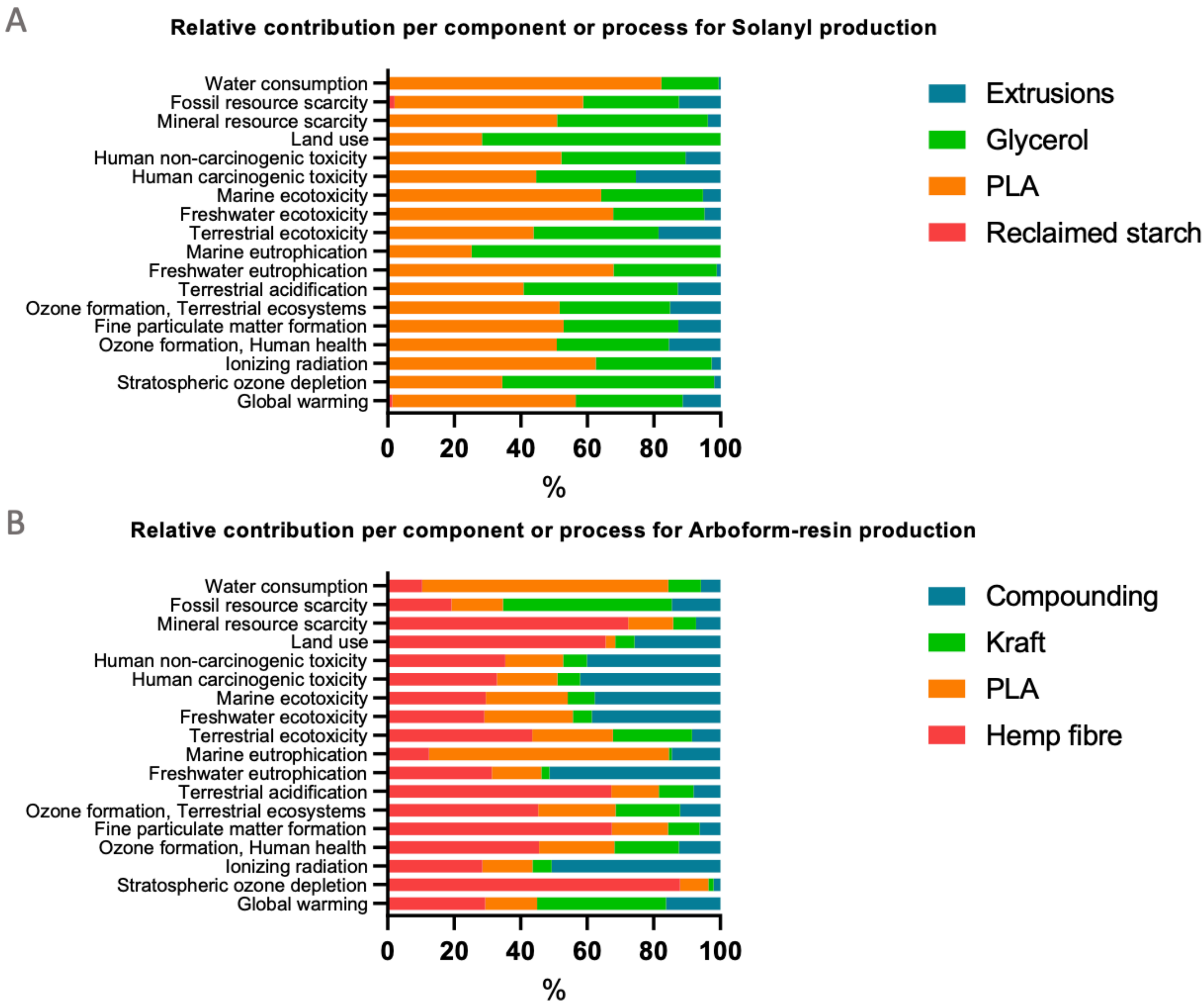

Figure 14. Relative contribution by each component or process for all impact categories. A: Contribution to impact categories per element for Solanyl resins. B: Contribution to impact categories per segment for Arboform resins.

6.1.3 Characterised impact scores at midpoint level

Table 7 represents the characterised impact scores at midpoint level for all 18 impact categories. The results indicate that all three alternatives have some environmental trade-offs. PS is estimated to contribute considerably more to global warming and fossil resource scarcity as could be expected due to the use of crude oil and natural gas as feedstocks. Arboform® resins occupy more land, which is mainly due to the need for arable land to cultivate hemp (Figure 14 B). Solanyl® scores quite poorly for multiple impact categories which are primarily the toxicity indicators and water use. The water use is mainly a result of PLA production. However, the high score for the toxicity indicators as terrestrial and human non-carcinogenic toxicity, which are mostly a result of glycerol and PLA production (Figure 14 B). The high scores obtained for the toxicity impacts are considered rather curious and will be discussed later in the paper. Both Solanyl® and Arboform® production score relatively higher in ionising radiation, indicating the potential hazard to human health by generating radioactive material, compared to PS. (In Table 36 in appendix F.1, the changes in impact per impact category compared to PS is represented.)

Table 7: Characterised impact scores at midpoint level. (In bold are the impact categories that were previously identified as immediately relevant (4.2.6). Red indicates the highest score for each impact category and green the lowest).

Impact category	Unit	Solanyl resins	Arboform Resins	PS resins
Global warming	kg CO2 eq	2.567	2.105	3.935
Stratospheric ozone depletion	kg CFC11 eq	0	0	0
Ionising radiation	kBq Co-60 eq	0.152	0.146	0.003
Ozone formation. Human health	kg NOx eq	0.006	0.003	0.006
Fine particulate matter formation	kg PM2.5 eq	0.005	0.003	0.003
Ozone formation. Terrestrial ecosystems	kg NOx eq	0.006	0.003	0.007
Terrestrial acidification	kg SO2 eq	0.015	0.01	0.01
Freshwater eutrophication	kg P eq	0.001	0.001	0.00005
Marine eutrophication	kg N eq	0.003	0.0002	0.00001
Terrestrial ecotoxicity	kg 1.4-DCB	5.865	2.276	1.775
Freshwater ecotoxicity	kg 1.4-DCB	0.07	0.041	0.017
Marine ecotoxicity	kg 1.4-DCB	0.093	0.057	0.023
Human carcinogenic toxicity	kg 1.4-DCB	0.074	0.059	0.061
Human non-carcinogenic toxicity	kg 1.4-DCB	2.463	0.991	0.409
Land use	m2a crop eq	1.671	2.561	0.004
Mineral resource scarcity	kg Cu eq	0.006	0.005	0.001
Fossil resource scarcity	kg oil eq	0.668	0.56	1.87
Water consumption	m3	0.141	0.036	0.053

6.1.4 Normalised impact scores at midpoint level – Internal baseline

Figure 15 represents the internally normalised impact results at midpoint level. The internal baseline used for normalisation is the highest characterised score obtained for each impact category. Environmental advantages for the bio-based alternatives can directly be observed for potential global warming and fossil resource scarcity as the bio-based plastics obtained scores that are about 50 and 75% lower in comparison to PS. However, the bio-based plastics also have some evident trade-offs compared to PS (Figure 15). The impact categories where the largest (>75%) differences are observed among the bio-based alternatives and PS are ionising radiation, marine eutrophication, all toxicity indicators except carcinogenic toxicity, land use and mineral resource scarcity. In between the bio-based options, the most significant differences (>50%) are observed for marine eutrophication, terrestrial ecotoxicity, human-non carcinogenic toxicity and water consumption.

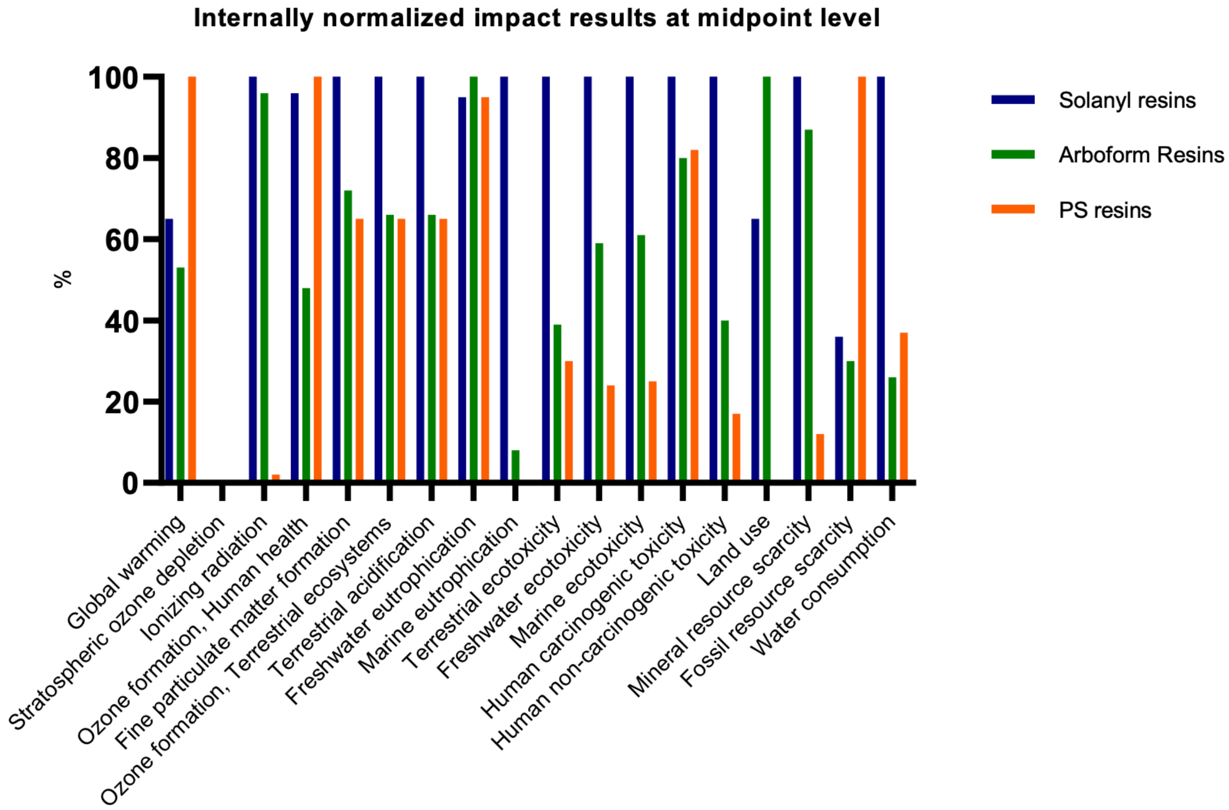

Figure 15: Internally normalised impact scores at midpoint level.

6.1.5 Normalised impact scores at midpoint level – External baseline

Figure 16 represents the impact results normalised by an external baseline. The external reference used for normalisation is a global normalisation reference "World 2010" where the normalisation factor represents the global average per person or person equivalent for each unit category, CO_2-eq per person for example (Huijbregts et al.,2016). The normalised values are also represented in percentages of the average global impact per person in Table 37 in appendix F.2.

Figure 16 consists of two separate diagrams (A and B) due to the difference in the order of magnitude between the toxicity categories and the other 13 impact categories. From figure 15A, it can be seen that PS obtained a higher score for potential fossil resource scarcity and climate change compared to the bio-based alternatives as seen in the figures above. As mentioned before this is mainly due the use of fossil resources as feedstock and the oil refinery practices used to produce PS. Impact categories where the biobased alternatives score considerable higher compared to PS are ozone depletion, ionising radiation, freshwater and marine eutrophication, land use and water consumption. Comparing both biobased alternatives, Solanyl® performs inferiorly compared Arboform® regarding climate change, fine particulate matter, ozone formation (health and ecosystems), terrestrial acidification, marine eutrophication, fossil resource scarcity and water consumption. In contrast, Arboform® contributes more to freshwater eutrophication and land use in comparison to Solanyl®.

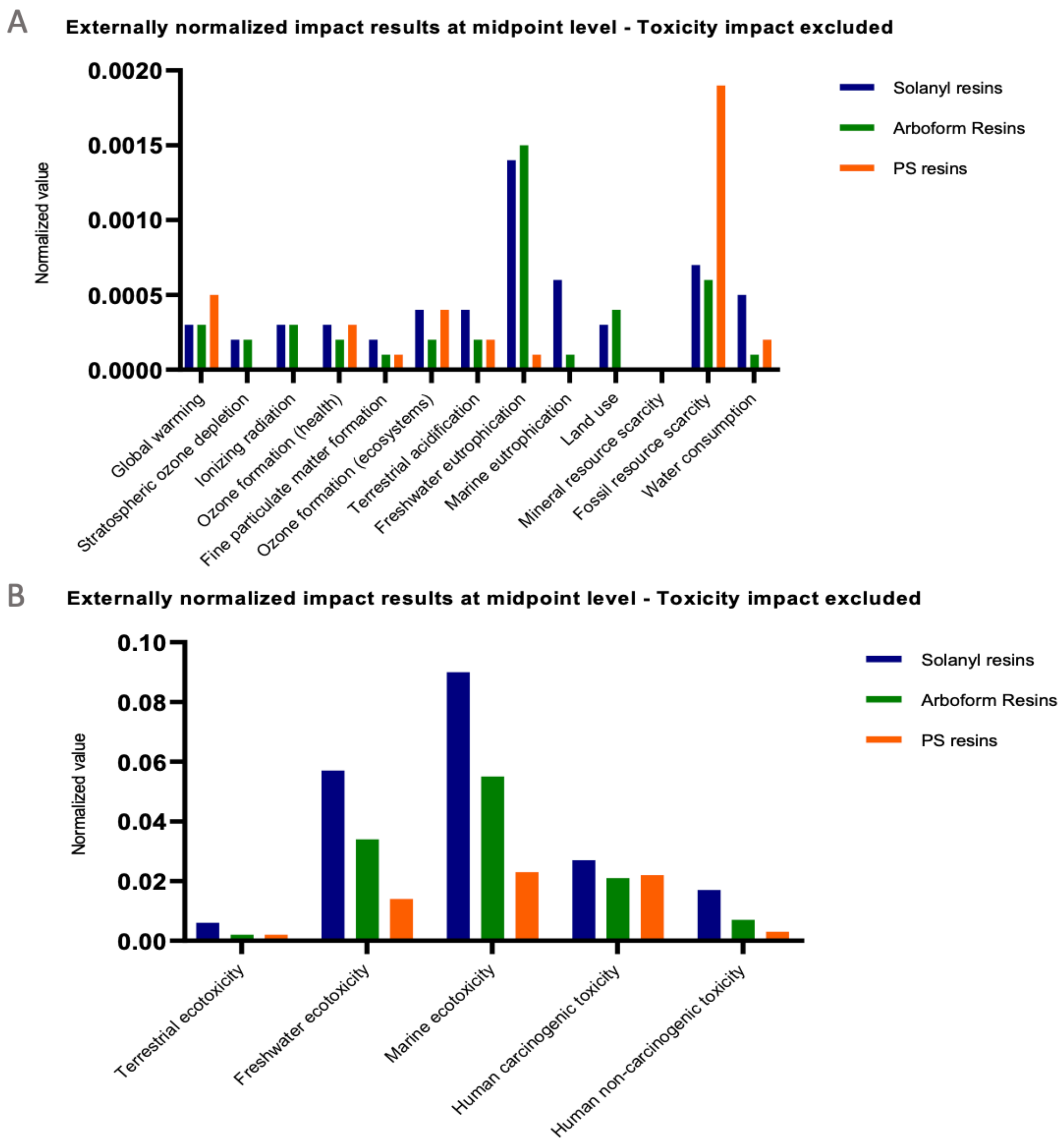

Figure 16: Externally normalised impact scores at midpoint level. A: Represents all impact categories and their normalised impact results excluding toxicity impact categories for all three studied plastics. B: Represents the toxicity categories and their normalised impact results for all three studied plastics.

In Figure 16 B represents the impact scores for the toxicity categories. Indeed, the toxicity categories indicate considerable high toxicity levels to ecosystems and human health for all three alternatives in comparison to other investigated environmental impacts. Nevertheless, the disparity in scores obtained for each plastic for the toxicity indicators is high as well. For all five toxicity categories, Solanyl® scores almost double compared to Arboform® and even triple compared to PS. Only for human carcinogenic toxicity, the scores for all three plastics are quite similar (around 0.02). In Figure 14 A, representing the relative contribution of producing all components and the final process, it can be seen that for Solanyl® PLA and glycerol production are predominant sources for toxicity. In contrast, hemp fibre production and electricity production to power the compounding process are the leading causes of Arboform®'s toxicity results. These processes are most likely estimated to be of high toxic potential because of the air and water emissions of heavy metals such as zinc, nickel, copper, mercury, lead, vanadium and chromium among others (Table 31- Table 35 appendix E represent the top 20 of substances contributing to the toxicity results). It is, however, plausible that the obtained normalised toxicity impacts are overestimated (Vink and Davies, 2015).

6.1.6 Characterised and normalised impact scores at endpoint level

The characterised and normalised results at midpoint level were rather complicated and did not directly indicate a seemingly superior alternative as both environmental trade-offs and benefits were identified for all three alternatives.

Table 8 and Figure 17 represent the damage assessment, where the midpoint results are harmonised into three central damage categories: human health, ecosystems and resources. Damage to human health is calculated by the number of years of a life of a healthy person that are "lost" due to the potential damage, which is referred to as disability-adjusted life years (DALY). Damage to ecosystems is represented by the number of species eradicated per year due to the potential damage caused. Damage to resources is calculated by the increase in cost (USD2013) of resources due to the resource use (Huijbregts et al., 2016). From Table 8 and Figure 17, it can be seen that indeed trade-offs are present for all three plastics as they all perform worse in one category. Only Arboform® performs better in two categories compared to Solanyl® and PS, suggesting that perhaps Arboform® is the environmentally superior option.

Table 8: Characterised impact results at endpoint level. (Red indicates the highest score for each damage category and green the lowest)

Damage category	Unit	Solanyl resins	Arboform Resins	PS resins
Human health	DALY	6.28E-06	4.60E-06	6.03E-06
Ecosystems	species.yr	2.73E-08	3.20E-08	1.48E-08
Resources	USD2013	0.204515	0.1643	0.754605

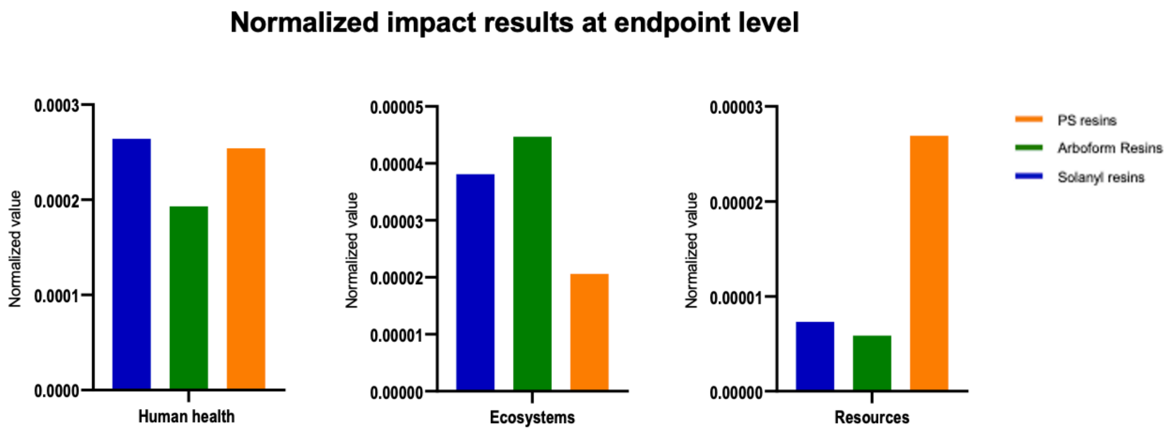

Figure 17: Normalized damage results at endpoint level for human health, ecosystems and resources.

6.1.7 Relative contribution of all impact categories to the endpoint damage categories

Figure 18 (A-C) represents the relative contribution of each impact category to the respective damage categories. The figure indicates global warming and fine particulate matter strongly dominate the end damage score for human health for all three plastics (Figure 18 -A). The dominating impact categories for ecosystem damage are primarily land use, global warming (terrestrial ecosystems) and terrestrial acidification for the biobased plastics whereas for PS it is mostly global warming (terrestrial ecosystems) and terrestrial acidification (Figure 18 -B). Regarding the availability of resources, only fossil resource scarcity is considered to have an impact for all three plastics (Figure 18 -C). From the results presented in Figure 18, it can be suggested that the scores obtained for terrestrial, freshwater and marine toxicity previously do not contribute on the obtained damage scores for ecosystems. The carcinogenic and non-carcinogenic toxicity impact posed on human health is relatively small and is likewise considered not to have a significant influence on the final damage score.

Relative contribution of impact categories to the endpoint result.

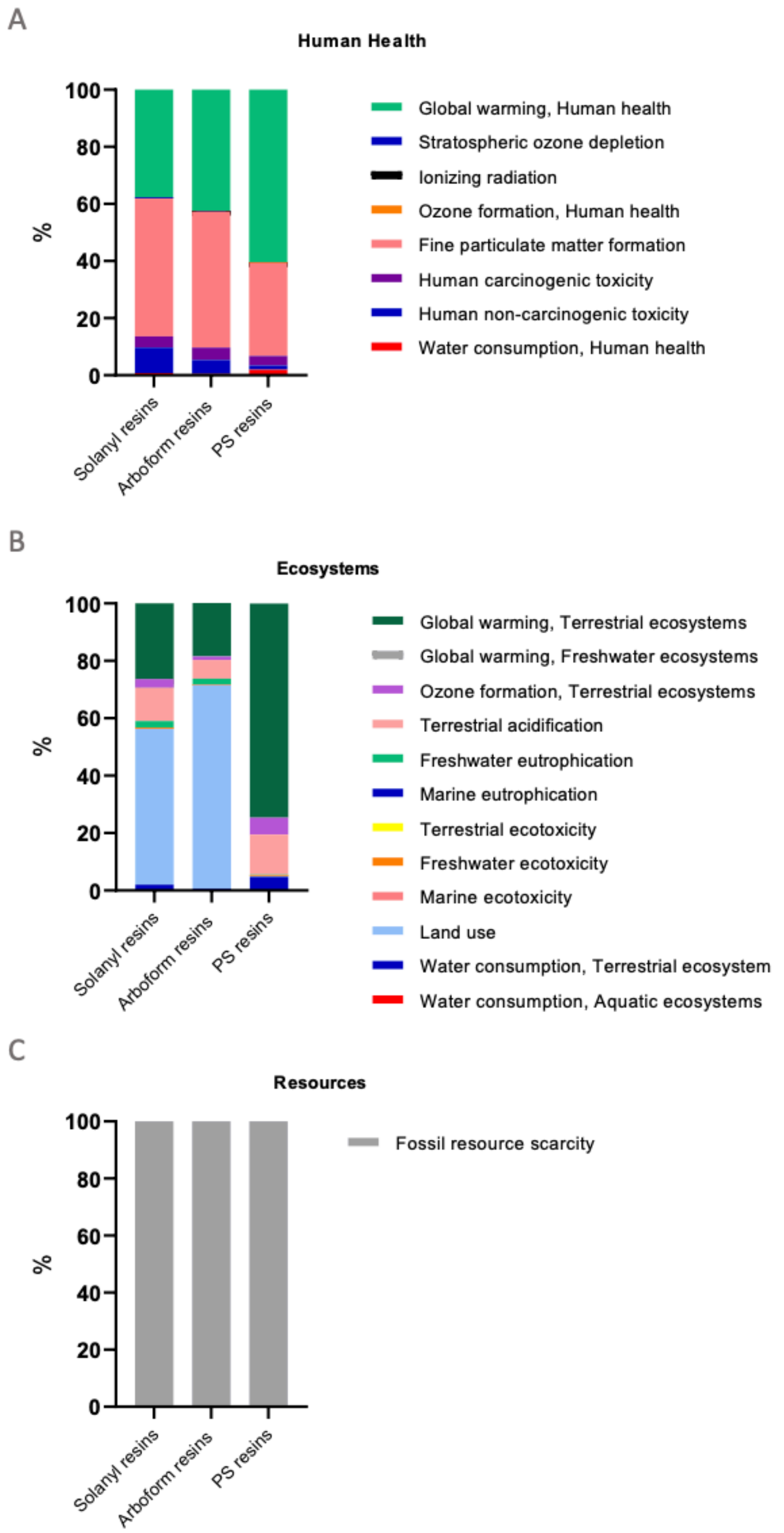

Figure 18: Diagrams representing the relative contribution of all impact categories towards the damage categories at endpoint level for the three studies plastics. (A represents the relative contribution of impact categories to damage to human health, B represents the relative contribution of impact categories to damage to ecosystems and C represents the relative contribution of impact categories to damage to resources)

6.1.8 Weighted impact scores at endpoint level

Both midpoint and endpoint impact results indicate that trade-offs are present in all of the analysed alternatives, complicating the process to distinguish the superior option. For this reason, a fourth step is conducted in order to determine the relative importance of all three damage categories. This process is called weighting and is performed by multiplying the normalised damage results with a weighting factor representing the relative importance (Meijer, 2014). By doing so, all damage results are expressed in the same unit (mPt), which enables to sum up the results obtained for each damage category per type of plastic resulting in one final score per plastic.

This step is considered controversial because the selected weighting factors determine the outcome and perhaps reflect an outcome that is not entirely correct. Considering this, weighted presented results in this report are only an indication of the potential damage. Weighting is done in accordance with the H perspective.

Figure 19 represents the weighted damage scores (mPt) for all three damage categories as well as the totals. It can be seen that Arboform® has the lowest total score (96mPt), suggesting it is the desirable alternative compared to Solanyl® and PS (according to the weighting factors). Solanyl® was scored as most inferior with 122 mPt in total, whereas PS is estimated to be the second-best alternative with a score of 155mPt.

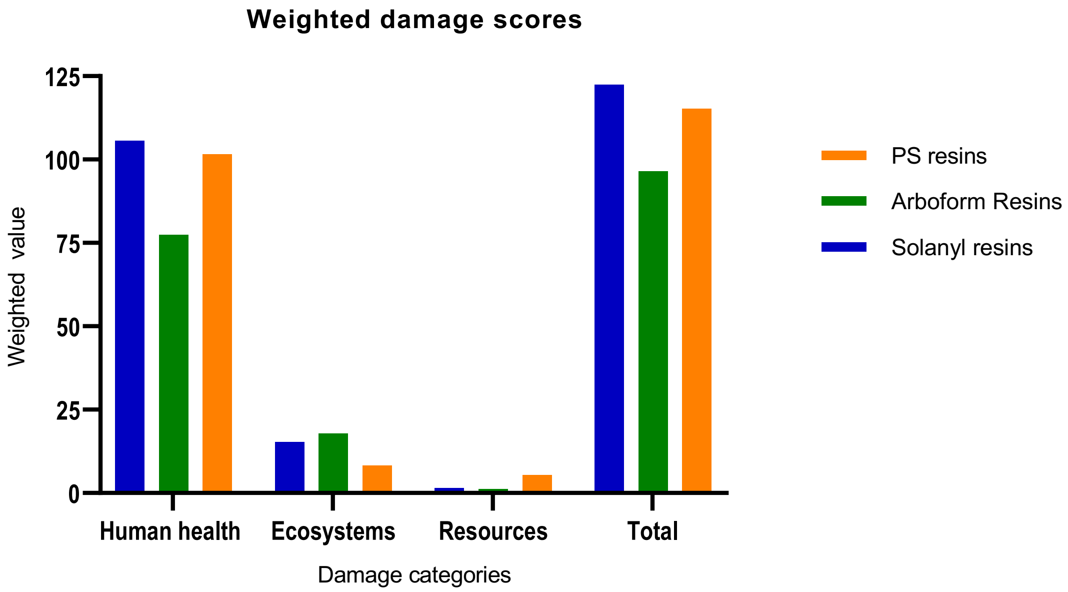

Figure 19: Weighted damage scores and totals for all Solanyl, Arboform and PS. The totals are obtained by summing up the weighted score of each damage category per type of plastic (Values are indicative only!)

6.2 LCIA using CED methodology

The Cumulative Energy Demand for all three alternatives is determined representing the total energy (lower heating values) consumed during the life cycle activities. The lower heating values are quantified, meaning only heat released during combustion is quantified (Hischier et al., 2010). Using CED, energy resources both non-renewables including fossil, nuclear and biomass derived from primary forests as well as renewables including wind, solar, geothermal and water are quantified.

Figure 20 represents the weighted cumulative energy demands for all three analysed plastics. It can be seen that PS demands the highest amount of energy which is almost entirely derived from non-renewable fossil resources. It can be seen that the bio-based plastics require a considerably smaller amount of energy compared to PS. The observed difference enforces the suggestion that fossil feedstock used to produce PS contributes notably to global warming and fossil resource scarcity. Although, when comparing Solanyl® with Arboform®, a substantial difference in CED scores is observed as well while the amount of non-renewable energy used to produce one kg of resins is relatively similar. The difference in energy required for Solanyl® is estimated to be supplied from renewable energy resources (87% biomass). The substantial difference in the amount of biomass-derived energy used for producing Solanyl® compared to Arboform® could perhaps explain differences in results obtained for the impact categories where a large difference is observed between both plastics such as freshwater and marine ecotoxicity.

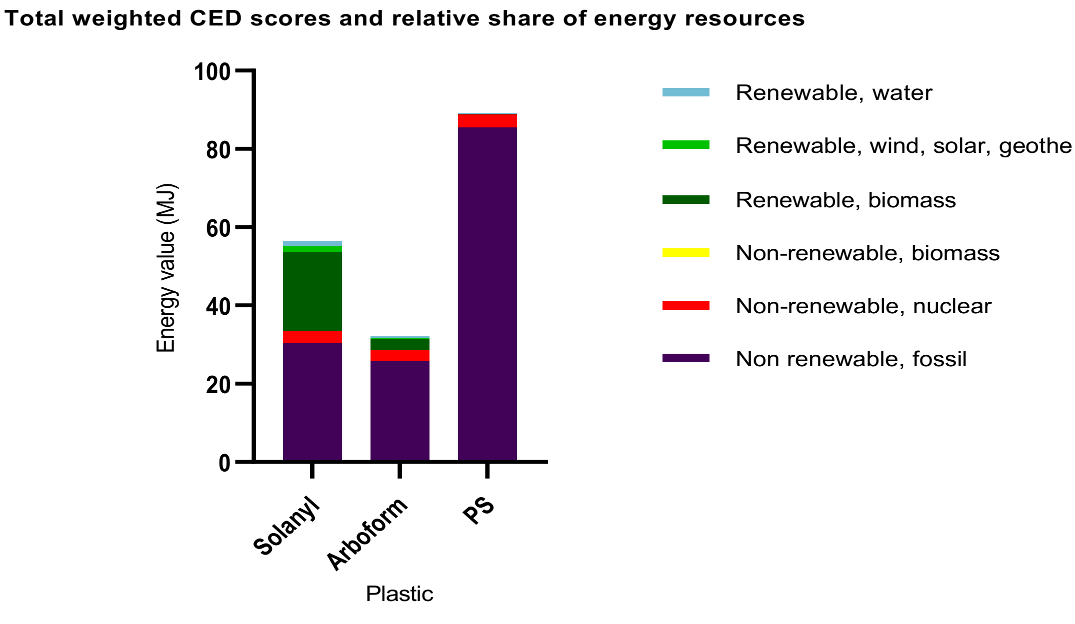

Figure 20: Contribution of energy resources to total weighted CED scores for Solanyl®, Arboform® and PS.

7. Sensitivity analysis

A sensitivity analysis is conducted with the aim to quantify certain uncertainties in the analysis. To do so, multiple alternative scenarios are tested with ReCiPe 2016 midpoint (H) methodology and reported in percentages. Note, the base case refers to the main model/system analysed throughout this report whereas the alternative scenarios presented in this section are object to the sensitivity analysis only.

7.1 Scenario 1: Solanyl® composition – influence of selected additive

Glycerol is selected as an additive due to its prominence in literature (3.4.1). However, it is possible that Rodenburg Biopolymers uses another additive, which changes the final impact of Solanyl® resins. Hence, the first scenario aims to measure the influence that the additive (glycerol) has on the impact results compared to another potential additive. In order to do so, three commonly used additives for thermoplastic starch applications are selected and compared in different combinations and ratios. These selected additives are urea, ethylene glycol and water (Zuo et al., 2015). The tested combinations are represented in Table 9. Note that the combination presented in Table 2 remains and that it is only the additive (32% of total composition) that is adapted.

Table 9: Multiple combinations of Solanyl® (A-I) simulated in Simapro in order to measure the influence on the impact results.

Combinations	Water (%)	Urea (%)	Ethylene glycol (%)
A	-	-	100
B	25	-	75
C	50	-	50
D	75	-	25
E	100	-	-
F	-	100	-
G	25	75	-
H	50	50	-
I	75	25	-

<u>*Results*</u>

Table 10 represent the changes in impact results obtained after running the different combinations of the first scenario. It can be seen that the newly tested compositions result in substantial changes. Quasi for every combination a decrease in all impact categories is observed. Impact categories like stratospheric ozone depletion, marine eutrophication, human-non carcinogenic toxicity and land use experience the largest changes with decreases between 37% and 75%. On average, eight out nine combinations indicate an average change above 15%, suggesting that the additive has a significant influence on the environmental performance of Solanyl® resins.

Table 10: Changes (%) in the impact results obtained for scenario 1 compared to the basecase. Orange indicates a change between 20 and 49% whereas yellow indicates a change of 50% or more.

Scenario 1									
Impact category	1A	1B	1C	1D	1E	1F	1G	1H	1I
Global warming	-7%	-13%	-19%	-25%	-32%	9%	-1%	-11%	-21%

Stratospheric ozone depletion	-63%	-63%	-63%	-63%	-64%	-60%	-61%	-62%	-63%
Ionizing radiation	-12%	-18%	-23%	-29%	-34%	-2%	-10%	-18%	-26%
Ozone formation. Human health	-12%	-17%	-22%	-27%	-32%	-14%	-18%	-23%	-28%
Fine particulate matter formation	-15%	-19%	-24%	-29%	-34%	-1%	-9%	-18%	-26%
Ozone formation. Terrestrial ecosystems	-11%	-16%	-21%	-27%	-32%	-13%	-18%	-22%	-27%
Terrestrial acidification	-34%	-37%	-40%	-43%	-46%	-13%	-21%	-30%	-38%
Freshwater eutrophication	-9%	-14%	-19%	-24%	-30%	-10%	-15%	-20%	-25%
Marine eutrophication	-74%	-74%	-75%	-75%	-75%	-73%	-74%	-74%	-74%
Terrestrial ecotoxicity	-14%	-20%	-25%	-30%	-35%	56%	33%	11%	-12%
Freshwater ecotoxicity	-5%	-10%	-16%	-21%	-27%	4%	-3%	-11%	-19%
Marine ecotoxicity	-5%	-11%	-17%	-22%	-28%	9%	0%	-10%	-19%
Human carcinogenic toxicity	-4%	-11%	-18%	-24%	-31%	-3%	-10%	-17%	-24%
Human non-carcinogenic toxicity	-49%	-53%	-58%	-63%	-67%	-37%	-45%	-52%	-60%
Land use	-71%	-71%	-71%	-72%	-72%	-71%	-71%	-71%	-71%
Mineral resource scarcity	-20%	-27%	-33%	-39%	-45%	9%	-5%	-18%	-31%
Fossil resource scarcity	24%	11%	-2%	-15%	-28%	36%	20%	4%	-12%
Water consumption	-11%	-13%	-14%	-16%	-17%	25%	14%	4%	-6%
Average change	**-22%**	**-26%**	**-31%**	**-36%**	**-40%**	**-8%**	**-16%**	**-24%**	**-32%**

7.2 Scenario 2: Arboform® composition – influence of selected lignin-hemp-PLA ratio

Nägele et al. (2002) mentioned that lignin-hemp fibre ratio for Arboform® resins can vary between 30:60 and 60:30. In the scope of this study, a ratio of 30:60 (lignin:hemp fibre) is selected to simulate the environmental performance. This scenario aims to measure the differences in impact results obtained for Arboform® with 60% lignin and 30% hemp fibre.

Results

By assessing the environmental performance with ReCiPe 2016 (H) midpoint, significant increases in the potential impact are observed for global warming and fossil resource scarcity. However, stratospheric ozone depletion, fine particulate matter, terrestrial acidification, land use and mineral resource scarcity are significantly reduced by the change in composition. On average, a decrease of 16% is observed, indicating the hemp fibre-lignin ratio has a significant influence on the environmental performance of Arboform® resins (Table 11).

Table 11: Changes (%) in the impact results obtained for scenario 2 compared to the basecase. Orange indicates a change between 20 and 49% whereas yellows indictes a change of 50% or more.

Impact category	Scenario 2
Global warming	19%
Stratospheric ozone depletion	-74%
Ionizing radiation	-9%
Ozone formation. Human health	-3%
Fine particulate matter formation	-32%

Ozone formation. Terrestrial ecosystems	-3%
Terrestrial acidification	-30%
Freshwater eutrophication	-15%
Marine eutrophication	-6%
Terrestrial ecotoxicity	2%
Freshwater ecotoxicity	-10%
Marine ecotoxicity	-7%
Human carcinogenic toxicity	-11%
Human non-carcinogenic toxicity	-12%
Land use	-91%
Mineral resource scarcity	-41%
Fossil resource scarcity	29%
Water consumption	4%
Average change	**16%**

7.3 Scenario 3: Influence productivity and according energy use for extrusion/compounding process to produce Solanyl® and Arboform® resins

The electricity required for the extrusion/compounding process for both Solanyl® and Arboform® in the base case is derived from Kent (2018). However, this energy value is extrapolated from generic data. In order to evaluate its influence, a more pessimistic and more optimistic alternative are simulated. The newly tested energy requirements are based on the extruder's productivity, which influences the electricity requirements. It is assumed that higher productivity results in a lower energy demand per kg of resins. The newly simulated productivities are 10kg/h (A) and 1000kg/h (B), (represented in Table 12).

Table 12: Alternative electricity demands simulated in scenario 3.

Variations	Electricity required (kWh)	Reference
A	0.875	Broeren et al. (2017)
B	0.383	Broeren et al. (2017)

Results

From Table 13, it is noticeable that the changes overall are relatively small. Accordingly, the influence of energy use is not considered to be significant. Adapting the productivity of the extruder/compounder however causes larger differences for Arboform® resin production compared to Solanyl®. In particularly, this trend is noticed with regard to the toxicity categories, freshwater eutrophication and ozone formation human health, where decreasing the compounding productivity leads to an increase of more than 20%.

Table 13:Changes (%) in the impact results obtained for scenario 3 compared to the basecase. Orange indicates a change between 20 and 49% .

Scenario 3

Impact category	A-Solanyl®	B-Solanyl®	A-Arboform®	B-Arboform®
Global warming	7%	-3%	11%	-4%
Stratospheric ozone depletion	1%	-1%	1%	-1%
Ionizing radiation	2%	-1%	33%	-14%
Ozone formation. Human health	10%	-5%	8%	-3%
Fine particulate matter formation	8%	-4%	4%	-2%
Ozone formation. Terrestrial ecosystems	9%	-4%	8%	-3%
Terrestrial acidification	8%	-4%	5%	-2%
Freshwater eutrophication	1%	0%	33%	-14%
Marine eutrophication	0%	0%	9%	-4%
Terrestrial ecotoxicity	12%	-5%	6%	-2%
Freshwater ecotoxicity	3%	-1%	25%	-11%
Marine ecotoxicity	4%	-2%	25%	-10%
Human carcinogenic toxicity	3%	-1%	27%	-12%
Human non-carcinogenic toxicity	1%	-1%	26%	-11%
Land use	0%	0%	0%	0%
Mineral resource scarcity	2%	-1%	5%	-2%
Fossil resource scarcity	8%	-4%	10%	-4%
Water consumption	0%	0%	4%	-2%
Average change	**4%**	**-2%**	**13%**	**-6%**

7.4 Scenario 4: Influence energy mix used to extrude/compound Solanyl® and Arboform® resins

In the base case, local energy mixes are assumed to be used for the extrusion/compounding process. It is to say, the Dutch energy mix is selected for extruding Solanyl® and the German energy mix is selected for compounding Arboform®. Hence, to investigate the influence the energy mix has on the impact results and in addition, investigate the potential benefits of using renewables rather than fossil fuels for energy production, a new scenario is simulated. Here, renewable energy, provided by a local energy supplier, is used. The local energy suppliers and their renewable energy mix are provided in Table 14.

Table 14: Selected energy suppliers and their according renewable energy mix. The presented energy mixes are used to simulate the extrusion/compounding processes for Solanyl® and Arboform®.

	Energy supplier	**Wind (%)**	**Hydro**	**Reference**
Solanyl®	Eneco	100	-	Eneco (2020)
Arboform®	ENGIE Deutschland AG	80	20	ENGIE (2020)

Results

Adopting 100% renewable energy supplied by a local energy supplier results in an overall estimated decrease in impact for both Solanyl® and Arboform® (Table 15). However, the overall change for Solanyl® is low with an average decrease of 7% and only a single impact category experiencing a decrease over 20%. Accordingly, the influence of the energy source is not considered to be powerful in the case of Solanyl® production. On the other hand, the impact results for Arboform® resin production experience a substantially larger change on average and therefore considered to be under influence of the energy resources. Indeed, significant changes around 50% are observed for about four of the toxicity categories while ionizing radiation and freshwater eutrophication even undergo changes of more than 100%

Table 15: Changes (%) in the impact results obtained for scenario 4 compared to the base case. Orange indicates a change between 20 and 49%, yellow indicates a change above 50% and blue indicates a change above 100%.

	Scenario 4	
Impact category	Solanyl®	Arboform®
Global warming	-13%	-19%
Stratospheric ozone depletion	-2%	-2%
Ionizing radiation	-3%	-101%
Ozone formation. Human health	-18%	-13%
Fine particulate matter formation	-14%	-6%
Ozone formation. Terrestrial ecosystems	-18%	-13%
Terrestrial acidification	-15%	-8%
Freshwater eutrophication	-1%	-103%
Marine eutrophication	0%	-17%
Terrestrial ecotoxicity	-21%	-4%
Freshwater ecotoxicity	0%	-43%
Marine ecotoxicity	-1%	-43%
Human carcinogenic toxicity	0%	-58%
Human non-carcinogenic toxicity	-1%	-60%
Land use	0%	0%
Mineral resource scarcity	1%	-1%
Fossil resource scarcity	-14%	-17%
Water consumption	-1%	-6%
Average change	**-7%**	**-29%**

7.5 Scenario 5: Influence of long-term emissions

ReCiPe 2016 midpoint (H) includes long term emissions: emissions that take place over more than 100 years. In order to test the influence that the long-term emissions have on the impact results, the system was simulated without considering the long term-emissions for Solanyl®, Arboform® and PS.

<u>*Results*</u>
Excluding long term-emissions (>100 years) causes a significant decrease in impact results for all three analysed plastics for ionizing radiation, freshwater eutrophication and all toxicity categories except terrestrial ecotoxicity (Table 16). Moreover, Arboform® and PS experience a decrease in marine eutrophication over 20%. These results indicate that long term emissions particularly affect the toxicity, eutrophication and ionizing radiation potential of products, while other impact categories are not affected. It should however be noted that the results are influenced by the hierarchist perspective where for example CO_2-eq emissions are not considered over 100 years.

Table 16: Changes (%) in the impact results obtained for scenario 5 compared to the basecase. Orange indicates a change between 20 and 49% whereas yellows indictes a change of 50% or more.

	Scenario 5		
Impact category	Solanyl® resins	Arboform® Resins	PS resins
Global warming	0%	0%	0%
Stratospheric ozone depletion	0%	0%	0%
Ionizing radiation	-89%	-91%	-73%
Ozone formation. Human health	0%	0%	0%
Fine particulate matter formation	0%	0%	0%
Ozone formation. Terrestrial ecosystems	0%	0%	0%
Terrestrial acidification	0%	0%	0%
Freshwater eutrophication	-67%	-80%	-89%
Marine eutrophication	-2%	-23%	-39%
Terrestrial ecotoxicity	-1%	-2%	-10%
Freshwater ecotoxicity	-93%	-97%	-95%
Marine ecotoxicity	-92%	-94%	-92%
Human carcinogenic toxicity	-79%	-87%	-75%
Human non-carcinogenic toxicity	-52%	-95%	-94%
Land use	0%	0%	0%
Mineral resource scarcity	0%	0%	0%
Fossil resource scarcity	0%	0%	0%
Water consumption	0%	0%	0%
Average change	**-26%**	**-32%**	**-32%**

7.6 Scenario 6: Influence of selected perspective for ReCiPe methodology

In order to perform the LCIA, ReCiPe 2016 midpoint (H) is used as the main methodology. H represents the point of view to certain choices in relation to the impact a product has based on common global policies. However, two other perspectives are available. First, the Egalitarian (E) perspectives which considers long-term impacts. Second, the Individualist perspective which only considers short-term impacts (PRé Consultants, 2019). In order to investigate the influence that the selected perspective has on the impacts results, both other perspectives are simulated as well.

<u>Results</u>
From the observed changes presented in Table 17. It can be seen that the largest changes are observed in marine and human toxicity (non-carcinogenic and carcinogenic). Here, the Egalitarian perspective causes a tremendous increase whereas the Individualist perspective causes a decrease around 90%. Furthermore, for all plastics studied, the Egalitarian perspective causes a significant increase in estimated stratospheric ozone depletion and ionizing radiation potential while the Individualist perspective causes a significant decrease in the estimated stratospheric ozone depletion, fine particulate formation and terrestrial ecotoxicity potential. With regard to global warming a trend is noticeable where the Egalitarian perspective results in a decrease (8-25%) while the Individualist results in an increase (6-39%). Considering these changes in estimated impacts, it is thought that the selected perspective expresses a significant influence.

Table 17: Changes (%) in the impact results obtained for scenario 6 compared to the base case. Orange indicates a change between 20 and 49%, yellow indicates a change above 50% and blue indicates a change above 100%.

Scenario 6						
	Solanyl		Arboform		PS	
Impact category	Egalitarian	Individualist	Egalitarian	Individualist	Egalitarian	Individualist
Global warming	-15%	8%	-15%	6%	-25%	39%
Stratospheric ozone depletion	53%	-35%	54%	-35%	35%	-19%
Ionizing radiation	75%	-3%	51%	-2%	249%	-11%
Ozone formation. Human health	0%	0%	0%	0%	0%	0%
Fine particulate matter formation	0%	-67%	0%	-53%	0%	-91%
Ozone formation. Terrestrial ecosystems	0%	0%	0%	0%	0%	0%
Terrestrial acidification	0%	0%	0%	0%	0%	0%
Freshwater eutrophication	0%	0%	0%	0%	0%	0%
Marine eutrophication	0%	0%	0%	0%	0%	0%
Terrestrial ecotoxicity	8%	-56%	7%	-55%	8%	-56%
Freshwater ecotoxicity	2%	-5%	1%	-4%	10%	-5%
Marine ecotoxicity	586165%	-78%	671581%	-78%	712831%	-78%
Human carcinogenic toxicity	6924%	-99%	6983%	-99%	7060%	-99%
Human non-carcinogenic toxicity	18007%	-99%	31766%	-99%	33366%	-99%
Land use	0%	0%	0%	0%	0%	0%
Mineral resource scarcity	0%	-18%	0%	-22%	0%	-10%
Fossil resource scarcity	0%	0%	0%	0%	0%	0%
Water consumption	0%	0%	0%	0%	0%	0%
Average change	**33957%**	**-25%**	**39468%**	**-25%**	**41863%**	**-24%**

8. Interpretation/Discussion

In this section, the results of the cradle-to gate study are first summarized. Thereafter, a brief qualitative uncertainty analysis is presented which is followed by a discussion. Here, the obtained impact and damage results for Solanyl®, Arboform® and PS resins are discussed along with other aspects like the toxicity impact categories, biogenic carbon, the sustainability considerations and critics to LCA studies.

8.1 Key findings

In this section the main and most important results obtained are summarized.

Characterized impact results
The cradle-to-resin comparison between Solanyl®, Arboform® and PS indicates that both studied bio-based plastic have a reduced impact on **climate change** compared to their petrochemical counterpart. The production of both bio-based alternatives also required fewer **fossil resources** compared to PS, resulting in a reduced impact on fossil resources. The CED results confirm these findings, as they indicate that PS resin production mainly relies on fossil energy resources, especially compared to the two other alternatives. These findings strongly indicate that that the high reliance on fossil energy resources is responsible for causing the airborne emissions, resulting in higher kg CO_2-eq score for PS.

On the other hand, for all 16 remaining (midpoint-level) impact categories, performed better compared to the bio-based alternatives, suggesting Solanyl® and Arboform® have environmental trade-offs. Both Solanyl® and Arboform® are estimated to have a more significant **ionizing radiation** impact. This outcome is mainly a result of the estimated radon-222 air emissions, representing about 90% of the total kBq Co-60 equivalency calculated for both types of resins. Industrial processes such as electricity generation and heat production used to extrude/compound the bio-based resins and produce other industrial materials such as fertilizers, limestone and agricultural machinery principally cause these emissions.

Moreover, in terms of **land use**, both bio-based resins also require substantially larger surface areas compared to the petroleum-derived alternative. Indeed, Solanyl® requires almost 420 times more land, while Arboform requires even 640 times more surface of land to produce one kg of resins. These findings seem to confirm the statement made by Boeren et al. (2017), mentioning that increased demand for land is a trade-off of bio-based plastics. Primarily, this is a result of the land used to cultivate hemp for fibre extraction and corn for PLA production. The production of both Solanyl® and Arboform® resins also results in 20 times more **freshwater eutrophication** compared to producing PS resins. Emissions of PO_4 to water and soil are the main causes for freshwater eutrophication. These emissions remarkably originate from primarily industrial processes such as electricity generation, while only a small contribution originates from fertilizer manufacturing and use.

Furthermore, the impact scores acquired for Solanyl® resin production indicate certain environmental drawbacks in comparison to Arboform®. In relation to **terrestrial acidification**, Solanyl® scores 15 times worse than Arboform® and PS, which is mainly due to the estimated emissions of substances like NH_3, SO_2, NO, NO_2, SO_3 and SO. These are estimated to be principally generated by processes like electricity and heat production and fuel combustion. Solanyl® production is also estimated to contribute 20 and 300 times more to **marine eutrophication** compared to Arboform® and PS resins, respectively. This is as a consequence of higher NO_3 concentrations emitted to water bodies caused by industrial processes such as electricity, heat and fuel production. Regarding **water use**, Solanyl® production induces a more significant environmental impact as it consumes about 3.9 and 2.6 times more water as compared to Arboform® and PS production. The higher water consumption is mainly a result of the water consumption for electricity production (highly specific to the Dutch energy mix) and processing and cooling water used to produce PLA.

Further on, Solanyl® resin production is estimated to have a 1.5-2.5 and 2.5-6 times higher **toxic impact** on ecosystems and human health in comparison to Arboform® and PS, respectively. As mentioned before, the LCI results suggest that emissions of heavy metals like copper, vanadium, zinc, nickel, lead, mercury and cadmium by industrial processes related to electricity, heat and fuel production, especially for glycerol and PLA production.

<u>*Normalised impact results*</u>
After normalizing the impact results to a global reference, the toxicity categories are estimated to have the highest potential impact. For all three plastics simulated in this study, the toxicity categories obtained 10-100 times higher normalized value compared to the other impact categories. It is difficult to understand the reason why the production processes are estimated to be of such toxic potential. The production of one kg of Solanyl® resins is estimated to represent about 9% of the total toxic impact an average person has on the marine environment throughout one year (Table 33, appendix F). Seeing, on average, a European person consumes about 100 kg of plastics annually; it seems very unlikely only one kg of Solanyl® resins already represents one-tenth of the total toxic impact introduced by a single person (The Globalist, 2017). Seeing the same analogy can be made for the other plastics and all toxicity categories as well as the toxicity impact results obtained by Arboform® and PS, the toxicity results are considered to be overestimated and therefore not reliable.

Excluding the toxicity indicators, only five impact categories obtained notable results (here considered to be 0.05% or more). First, the production of one kg of PS resins is estimated to generate a CO2-eq equal to 0.5% of the global average carbon footprint per person, while Solanyl® and Arboform® generate around 0.3%. Second, for freshwater eutrophication, both bio-based alternatives are estimated to have an impact comparable to 0.15% of the average impact per person globally. Third, for marine eutrophication, only Solanyl® is estimated to have a relatively high impact representing about 0.06%, whereas Arboform® and PS production causes six times less to marine eutrophication. Fourth, all three types of plastic consume a relatively high amount of fossil resources. Nevertheless, PS scores more than double compared to the bio-based alternatives. Finally, the production of one kg of Solanyl® resins is estimated to consume about 0.05% of the average water budget per person, which is about five times more than Arboform® and PS.

<u>*Damage results*</u>
When harmonized into three damage categories, it can be seen that all three plastics offer both environmental benefits and trade-offs. Both the characterized and normalized results indicate that Solanyl® resin production poses the most significant damage to **human health**, while Arboform® resins cause the most significant damage to **ecosystems** and PS contributes the most to r**esource scarcity**.

Overall, the normalized results, Solanyl® obtains the highest total score (if all results are added up), which is slightly higher compared to PS. Arboform® obtains the lowest score, indicating it might be the superior alternative. These findings are confirmed by the controversial step where the normalized values are multiplied by a weighting factor to determine the relative importance of each damage category.

Furthermore, investigating the relative contribution of each impact category to the damage score for each category, indicates that human health is mainly affected by global warming and fine particulate matter. In contrast, ecosystems are primarily affected by land use, global warming and terrestrial acidification. Both damage categories are affected very little by the toxicity categories.

Sensitivity analysis
Finally, the sensitivity analysis indicates that the additive has a significant influence on the impact results obtained for Solanyl®. Changes to hemp fibre-lignin ratio do, however, not influence the impact results significantly. For both bio-based alternatives, the electricity required for extruding/compounding the resins does not affect the results significantly. The selected energy mix does influence the impact results for Arboform®, which is not the case for Solanyl®. The estimated long term emissions significantly affect the results obtained for the ionizing radiation, eutrophication and toxicity categories. Lastly, the chosen perspective, reflecting a specific paradigm of human behaviour, does express the significant influence on the final impact results.

8.2 Uncertainty analysis

The uncertainty analysis is conducted qualitatively to identify uncertain variables introduced to the analysis either through inventory data or through the methodology. When analysing and interpreting the LCI and LCIA results, it is crucial to bear these in mind.

1. The additive used to produce Solanyl® has a significant influence on the impact results,
2. The lignin-hemp fibre ratio in Arboform® resins has a significant influence of the impact results,
3. The energy mix used to simulate the impact of the bio-based plastics affects the results of Arboform® significantly,
4. The selected perspective has a significant influence on the results obtained,
5. The long-term emissions influence the results significantly,
6. Toxicity indicators: It is unclear if the used characterisation factors and normalisation factors as well as the calculation methodology, are correct and represent a close-to-real life scenario.

Overall, these uncertainties should not change the main outcomes of this study. The additive for Solanyl® does have a significant impact on the environmental performance. However, the additive used by Rodenburg Biopolymers is unknown and therefore, it is not possible to determine the exact environmental performance. Nevertheless, the estimated results in this study can be considered as an indication to facilitate any following decision-making. The fact that Arboform's environmental performance is enhanced by increasing the lignin share in the composition or by expanding the share of renewables, indicates that there is room for improvement.

Moreover, it is possible that the estimated improvement for Solanyl® by integrating a different additive is cancelled out by the estimated improvement for Arboform® by expanding the lignin share in Arboform® resins or the renewables in the energy mix used to compound Arboform® resins.

The remaining three uncertainties identified are introduced by the chosen methodology. A change in perspective showed to significantly influence the impact results. Therefore, (H) perspective is considered the most adequate default methodology, since it is a compromise between the other two perspectives and consideres the most common principles and policies (Muthu, 2014). Concerning the toxicity results, it is very likely that uncertainties in ReCiPe are embedded, resulting in overestimated results. Seeing the toxicity categories have very little influence on the total damage scores, they can be disregarded and hence no changes must be made to the overall conclusions.

8.3 Discussion

This section is meant to further interpret the obtained results by discussing the results, value choices made for the LCA methodology, sustainability considerations for the resins and critics to LCA

8.3.1 Discussion on main results

High scores obtained for toxicity indicators

The impact results indicate that all plastics are estimated to have a significant toxic impact on ecosystems and human health. The reason of these high toxic impacts associated with the production of the resins probably is a result of the high level of uncertainty in the underlying methodologies.

Indeed, the ReCiPe 2016 (H) methodology calculates the toxicity impact by multiplying the persistence of the "toxic substance" in the environment with the bio-accumulation factor (accumulation of the substance in organisms) and the effect of the toxic substance. The factors used to determine the persistence, bioaccumulation and effect are mainly based on standard models and experimental data. However, some assumptions and value choices included in the methodology, result in a high level of uncertainty (Huijbregts et al., 2016; Thinkstep, 2015).

For example, the persistence is based on a specific time frame. Depending on the ReCiPe perspective, either 20 or 100 years are assumed to be the time period. Then, it is considered that exposure takes place through inhalation and ingestion (drinking and eating). Both the time frame for substance persistence and intake could result in an overestimation since they are based on assumptions (Huijbregts et al., 2016).

Further on, to determine the effect of a substance, cadmium for example, on a species or humans, it considered sufficient to base the effect factor on one testing only. This is because no minimum tested organisms is required in the hierarchic perspective in ReCiPe (Huijbregts et al., 2016). Therefore, some assumptions in the methodology might lack adequate scientific evidence. In consequence, it is possible that the toxic impact on ecosystems and human health is wrongly estimated.

Moreover, for marine ecotoxicity, essential metals like copper and manganese are assumed to have a toxic impact on both seas and ocean. However, scientific data is on the effect of essentials metals on oceans is very limited. Considering a similar effect on oceans as on seas can result an overestimation of the toxic effect of a product on marine ecosystems (Huijbregts et al., 2016). These assumptions are also described to result in inaccurate use of the characterization factors to obtain the results at midpoint level (Thinkstep, 2015; Vink and Davies, 2015).

The uncertainties in the methodology used to calculate the toxicity impact at midpoint level should, however, not mean that endpoint results should be disregarded. In figure 19, the relative contribution of each impact category to the damage category is represented. Here it can be seen that the toxic impact categories contribute very little to the overall damage result. The small contribution is likely a result of the endpoint conversion factors that are very small due to the considered species density (Huijbregts et al., 2016).

Biogenic carbon in polymers and the carbon balance

From the results, it is seen that the bio-based alternatives are estimated to emit about approximately 1.5kg less of gross CO_2-eq compared to the counterpart PS. If potential carbon sequestration as a result of the phototrophic growth of the renewable feedstocks is considered, the differences in net GHG is even larger. Indeed, the net GHG for Solanyl® is about 2.8 times lower compared to PS, and for Arboform® it is even about 30 times lower. Although it is essential to mention these the biogenic carbon uptake separately, there are different factors that affect carbon neutrality (ISO 14067:2018).

An important factor is the processes carried out to produce the biomass. Dew-retting for hemp cultivation is an example. During this process, the biomass is partly digested by microorganisms, which can emit CO_2 but also other GHG like N_2O and CH_4. These GHG have a greater global warming potential compared to CO_2 and contribute thus more to global warming (Sign, n.d.). Another factor is the end-of-life treatment, which is highly case-specific. Biodegradable plastics that are composted can be converted into CO_2 and H_2O as well as other GHG like CH_4. The formation of potent GHG (like CH_4) can be achieved by industrial composting where biomass is degraded under a specific set of parameters (Groot and Borén, 2010). The carbon balance is also further affect by the fact that biodegradable plastics are also partly converted into biomass and secondary metabolites likes organic acids (Broeren et al., 2017). The transformation of land is another factor that can affect the carbon balance by reducing or increasing the CO_2 removal "capacity" (Sign, n.d.). Considering these factors, more research regarding carbon fixations and emissions must be conducted in order to conclude on the carbon neutrality of a certain product.

Impact results Solanyl®

When observing the relative contribution of the components for each impact category, it can be seen that PLA dominantly contributes to most of the impact categories, which due to multiple factors.

First, the considerable energy consumption to produce PLA strongly affects the overall impact of Solanyl® resins. The cumulative demand for non-renewable fossil energy is about 85% of the energy used. Fossil fuel combustion for energy production releases molecules containing N, S and heavy metals which affect almost all impact categories. Fossil fuel combustion is the largest source contributing to NO_x emissions (Vouk and Piver, 1983). NOx substances are fine particulates that strongly influence the atmosphere's chemistry, by impacting the ozone layer, and have a damaging effect on human health when inhaled (Boningari and Smirniotis, 2016). The NO_X group also includes N_2O, which is a GHG that is about 260 times more powerful than CO_2 (Environmental Protection Agency, 2020). Additionally, NO_X emissions contribute to eutrophication of water bodies (World Resources Institute, 2020). Fuel combustion is also a significant contributor to sulphur emissions mainly as SO_2, which causes terrestrial acidification and affects human health (Queensland Government; 2020). Finally, fuel combustion also emits fuel-bound heavy metals which are toxic to both ecosystems and human health.

Second, PLA resin production demands a relatively high amount of water (86.87kg/kg[PLA]). Although the largest share is river water which is sent back to the river after use, there is still about 35 kg of net water use. About 20 kg of water are used for crop irrigation and the remaining water is for processing and cooling purposes. The water used for PLA production thus influences the water impact category and other potential environmental damages like soil quality.

Third, PLA is produced from starch which in this case is extracted from corn. These crops require agricultural land for cultivation. Indeed, approximately 1.50m^2 of cultural land is required to produce about one kg of PLA. The requirement for agricultural land contributes to the demand for land and the transformation of land.

The impact of PLA could be reduced by envisioning different options. First, seeing the little contribution reclaimed starch has to the overall environmental impact of Solanyl®, it is perhaps possible to produce PLA from starch reclaimed from potato processing facilities. Hence, reducing the need for land and other resources by avoiding the cultivation step. Another possibility could be to use recycled PLA. Broeren et al. (2017) analysed a scenario where PLA scrap was used and found that GHG emissions and land use could be reduced by 33 and 67% respectively.

Besides PLA, glycerol is the other dominant contributor to the environmental impact. Broeren et al. (2017) mention that additives are significant contributors to the environmental impact of starch-based plastics. Glycerol can be derived from two chemical pathways. First, petrochemical feedstocks like gas can be converted into glycerol. Considering the known environmental hazards associated to oil refineries such as the emission of pollutants harming both ecosystems and human health could likely be the cause of the estimated impacts of glycerol production in this study (Prioleau, 2003). However, glycerol can also be obtained as a by-product from biodiesel production, which is done through transesterification of fats derived from renewable feedstocks (Rossi and Pagliaro, 2008). Although crude glycerol often requires specific purification steps beforehand, it could be interesting to envision crude glycerol derived from biodiesel production as an additive for Solanyl®, as it could be a strategy to lower its overall environmental impact.

Impact results Arboform®

While Arboform® requires the largest land surface mainly due to hemp cultivation, it also contributes considerably to eutrophication. This is because of the airborne NO_X emissions mainly caused by fuel combustion and electricity production as well as waterborne N and P emissions caused by fertilizer production and use.

The largest contributors to water consumption are PLA production, electricity generation, fertilizer production and washing lignin. Hemp fibre, which is the main component in Arboform®, does not require any irrigation water enabling a minimized overall water consumption. With regard to fossil resource scarcity, it is observed that Arboform® contributes the least. Considering the CED scores, where Arboform® is calculated to have the smallest cumulative energy value, it can be suggested that a reduced energy consumption enables a decrease in fossil fuel use. In consequence, it is possible that lower fossil fuel use also resulted in reduced fine particulate matter emissions (CO, NO_X, O_3 etc) as fuel combustion for energy production and transportation is the main source of particulate matter (Franklin Associates, 2016). Additionally, ozone formation is lower compared to the two other types of resins. It is likely that the lower concentration of fine particulate matter results in lower impact caused by ozone formation. Tropospheric ozone is formed when volatile organic compounds, like CO, CH_4 and NMVOCs, react with NO_x molecules under the presence of sunlight.

In the second scenario of the sensitivity analysis, the hemp-lignin ratio is adapted. Although the average change observed is not considered significant, some considerable changes are seen. The most significant changes are observed for land use which, decreased by 91%, suggesting a higher lignin concentration as a solution to decrease the need for land. On the other hand GHG emissions increased by 19% (CO_2

eq) and fossil resource depletion by 29%. These results hence suggest a trade-off between GHG emissions and fossil fuel depletion, and land use for Arboform® resins. Perhaps, this trade-off can be solved by envisioning other, less fuel intensive lignin extraction methods.

Impact results PS

PS is estimated to require about 1.87 kg of fossil resources to produce one kg of PS resins, which are used both for energy supply as well as raw materials to produce the monomers. In consequence, one kg of PS emits almost four kg of CO_2-eq, suggesting a causal connection between fossil resource consumption and GHG emissions. These scores are also considerably higher in comparison with Solanyl® and Arboform®. On the contrary, PS scores relatively better for some impact categories that were identified as immediately relevant like water consumption, land use and eutrophication. Indeed, PS production requires less land as industrial processes can be concentrated on a smaller land surface and there is no need for agricultural land. With regard to water consumption, water is mainly used to produce processing materials such as the catalyst and only 17% is used for processing purposes such as cooling (Franklin Associates, 2016). Comparing to Solanyl® for example, PS production requires no water for crop irrigation, which could be the reason why PS has a smaller water footprint. In terms of eutrophication, the most significant contributors are the extraction of raw materials, benzene production and diesel combustion for transportation (Franklin Associates, 2016). Nonetheless, the overall eutrophication impact is relatively small, which could also be due to the absence of agricultural activities such as fertilization.

8.3.2 LCA methodologies

Cradle-to-resin

In this study, a cradle-to-resin assessment is conducted, meaning the processes related to the production of plastic products (tokens), usage and disposal are not included. Impacts or even “avoided impacts” related to these processes could influence decision-making regarding environmental superiority of these resins.

The manufacturing process is done by moulding the resins into the desired shapes through injection moulding. During this process, temperatures and loading times specific to the type of resins are required, influencing the necessary electricity (communication with b-token). However, Vink and Davies (2015) mention that the impact of these processes is insignificant in comparison to the impact caused for the production of resins. Concerning the use phase, one could argue that it might be totally disregarded as the tokens serve the same purpose regardless of the type of resin used. Hence these processes could potentially be neglected. The disposal and treatment processes of the tokens could, however, affect the environmental performance significantly seeing the biodegradable functionality of Solanyl® and Arboform®. Therefore, further considerations regarding the end-of-life should be included as well.

Cut-off approach for lignin and reclaimed starch

Considering that the global pulp market is forecasted to grow 3.45% per annum until 2027 and the European potato chips market is forecasted to grow 4.42% per annum until 2025, it is assumed that demand for pulp and potato products will remain the fundamental drivers for wood and potato processing (Watson, 2020; Market ltd, 2020). In consequence, lignin and starch-rich wastewater are considered to remain industrial by-products with little economic value. Therefore, processes taking place prior lignin extraction and wastewater evaporation are considered outside the system boundaries.

If these market trends tend to change in the future, and lignin or starch wastewater are becoming more valuable due to an expansion in valorisation pathways. Then, a cut-off approach is probably not the ideal allocation method. Instead, mass or economic allocation could then be considered.

Impact assessment methodologies

SimaPro offers multiple life cycle assessment methodologies. In this study, CED and ReCiPe (2016) are selected to perform the LCIA. CED is a well-established single-issue methodology. The fact that it focuses on one environmental indication (energy demand throughout the life cycle) simplifies the LCA study as it requires less complex data regarding raw materials and emissions (Huijbregts et al., 2006). On the other hand, ReCiPe analyses multiple environmental indicators and enables to generate a more "holistic" view. ReCiPe, however, requires much and complex data regarding resource extraction and emissions making the process more difficult. In addition, due the high complexity, a higher level of uncertainty can occur (Huijbregts et al., 2006).

Although the impact assessment methodologies often analyse similar impact categories, different results are often obtained for the same life cycle inventory. The discrepancies in results are often caused by differences in value choices, background data, contributing substances and characterization factors (Dekker et al., 2019). Considering, this study does not investigate the influence the selected methodologies have on the impact results, these results should not be considered as the absolute impact but rather as an indication for environmental decision-making.

Capital equipment and support personnel

No impacts related to major capital equipment, factory buildings or infrastructure required for the final stage (resin extrusion/compounding) are included in the study due to the lack of data. This is due to the lack of accurate data and the fact that Vink and Davies (2015) mentioned that the contribution is not significant. Electricity required for space conditioning (heating, cooling, lighting, etc.) is, however included. The average electricity demand is provided by Kent (2018). Finally, no impacts related to R&D, sales, administration and management activities are not included as well. Here too, it is assumed that the impact is negligible for one kg of resins (Franklin Associates, 2016).

8.3.3 Sustainability considerations

Having a renewable origin does not requisite a superior environmental performance in comparison to the petrochemical-derived counterpart. For this reason, it is critical to analyse the life cycle of the products in question and conduct a cradle-to-resin analysis to analyse the environmental performance quantitatively. In order to create a complete and justified judgement regarding these types of resin, qualitative considerations must complement the LCA results. Therefore, all three plastics are discussed with regard to the sustainability considerations that are mentioned in the background, namely climate change, waste accumulation and fossil resource depletion. An overview of the leading environmental advantages and disadvantages is summarized in Table 19.

Climate change

As mentioned previously, Zhen and Suh (2019) mention that the consumption of plastics emit considerable GHG and therefore contribute actively to climate change. To tackle this global threat, it is of high importance that plastics can be produced while emitting less GHG. Through the cradle-to-resin study, it is found that Solanyl® and Arboform® emit considerable lower amounts of GHG compared to PS resins. Hence, Solanyl® and Arboform® are considered good strategies to lower the carbon footprint of plastic products.

Waste accumulation

The disposal and treatment processes at the token's end-of-life eventually affect the environmental performance as well. Seeing the variety of possible WMR, it is evident that the environmental performance is strongly influenced by the waste treatment taking place. Seeing the fact that b-token's clients are spread throughout Europe and even the USA, it is difficult to determine to most likely end-of-life treatment. In 2018, about 32% was recycled while almost 43% was incinerated to recover energy and 25% was landfilled in Europe Plasticseurope, 2019).

Considering that incineration and landfills are the dominating end-of-life options in Europe, one could argue that the biodegradable nature of Solanyl® and Arboform® offers relief to this problem. First of all, everlasting piles of plastic waste on landfills can be avoided since these types of plastic can be degraded biologically. These resins can also be degraded anaerobically, yielding biogas that can be used as an energy source for electricity production. Moreover, the plastics can also be incinerated where only biogenic carbon will be re-emitted as CO_2 while enabling energy recovery (Broeren et al., 2017). Then, recycling seems to also be a potential end-of-life option. Solanyl® should be recyclable up to five times while Arboform is recyclable up to ten times (Shojaeiaran et al., 2019; Tecnaro GmbH, 2020).

In the case of PS, it is more complicated since the most preferable WMR would be mechanical or chemical recycling as it reduces the need for virgin PS production and the related CO_2 emissions while stimulating the circular economy (Zheng and Suh, 2019). However, to ensure recycling can take place governmental regulation and stimulation for enhanced waste management is required. Unfortunately, these are often lacking, resulting in plastic incineration and landfilling (Defra, 2011). In the case of incineration, the embedded carbon is emitted as CO_2 contributing to an increase of net CO_2 emissions and devaluation of the resources. In the case of landfilling the plastic would remain present for hundreds of years while releasing micro-plastics, hence potentially pose a threat to human and environmental well-being (Woods, Rødder and Verones, 2019). Hence, to further investigate the environmental performance of PS at its end-of-life, three different possibilities are simulated using SimaPro software.

First, a scenario where PS is recycled mechanically is simulated. Seeing the recycled PS resins can be used for new applications, credits are allocated for avoided impacts resulting in negative scores. Then, a scenario where PS is incinerated in a municipal incinerator with energy recovery is simulated. It is considered that 5.04kg of electric energy is recovered per kg of PS waste treated. Credits for avoided impacts due to electricity generation by the incineration process. At last, a scenario where PS is deposed on an "unsanitary" landfill, where pollution control is absent. Unsanitary landfilling is selected based on the estimation that 90% of all landfills in Europe lack sufficient pollution control (Cocoon, 2020). Life cycle inventory data for the end-of-life options are provided by Ecoinvent 3.5. The characterized midpoint results are presented in Table 18.

From the impact results, it can be seen that recycled PS results in a negative global warming potential as a result of the avoided emissions during the production of virgin PS. Negative results are observed for 14 other impact categories including fine particulate formation, terrestrial acidification, all toxicity categories and fossil resource scarcity. An increase in impact potential compared to virgin PS is observed for ionizing radiation, freshwater eutrophication and land-use, which are considered as trade-offs for recycled PS.

Solely based on the results represented in Table 18, landfilling seems like the second-best end-of-life option, which is a contradiction to the waste management hierarchy. The impacts may be estimated too little as it not as process-intensive in comparison to recycling and municipal incineration and that ReCiPe does not measure some impacts. Indeed, environmental impacts related to landfilling like the effects of microplastics on human health, debris ingestion by animals or even landscape aesthetics are not yet assessed (Woods, Rødder and Verones, 2019). As a consequence, the impacts are likely estimated too optimistically.

Despite credits allocated for avoided impacts due to energy recovery, municipal incineration is estimated to have the highest potential impact on the environment. In particular, for global warming, a considerable high score is estimated in comparison to the other end-of-life options. Only land-use municipal incineration offers an advantage.

Overall, the impact results presented in table 18 suggest that recycling is potentially the environmental superior end-of-life option. In comparison to the results previously obtained for Solanyl®, Arbform® and virgin PS, it seems that recycled PS is also superior in terms of environmental performance. However, it should be mentioned that recycling of PS is only done once or twice due to the decreasing polymer quality. After the recycling stages, the plastic is either landfilled or incinerated. Maintaining polymer quality can be achieved by more advanced technologies like chemical recycling. Unfortunately, these technologies are not yet cost-effective for PS (Ritchie and Roser, 2018).

Table 18: Characterized impact scores for PS end-of-life options at midpoint level.

Impact category	Unit	Recycling	Municipal incineration	Landfilling
Global warming	kg CO2 eq	-3,3792	3,1961	0,2443
Stratospheric ozone depletion	kg CFC11 eq	0,0000	0,0000	0,0000
Ionizing radiation	kBq Co-60 eq	0,0528	0,0003	0,0001
Ozone formation. Human health	kg NOx eq	-0,0050	0,0005	0,0001
Fine particulate matter formation	kg PM2.5 eq	-0,0016	0,0001	0,0000
Ozone formation. Terrestrial ecosystems	kg NOx eq	-0,0053	0,0005	0,0001
Terrestrial acidification	kg SO2 eq	-0,0074	0,0002	0,0000
Freshwater eutrophication	kg P eq	0,0002	0,0000	0,0000
Marine eutrophication	kg N eq	0,0000	0,0000	0,0002
Terrestrial ecotoxicity	kg 1,4-DCB	-0,3558	1,2795	0,0047
Freshwater ecotoxicity	kg 1,4-DCB	-0,0050	0,0946	0,2302
Marine ecotoxicity	kg 1,4-DCB	-0,0068	0,1313	0,3218
Human carcinogenic toxicity	kg 1,4-DCB	-0,0448	0,0373	0,0052
Human non-carcinogenic toxicity	kg 1,4-DCB	-0,0888	2,2160	7,1119
Land use	m2a crop eq	0,0087	0,0003	0,0017
Mineral resource scarcity	kg Cu eq	-0,0002	0,0002	0,0000
Fossil resource scarcity	kg oil eq	-1,7316	0,0066	0,0015
Water consumption	m3	-0,0489	0,0003	0,0000

Fossil resource depletion

Reduced fossil resource usage to produce Solanyl® and Arboform® is identified as an advantage compared to virgin PS. Indeed, the production of these bio-based resins requires about three times less fossil resources. Hence, Solanyl® and Arboform® are considered good alternatives to reduce demand for fossil resources.

References, guidelines and policies

Growing awareness regarding the negative impacts that plastics have on the environment and climate is causing more governmental actions dedicated to tackling these problems. On a European level, a variety of objectives are designed to stimulate a carbon neutral and waste-free Europe by 2050. In order to do so, the EU set up roadmaps, strategies and incentives accommodated by budget funds to accommodate the transition (European Commission, 2019). One of them is an EU portfolio of strategies to facilitate the transition to a (bio)circular economy by 2030 (Directorate-General for Research and Innovation, 2018).

Considering, the tremendous role plastics presently have in the EU, these strategies are widely addressing the current plastic problems. First of all, the EU aims to limit the dependence of plastics on fossil fuels to achieve global climate goals. To do so, plastics must be redesigned in such a way that they can be recycled cost-effectively by 2030. Plastics that are difficulty recycled should be phased out (European Commission, 2018). The strategy also included efforts to develop bio-based plastics and biodegradable plastics to offer to reduce the impact on the environment and reduce waste accumulation. The bio-circular economy strategy also promotes cascading biomass, industrial by-products and waste streams as feedstocks through newly developed production pathways (Directorate-General for Research and Innovation, 2018). Moreover, in order to protect human health chemicals and additives known to be harmful will be banned in Europe (Watkins et al., 2019).

Table 19: Overview of advantages and disadvantages of Solanyl®, Arboform® and PS. (√ indicates an advantage and × indicates a disadvantage)

Category	**Solanyl®**	**Arboform®**	**PS**
Climate change	√ Reduced CO_2-eq √ Phototrophic growth of components contributes to potential carbon neutrality	√ Reduced CO_2-eq √ Phototrophic growth of components contributes to potential carbon neutrality	× More CO2-eq emissions
Waste accumulation	√ Biodegradable √ Mechanical recycling √ No microplastics formed × Industrial composting to avoid strong GHG (CH_4)	√ Biodegradable √ Mechanical recycling √ No microplastics formed × Industrial composting to avoid strong GHG (CH_4)	√ MR and CR × Not biodegradable × Resource value decreases through MR × Microplastics
Fossil fuel depletion	√ 2.7x less fossil feedstocks	√ 3x less fossil feedstocks	× Requires fossil feedstocks
Circular economy	√ Contributes to bio-CE × Governmental support is required	√ Contributes to bio-CE × Governmental support is required	√ MR and CR to contribute to CE

			× Governmental support is required
Other impacts	× Higher and use × Higher terrestrial acidification potential × High water consumption × High eutrophication potential	× High land × High freshwater eutrophication potential √ Low water use	√ Low land use √ Low eutrophication potential
References, policies and guidelines	√ Biological resources √ Biodegradable & recyclable, √ No harmful additives √ Contributes to EU guideline to cascade by-products	√ Biological resources √ Biodegradable & recyclable √ No harmful additives √ Contributes to EU guideline to cascade biomass	× Needs further developments to enable infinite recycling × Styrene is known to be harmful to human health (Sillers, 2010)

8.3.4 Comparison to other Bio-based and biodegradable plastics

This study investigated the environmental performance of Solanyl® and Arboform® and compared is it with the environmental performance of PS. By doing so, both potential benefits and trade-offs are revealed. However, it is also interesting to benchmark the environmental performance of Solanyl® and Arboform® against some other commonly used bio-plastics. Therefore, the environmental performance of four bio-based plastics is simulated using SimaPro. ReCiPe (H) at midpoint level as a methodology. Similar functional units and system boundaries are considered to conduct the analysis. The investigated impact categories are global warming, terrestrial acidification, freshwater and marine eutrophication, land use and fossil resource scarcity as these are identified as immediately relevant. The selected bio-based plastics are PHB, PLA, PBS and Bio-polyester (commercial name Mater-bi, Novamont) (Novamont, 2020; Ecoinvent 3.5. Data sources used for modelling are presented in Table 20.

Table 20: Data sources for modelling PHB, PLA, PBS and Bio-polyester

Polymer type	Data source	Comment	
PHB	Literature		Harding et al. (2007)
PLA	Database + literature	Same life cycle inventory used as for PLA used in Solanyl® and Arboform®	Natureworks (Vink and Davies, 2015)
PBS	Literature + Database	Ratio 1,4-Butanedial: Bio-succinic acid 50:50, 1,4-Butanediol is derived from petrochemical feedstock, bio-succinic acid is derived from sugar cane	Moussa, Elkamel and Young (2016) and Ecoinvent 3.5
Bio-polyester	Database	Bio-polyester derived from starches and celluloses. Commercialized by Novamont (Ecoinvent 3.5).	Ecoinvent 3.5

Figure 21 represents the characterised impact scores for the bio-plastics. It can be seen that both Solanyl® and Arboform® are estimated to have a relatively low global warming potential. Only bio-polyester is estimated to have a lower CO2-eq. Regarding terrestrial acidification, differences between the bio-based plastics are relatively small. PHB score the worst with approximately 0.020 kg SO_2- eq while Solanyl is estimated to have the second-largest potential and Arboform® the lowest. The freshwater eutrophication potential for both Solanyl® and Arboform® is relatively low compared to PHB, PLA and PBS. The marine eutrophication potential for Arboform® is considerable lower compared to all other analysed bio-based plastics, while Solanyl® scores considerably higher compared to PLA PBS and bio-polyester. In terms of land use, both Arboform® and Solanyl® require more land surface compare to PLA, PBS and bio-polyester. Only PHB is estimated to require more land than Arboform®. Potential contribution to fossil resource scarcity is estimated to be reduced the most by Solanyl® and Arboform® compared to the other bio-based plastics. Overall, it can be said that Solanyl® and Arboform® have both advantages and disadvantages compared to some other bio-based plastics.

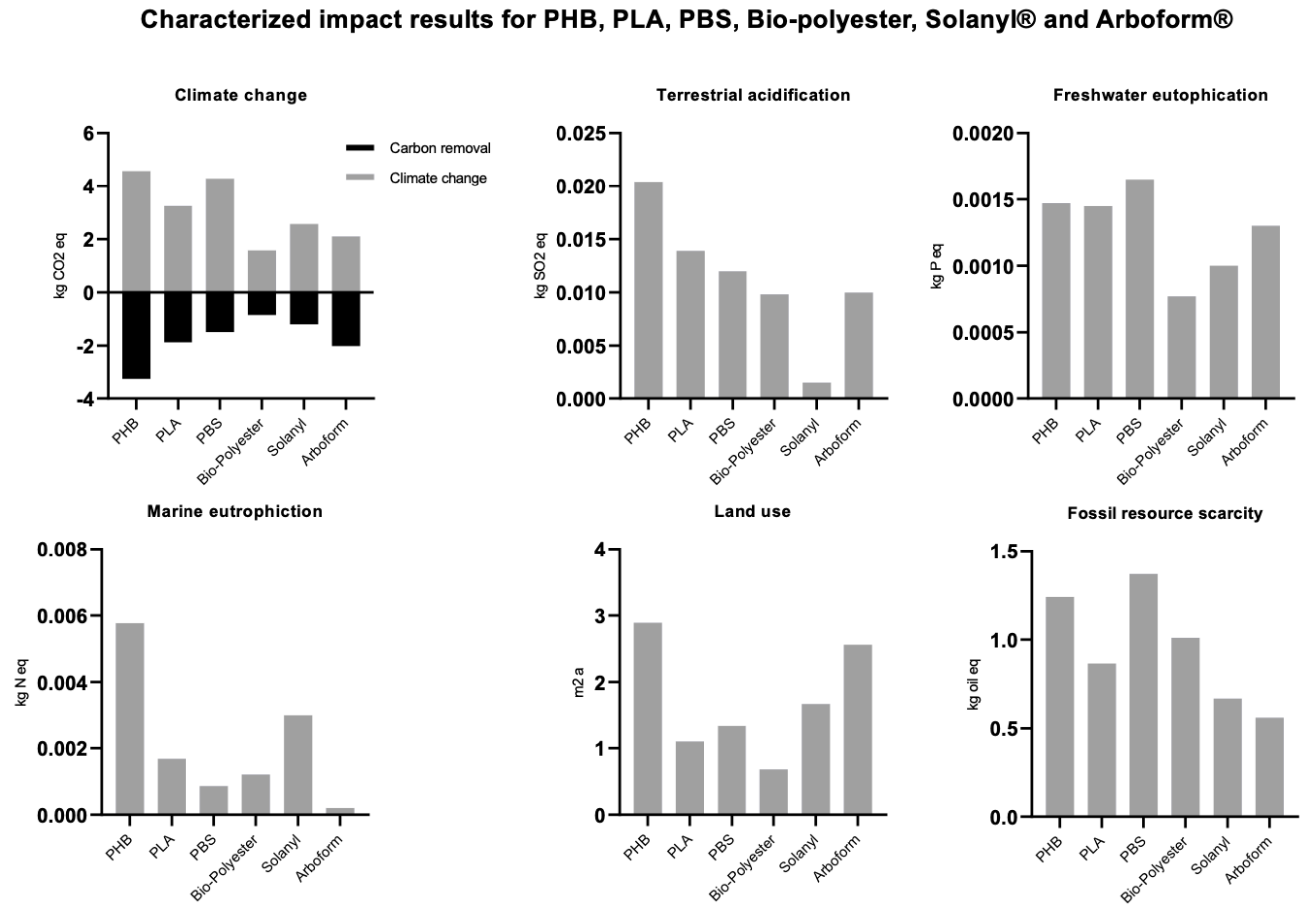

Figure 21: Characterized impact results at midpoint level for PHB, PLA, PBS, Bio-polyester, Solanyl® and Arboform®. The grey graphs indicate the characterized impact results, the black graphs indicate the carbon removal.

8.3.5 Critics and limitations to LCA

LCA studies offer many beneficial applications to evaluate the potential environmental impact of products allowing comparison between alternatives and improving insights on existing technologies. Nevertheless, there are some critics to LCA and its limitations. First of all, the fact that generic data or site-specific data is extrapolated and applied to unique technical processes and spatial locations result in a certain level of uncertainty and unrepresentativeness of the obtained results (Michalski, 2015). There are still impacts, for example, microplastic or entanglement of marine animals by plastic litter, that are not yet investigated by the existing methodologies. As a result, products or services might obtain too optimistic scores, as is potentially seen for the landfilling scenario (Woods, Rødder and Verones, 2019). Moreover, differences in life cycle inventory data among databases and variations in background data among methodologies often result in different impact results for similar studied systems. As a consequence, some question the reliability and accuracy of these types of studies (Zampori, Dotelli and Vernelli, 2013).

The allocation methods used in the case of multi-functional processes are another factor that raises some concerns, as it requires physical properties and economic values of processes to be independent of one another. Seeing the fact that economic and physical properties are rarely independent, the representativeness of the results is reduced (Michalski, 2015). Another common point of criticism of this type of study is the notion that socioeconomic factors are often neglected (Michalski, 2015). This could result in a misinterpretation of the technological solution offered by the new product or service. Within the LCA framework, it is assumed that a particular unit or unit of mass can completely comply with the alternative solution. Meanwhile, ancillary benefits such as price, convenience or aesthetics are often neglected within the scope of the LCA analysis (Gutowski, 2018). For example, the oil price war currently happening could sharply decrease the market price for petrochemical plastics hence providing a greater competitive advantage to PS in comparison to bio-based plastics (Logan, 2020). In addition, technologies, products or services are granted with unfair advantages resulting in an undeserving positive outcome, an example here could be assuming better control of WMR that will enhance recycling and composting of solid waste Gutowski, 2018).

8.4 Limitations to this study

This section describes the limitations of this study.

Due to the limited availability of primary sources, mainly secondary sources are consulted in order to acquire all necessary data. Ideally, more site-specific data is included derived from local sources such as German hemp farmers for example. It is considered as a limitation as it can be questioned how representative these generic datasets are.

When extrapolating datasets, data is selected to match the geographic location as much as possible. However, sometimes data location-matching data is not available. In such cases, European or Global data sets are used in this study.

Transport distances of all components to the central production site are included as the average distance between the most probable supplier and Rodenburg Biopolymers or Tecnaro. Sometimes the locations are not known or precise routes might vary from time to time and therefore, it can be that estimated impacts related to transport vary from the absolute impact.

Moreover, transportation trucks conforming to the European Emission standards EUR4 are selected. These trucks date back from around 2005. It is, however, possible that at present trucks do conform with newer standards such as EUR6 and EUR7.

During this report, the CO_2-eq is estimated based on the emissions of GHG caused by the processes included in the system boundaries. However, certain activities require a land surface which transforms land. As a result, direct and direct CO_2 emissions can take place. These emissions are not considered in within study due to lacking and inconsistent data availability.

Furthermore, some impacts are not yet detected by the models supporting the LCAI methodology ReCiPe. As a result, some processes obtain too optimistic scores which might wrongly influence the outcome of this study.

PLA modelling is provided by Natureworks in Ecoinvent 3.5, which is a PLA supplier in the Netherlands. It could be that another provider is used by Rodenburg Biopolymers or Tecnaro, which uses a different production system. Another systems likely results in a different absolute impact.

Besides, the maize used for PLA production is based on farmer surveys hold in Nebraska, U.S. Maize cultivation in Europe likely demands different processes, resulting in different impacts. This study does not investigate these differences.

Regarding the lignin present in Arboform® resins, only the extraction of Kraft lignin is assessed within this study. However, Tecnaro reports that up to ten different sources of lignin are mixed. The different processes used to extract lignin likely cause different environmental impacts. The variation in potential impacts among different lignin extraction technologies is not reported in this study.

Data concerning specific emissions to water resulting from Kraft lignin extraction is lacking. As a result, this data is not included.

Finally, the life cycle inventory used to simulate the potential environmental impact caused by PS production does not consider the addition of additives. These additives might be added to tailor specific processing properties specific to the applications. In case, additives are mixed into the polymer resins, the potential impact likely changes.

9. Recommendations

This section entails the recommendation proposed to b-token regarding the plastics and the recommendations for future research regarding the environmental performance of Solanyl®, Arboform® and PS.

9.1 Recommendations to b-token

Seeing the fact that the toxicity results were likely overestimated, it is recommended to further investigate the toxic impact caused by the plastics in order to determine more precise indication of the environmental performance.

However, the overall outcome of this study including the discussion regarding the end-of life suggests that the environmental performance of Solanyl® and Arboform® is superior compared to PS and potentially even recycled PS. Therefore, it is recommended to use as these materials as much as possible. Considering the fact that consumer demand and wishes strongly influences b-token's activities, it is recommended to provide a competitive edge to these tokens in order to stimulate consumer demand. This can be achieved by making tokens made of Solanyl® and Arboform® more desirable through pricing or promotions strategies. Another possibility can be by offering a greater variety of aesthetic touches such as colours and shapes.

9.2 Recommendations for further research

During this study it is assumed that the toxicity impact scores are overestimated by ReCiPe due to methodological value choices. In consequence, these impact are not further considered. However, these impacts are still important for determining the absolute environmental impact of products. It is therefore recommended to improve the underlying methodology and background data in order to enable better toxicologic assessment by ReCiPe.

When comparing biobased materials it is very important to consider the carbon footprint. It is therefore recommended to further research the absolute carbon footprint of Solanyl® and Arboform®. In order to so all related factors like land transformation and biodegradation must be considered.

It is also recommended to further research the environmental performance of Solanyl® and Arboform® in collaboration with Rodenburg Biopolymers and Tecnaro in order to enable more precise modelling as precise information regarding the additives, extrusion process and travel distances will be known. Moreover, it will be possible to concentrate on the hotspots in order to further improve these composites in terms of environmental performance.

10. Conclusion

The environmental performance of Solanyl® and Arboform®, two bio-based plastics, is simulated and compared with the environmental performance of their petrochemical counterpart PS using the Life Cycle Assessment.

The most important environmental benefits observed for Solanyl® and Arboform® are the potential to reduce GHG emissions (-35% and -47% respectively) and dependence on fossil resources (-64% and -70% respectively). This is likely due to its biological origin and the industrial or agricultural residues integrated into the composites. In consequence, increased land use (+39228% and +60186% respectively), eutrophication (+25272% and +1962% respectively) and fine particulate matter (+54% and +11%) potentials are observed as trade-offs. During the analysis, high human- and ecotoxicity results are obtained for all plastics studied, which is likely due to an overestimation.

After harmonizing the potential impact results into three potential damage categories, it is seen that Solanyl® is estimated to induce the most considerable harm to human health mainly due to the fine particulate matter and the climate change potential. On the other hand, Arboform® is estimated to cause the most considerable damage to ecosystems due to a large amount of land required while PS causes the most considerable damage to resource availability because of its entire dependence on fossil feedstocks.

Both the impact results as well as the damage results pointed out that the biobased plastics offer certain benefits in comparison to PS, but do also have some environmental trade-offs, like land use to name an example. However, when further considering the end-of-life options and guidelines provided by the EU, additional advantages are appropriated to Solanyl® and Arboform® due to their biodegradable and recyclable functionality.

When comparing just both bio-based alternatives, it could be said that the potential impact caused by Arboform® is smaller compared to Solanyl®, which is particularly seen for marine eutrophication, fine particulate matter and water use. Only for potential freshwater eutrophication and land use, Arboform® is estimated to have a higher impact resulting in the highest endpoint result for ecosystems damage.

Furthermore, multiple hotspots are identified that could help to optimize the environmental performance of both Solanyl® and Arboform®. First, PLA and the additive contribute significantly to the total impacts of Solanyl®. Therefore, strategies to reduce the impact of both components is considered a good strategy to reduce the overall impact of Solanyl®. Second, for Arboform®, it is seen that increasing the lignin volume can decrease the need for agricultural land. However, more GHG would be emitted as a result of increased fossil fuel use in such a case.

Overall, the results obtained in this study provide an indication of the potential environmental impact caused by Solanyl®, Arboform® and PS resins and enables comparison. However, in order to determine the absolute impact, further research regarding the background data supporting the impact assessment methodology must be conducted. Moreover, better collaboration with the producers, Rodenburg Biopolymers and Tecnaro, is necessary to obtain more primary data regarding the composition, energy consumptions and energy mixes.

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13. Appendix

Appendix A – Impact categories and characterization factors

Table 21: Overview of all impact categories and characterization factors for ReCiPe 2016.. Adapted from: Van Eynde, H (2015) and Huijbregts (2016).

Impact category		Indicator name	Unit	Categorization factor		Unit
Midpoint						
Climate change	CC	Infra-red radiative forcing	W*yr/ m^2	Global warming potential	GWP	kg CO_2-eq
Ozone depletion	OD	Stratospheric ozone concentration	Ppt*yr	Ozone depletion potential	ODP	kg CFC-eq
Ionising radiation	IR	Absorbed dose	man*Sv	Ionising radiation potential	IRP	kBq Co-60 eq
Particulate matter formation	PMF	PM_{10} intake	kg	Particulate matter formation potential	PMFP	kg PM_{10}-eq
Photochemical oxidant formation (health)	POF	Photochemical ozone concentration	kg	Photochemical oxidant formation potential	POFP	kg NMVOC-eq
Photochemical oxidant formation (ecosystems)	POF	Photochemical ozone concentration	kg	Photochemical oxidant formation potential	POFP	kg NMVOC-eq
Terrestrial acidification	TA	Base saturation	Yr*m^2	Terrestrial acidification potential	TAP	kg SO_2-eq
Freshwater eutrophication	FE	Phosphorous concentration	Yr*kg/ m^3	Freshwater eutrophication potential	FEP	kg P-eq
Marine eutrophication	ME	Nitrogen concentration	Yr*kg/ m^3	Marine eutrophication potential	MEP	kg N-eq
Terrestrial ecotoxicity	TET	Hazard-weighted concentration	m^2*yr	Terrestrial ecotoxicity potential	TETP	kg 1,4-DB-eq
Freshwater ecotoxicity	FET	Hazard-weighted concentration	m^2*yr	Freshwater ecotoxicity potential	FETP	kg 1,4-DB-eq◊
Marine ecotoxicity	MET	Hazard-weighted concentration	m^2*yr	Marine ecotoxicity potential	METP	kg 1,4-DB-eq
Human toxicity (carcinogenic)	HT	Hazard-weighted dose	-	Human toxicity potential	HTP	kg 1,4-DB-eq
Human toxicity (no-carcinogenic)	HT	Hazard-weighted dose	-	Human toxicity potential	HTP	kg 1,4-DB-eq
Agricultural land occupation	ALO	Occupation	m^2*yr	Agricultural land occupation potential	ALOP	m^2*yr
Water use	WD	Amount of water	m^3	Water depletion potential	WDP	m^3
Mineral resource scarcity	MRD	Grade decrease	kg^{-1}	Mineral resource depletion potential	MDP	kg Fe-eq
Fossil resource scarcity	FRD	Upper heating value	MJ	Fossil resource depletion potential	FDP	kg oil-eq
Endpoint						
Damage to human health	(HH)	Disability-adjusted loss of life years (DALY)	yr			

Damage to ecosystem diversity	(ED)	Loss of species during a year	yr^{-1}
Damage to resource availability	(RA)	Increased cost	$

Appendix B – Data quality

Table 22: Data type and quality for modelled operations.

Solanyl®				
Operation	*Data type*	*Data specificity*	*Data reference*	*Comment*
Composition	Secondary (literature)	Medium	Broeren et al. (2017)	The composition was published by Broeren et al. (2017) in a scientific journal.
Compounding process	Primary (personal communication)	High	Rodenburg Biopolymers	The compounding process was provided by Rodenburg Biopolymers.
Extrusion energy	Secondary (literature)	High	Kent (2018)	Kent provides details regarding extrusion energy consumption.
Transport starch to central plant	Primary (personal communication)	Medium	Rodenburg Biopolymers	Starch from wastewater comes from local providers (provided by Rodenburg Biopolymers).
Starch processing	Secondary (literature)	Medium	Broeren et al. (2017)	Processes and according energy consumption are provided by Broeren et al. (2017)
Corn cultivation and PLA production	Secondary (literature + database)	Medium	Natureworks (2014)	Natureworks provided a complete eco-profile with all materials and energy required for the production of PLA. The data can be used for European applications.
Glycerol production / transport	Secondary (database)	Low	Ecoinvent 3.5	LCI data regarding glycerol production was provided by Ecoinvent 3.5.
Arboform®				
Operation	*Data type*	*Data specificity*	*Data reference*	*Comment*
Composition	Secondary (literature)	Medium	Hu (2002)	Hu (2002) provided the composition for general purpose Arboform®.
Compounding process	Secondary (literature)	High	Nägele et al. (2002)	Nägele et al. describes the process to manufacture Arboform® resins.
Compounding energy	Secondary (literature)	Low	Kent (2018)	Kent provides details regarding extrusion energy consumption.
Lignin extraction and processing	Secondary (literature)	Medium	Bernier, Lavigne and Robidoux (2012)	Bernier, Lavigne and Robidoux published a detailed LCA inventory for extracting lignin in Kraft pulping process.
Hemp cultivation and processing	Secondary (literature)	Medium	González-García et al. (2010)	González-García et al. published a LCA inventory for hemp cultivation.

Corn cultivation and PLA production	Secondary (literature + database)	Medium	Natureworks (2014)	Natureworks provided a complete eco-profile with all materials and energy required for the production of PLA. The data can be used for European applications.

PS

Operation	*Data type*	*Data specificity*	*Data reference*	*Comment*
PS production	Secondary (literature + database)	Low	Ecoinvent 3.5	Global LCI published by Ecoinvent 3.5.

Appendix C – Reasonings to calculate LCI data

C.1. Kraft lignin – output multi-effect boiler

Table 23: Reasoning for emissions from multi-effect boiler

Emissions factors - from multi-effect boiler		
SO2	0.3kg/ton[pulp]	Industrial Emissions Directive 2010/75/EU (2015)
H2S	0.2kg/ ton[pulp]	
NO2	1.36/ ton[pulp]	
Particulates (undefined)	0.8kg/ ton[pulp]	
CO2	Equal to the injected liquid CO2	Bernier, Lavigne and Robidoux (2012)

C.2. Hemp fibre - Input Fuel (tractor)

Table 24: fuel used (kg) per hour of tractor use and hours required per specific activity to produce 1kg of hemp fibre.

Activity	Fuel use/hour(h)	h/ton[Hemp fibre]	
	kg	h	Zampori, Dotelli and Vernelli (2013)
Ploughing	14.63	1.92	
Harrowing	14.63	0.96	
Fertilization	8.73	0.62	
Sowing	8.73	0.77	
Harvesting	48.25	1.54	
Windrowing	4.88	1.54	
Baling	4.88	1.55	

C.3. Hemp fibre – Output fuel use (emission)

Table 25: Emission factors (EF) in g per kg of diesel combusted.

Substance	EF (g/kg)	g/ton[Fibre]
CO2	3,12E+03	104644,800
SO2	1,01E+00	33,875
CH4	1,29E-01	4,327
C6H6	7,30E-03	0,245
PM2,5	5,63E+01	1888,302
Cd	1,00E-05	0,000
Cr	5,00E+00	167,700
Cu	1,70E-03	0,057
N2O	1,20E-01	4,025
Ni	7,00E-05	0,000
Zn	1,00E-03	0,034
NH3	2,00E-02	0,671
Selenium	1,00E-05	0,000
NOx	2,49E+01	834,190
HC	2,72E+00	91,298

C.4. Hemp fibre – Input seeds

Table 26: Reasoning for input for seeds.

Input Seeds (IS)	
Factor = 0.0485	Van Eynde (2015)
IS = Input Hemp fibre * 0.0485	

C.5. Hemp fibre – Output fertilizers (emissions)

Table 27: Reasoning for fertilizer emissions. Factors for emissions of fertilizers.

Emissions from N fertilizer		
To air		
NH_3	6% of added N fertilizer	Stoessel et al. (2012)
NO	1.7% of added N fertilizer	Stoessel et al. (2012)
N_2O	1.7% of added N fertilizer	Stoessel et al. (2012)
To soil		
NO_3	35% of added N fertilizer	Stoessel et al. (2012)
Emission from P fertilizer		

To water – groundwater		
PO_4	0.07 kg/ha (constant value)	Stoessel et al. (2012)
To water – Surface water		
PO_{4i}	0.245 kg/ha (constant value)	Stoessel et al. (2012)
To soil		
PO_4	0.87 kg/ha (constant value)	Van Eynde (2015)
NMVOC emissions (to air)		
NMVOC	0.87 kg/ha (constant value)	Hutchings, Webb and Amon (2013)

C.6. Hemp fibre – Output dew-retting (emissions)

Table 28: Emission factors for dew-retting process.

Substance	EF	
N_2O NH_3 NO_X	0.05ton/ton[N] 0.1ton/ ton[N] 1.10ton/ ton[N]	Hutchings, Webb and Amon (2013) and De Klein et al. (2006)

Appendix D – System modelling inputs

D.1. Solanyl®

Table 29: Overview of all inventory data selected from Ecoinvent 3.5 for one kg of Solanyl® resins production.

Reclaimed starch (PER KG OF RECLAIMED STARCH)			
Category	*Selected unit*	*Value*	*Comments*
Inputs from nature	Carbon dioxide, in air	1630g	
Heat	Heat, district or industrial, natural gas {RER}| market group for | APOS, S	2.36MJ	
Transportation	Transport, freight, lorry >32 metric ton, euro4 {RER}| market for transport, freight, lorry >32 metric ton, EURO4 | APOS, S	0.08tkm	
Emission to air	Water vapor	0.22kg	
PLA			
Category	*Selected unit*	*Value*	*Comments*
Materials	Polylactide, granulate {GLO}| production | APOS, S	0.430kg	
Transportation	Transport, freight, lorry 7.5-16 metric ton, euro4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	0.08tkm	.
Glycerol			

Category	*Selected unit*	*Value*	*Comments*
Materials	Glycerine {RER}| market for glycerine | APOS,	0.320kg	Average
Extrusions process at Rodenburg Biopolymers			
Category	*Selected unit*	*Value*	*Comments*
Electricity	Electricity, medium voltage {NI}| market for electricity, medium voltage | APOS, S	0.54 kWh	Value provided by Kent (2018).
Material	Reclaimed starch	250g	
Material	PLA	430g	
Material	Glycerol	320g	

D.2. Arboform®

Table 30: Overview of all inventory data selected from Ecoinvent 3.5 for one kg of Arboform® resins production.

Lignin (PER KG OF LIGNIN)			
Category	*Selected unit in Ecoinvent 3.5*	*Value*	*Comments*
Inputs from nature	Carbon dioxide, in air	2300g	
Materials	Carbon dioxide, liquid {RER}| market for | APOS, S	300g	
Materials	Sulfuric acid {RER}| production | APOS, S	230g	
Materials	Sodium hydroxide (50% NaOH), production mix/RER Mass	107g	
Materials	Limestone, crushed, for mill {CH}| market for limestone, crushed, for mill | APOS, S	230g	
Materials	Tap water {Europe without Switzerland}| market for | APOS, S	4480g	
Transport	Transport, freight, lorry 16-32 metric ton, euro4 {RoW}| market for transport, freight, lorry 16-32 metric ton, EURO4 | APOS, S	0.43tkm	Transportation of chemicals
Transport	Transport, freight, lorry 7.5-16 metric ton, euro4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	0.03tkm	Transportation to Tecnaro
Electricity	Electricity, medium voltage {DE}| market for | APOS, S	0.010kWh	
Heat	Heat, district or industrial, natural gas {Europe without Switzerland}| heat production, natural gas, at industrial furnace >100kW | APOS, S	31.5MJ	
Emission to air	Carbon dioxide	300g	
Emission to air	Particulates, unspecified	2.49g	
Emission to air	Nitrogen dioxide, DE	4.08g	
Emission to air	Hydrogen sulphide	0.6g	
Hemp (FOR ONE TONNE OF FIBRE PRODUCED)			
Category	Selected unit	Value	Comments
Inputs from nature	Occupation, agriculture	0.385ha	
Inputs from nature	Carbon dioxide, in air	1.83ton	
Material	Potassium chloride (NPK 0-0-60), at plant/RER Mass	83kg	
Material	Ammonium nitrate, as 100% (NH4)(NO3) (NPK 35-0-0), at plant/RER Mass	57kg	

Material	Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, S	43kg	
Material	Hemp seeds	50kg	Inventory data included shown below.
Transportation	Transport, freight, lorry 7.5-16 metric ton, euro4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	60tkm	
Transportation	Transport, freight, lorry 7.5-16 metric ton, euro4 {RoW}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	0.06tkm	Transportation to Tecnaro
Electricity	Electricity, medium voltage {DE}| market for | APOS, S	336kWh	
Fuel	Diesel {Europe without Switzerland}| market for | APOS, S	33.54kg	
Material	Agricultural machinery, unspecified {CH}| production | APOS, S	15.366kg	
Emission to air	Dinitrogen monoxide	1.10kg	
Emission to air	Nitrogen oxides	1.30kg	
Emission to air	Ammonia	3.4kg	
Emission to air	NMVOC, non-methane volatile organic compounds, unspecified origin	334,6gg	
Emission to air	Nitrogen oxides, NO	834.19g	
Emission to air	Hydrocarbons, unspecified	91.3g	
Emission to air	Carbon dioxide, fossil	104.64kg	
Emission to air	Sulfur dioxide	33.88g	
Emission to air	Methane	4.33g	
Emission to air	Particulates, <2.5µ	1888g	
Emission to air	Chromium	167.7g	
Emission to air	Copper	0.06g	
Emission to air	Nitrogen dioxide	4.02g	
Emission to air	Nickel	0.002g	
Emission to air	Zinc	0.03g	
Emission to air	Ammonia	356.867g	
Emission to air	Selenium	0.0003g	
Emission to water [groundwater]	Phosphate	26.9g	
Emission to water [lake]	Phosphate	47.115g	
Emission to water [river]	Phosphate	47.115g	
Emission to soil	Nitrate	19.833kg	
Emission to soil	Emission to soil	334.6g	
Final waste	Dust, unspecified	52.63kg	

Hemp seeds (FOR 50KG OF SEED PRODUCTION)

Category	*Selected unit*	*Value*	*Comments*

Inputs from nature	Occupation, agriculture	0.018673 ha	
Inputs from nature	Carbon dioxide, in air	90kg	
Material	Potassium chloride (NPK 0-0-60), at plant/RER Mass	4.04kg	
Material	Ammonium nitrate, as 100% (NH4)(NO3) (NPK 35-0-0), at plant/RER Mass	2.748kg	
Material	Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, S	2.102kg	
Transportation	Transport, freight, lorry 7.5-16 metric ton, euro4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	2.92tkm	
Fuel	Diesel {Europe without Switzerland}| market for | APOS, S	1.627kg	
Material	Agricultural machinery, unspecified {CH}| production | APOS, S	740g	
Emission to air	Dinitrogen monoxide	35,73g	
Emission to air	Nitrogen oxides	35,73g	
Emission to air	Ammonia	164.9g	
Emission to air	NMVOC, non-methane volatile organic compounds, unspecified origin	16.25g	
Emission to air	Nitrogen oxides, NO	40.458g	
Emission to air	Hydrocarbons, unspecified	4.4279g	
Emission to air	Carbon dioxide, fossil	5.075kg	
Emission to air	Sulfur dioxide	1.643g	
Emission to air	Methane	0.21g	
Emission to air	Particulates, <2.5µ	91.58g	
Emission to air	Chromium	8.13345g	
Emission to air	Copper	0.00277g	
Emission to air	Nitrogen dioxide	0.1952g	
Emission to air	Zinc	0.00163g	
Emission to air	Ammonia	0.03253g	
Emission to water [groundwater]	Phosphate	1.31g	
Emission to water [lake]	Phosphate	2.33g	
Emission to water [river]	Phosphate	2.33g	
Emission to soil	Nitrate	961g	
Emission to soil	Emission to soil	16.25g	
PLA			
Category	*Selected unit*	*Value*	*Comments*
Transport	Transport, freight, lorry 7.5-16 metric ton, euro4 {RER}| market for transport, freight, lorry 7.5-16 metric ton, EURO4 | APOS, S	0.00319t km	
Materials	Polylactide, granulate {GLO}| production | APOS, S	0.430kg	

Compounding process at Tecnaro (1KG OF RESINS)

Electricity	Electricity, medium voltage {NI}| market for electricity, medium voltage | APOS, S	0.54 kWh
Material	Lignin	300g
Material	Hemp fibre	600g
Material	PLA	100g

Appendix E – LCI results: Top 20 substances contributing to toxicity

E.1. Top 20 substances contributing to terrestrial ecotoxicity

Table 31: Substances with most significant contribution to terrestrial ecotoxicity.

TET							
Substance	*Compartment*	*Solanyl resins*	*%*	*Arboform Resins*	*%*	*PS resins*	*%*
Copper	Air	3,35E-03	59,22	1,54E-03	70,00	1,05E-03	61,13
Zinc	Air	3,96E-04	6,99	2,59E-04	11,77	7,76E-05	4,53
Nickel	Air	5,68E-04	10,04	1,32E-04	6,01	5,36E-04	31,31
Vanadium	Air	1,02E-03	17,97	9,16E-05	4,17	8,09E-06	0,47
Mercury	Air	9,05E-05	1,60	5,63E-05	2,56	9,52E-06	0,56
Lead	Air	1,03E-04	1,82	3,95E-05	1,80	1,87E-05	1,09
Monoethanolamine	Air	1,29E-07	0,00	3,34E-05	1,52	5,78E-10	0,00
Cadmium	Air	4,44E-05	0,78	1,50E-05	0,68	1,30E-06	0,08
Chromium VI	Air	1,29E-05	0,23	6,87E-06	0,31	3,09E-07	0,02
Tin	Air	1,04E-05	0,18	6,08E-06	0,28	5,25E-06	0,31
Selenium	Air	1,61E-05	0,28	5,86E-06	0,27	3,36E-07	0,02
Silver	Air	1,54E-05	0,27	5,79E-06	0,26	6,73E-06	0,39
Cobalt	Air	1,08E-05	0,19	2,55E-06	0,12	1,83E-07	0,01
Barium	Air	2,60E-06	0,05	1,41E-06	0,06	1,15E-06	0,07
Chlorpyrifos	Soil	4,86E-06	0,09	1,16E-06	0,05	6,54E-11	0,00
Beryllium	Air	1,30E-06	0,02	3,86E-07	0,02	4,37E-08	0,00
Acetic acid	Air	1,09E-06	0,02	3,58E-07	0,02	3,05E-09	0,00
Atrazine	Soil	1,29E-06	0,02	3,02E-07	0,01	3,75E-12	0,00
Chlorothalonil	Soil	2,62E-07	0,00	2,38E-07	0,01	1,23E-09	0,00
Chloramine	Air	4,81E-06	0,09	2,09E-07	0,01	1,48E-10	0,00

E.2. Top 20 substances contributing to freshwater ecotoxicity

Table 32: Substances with most significant contribution to freshwater ecotoxicity.

FET							
Substance	*Compartment*	*Solanyl resins*	*%*	*Arboform Resins*	*%*	*PS resins*	*%*
Zinc	Water	2,74E-02	47,7908	1,94E-02	57,40	7,86E-03	57,133
Copper	Water	2,21E-02	38,6671	9,35E-03	27,72	4,62E-03	33,581
Nickel	Water	2,38E-03	4,1578	2,74E-03	8,12	3,16E-04	2,296
Vanadium	Water	1,60E-03	2,7877	8,38E-04	2,48	1,93E-04	1,401

Chromium VI	Water	6,28E-04	1,0973	5,23E-04	1,55	5,58E-04	4,059
Chlorpyrifos	Soil	8,18E-04	1,4292	1,96E-04	0,58	1,10E-08	0,000
Atrazine	Soil	7,10E-04	1,2400	1,66E-04	0,49	2,07E-09	0,000
Cobalt	Water	9,58E-05	0,1673	9,30E-05	0,28	5,87E-06	0,043
Barium	Water	1,29E-04	0,2253	7,83E-05	0,23	1,33E-05	0,096
Silver	Water	1,57E-04	0,2740	5,86E-05	0,17	1,28E-05	0,093
Beryllium	Water	6,48E-05	0,1133	5,54E-05	0,16	9,59E-05	0,697
Metolachlor	Soil	2,10E-04	0,3675	4,93E-05	0,15	3,03E-09	0,000
Selenium	Water	4,10E-05	0,0717	3,43E-05	0,10	3,68E-06	0,027
Terbufos	Soil	1,02E-04	0,1789	2,57E-05	0,08	4,63E-09	0,000
Pyrene	Water	1,58E-05	0,0277	2,29E-05	0,07	3,62E-08	0,000
Cadmium	Water	3,05E-05	0,0533	1,69E-05	0,05	4,96E-06	0,036
Mercury	Water	7,37E-06	0,0129	1,21E-05	0,04	3,50E-06	0,025
Fluoranthene	Water	7,18E-06	0,0125	1,04E-05	0,03	1,64E-08	0,000
Chloroacetic acid	Water	1,14E-04	0,1985	1,03E-05	0,03	1,28E-09	0,000
Diflubenzuron	Soil	1,17E-05	0,0204	8,27E-06	0,02	8,10E-08	0,001

E.3. Top 20 substances contributing to marine ecotoxicity

Table 33: Substances with most significant contribution to marine ecotoxicity.

MET							
Substance	*Compartment*	*Solanyl resins*	*%*	*Arboform Resins*	*%*	*PS resins*	*%*
Zinc	Water	4,69E-02	51,94	3,40E-02	61,38	1,33E-02	58,44
Copper	Water	3,14E-02	34,79	1,33E-02	23,95	6,54E-03	28,81
Nickel	Water	3,52E-03	3,90	4,05E-03	7,31	4,66E-04	2,05
Vanadium	Water	2,69E-03	2,98	1,41E-03	2,55	3,25E-04	1,43
Chromium VI	Water	1,12E-03	1,24	9,33E-04	1,68	9,97E-04	4,39
Copper	Air	1,41E-03	1,56	6,47E-04	1,17	4,41E-04	1,94
Zinc	Air	3,37E-04	0,37	2,21E-04	0,40	6,65E-05	0,29
Cobalt	Water	1,41E-04	0,16	1,37E-04	0,25	8,64E-06	0,04
Barium	Water	2,18E-04	0,24	1,32E-04	0,24	2,25E-05	0,10
Beryllium	Water	9,93E-05	0,11	8,48E-05	0,15	1,47E-04	0,65
Silver	Water	2,11E-04	0,23	7,90E-05	0,14	1,73E-05	0,08
Vanadium	Air	8,40E-04	0,93	7,56E-05	0,14	6,68E-06	0,03
Nickel	Air	3,18E-04	0,35	7,36E-05	0,13	3,02E-04	1,33
Chlorpyrifos	Soil	3,07E-04	0,34	7,36E-05	0,13	4,14E-09	0,00
Selenium	Water	6,09E-05	0,07	5,10E-05	0,09	5,48E-06	0,02
Cadmium	Water	4,29E-05	0,05	2,47E-05	0,04	6,90E-06	0,03
Atrazine	Soil	7,07E-05	0,08	1,65E-05	0,03	2,06E-10	0,00
Mercury	Water	9,17E-06	0,01	1,49E-05	0,03	4,30E-06	0,02
Thallium	Water	2,60E-05	0,03	1,14E-05	0,02	6,25E-07	0,00
Mercury	Air	1,58E-05	0,02	9,83E-06	0,02	1,66E-06	0,01

E.4. Top 20 substances contributing to human toxicity (carcinogenic)

Table 34: Substances with most significant contribution to human toxicity (carcinogenic).

CARC							
Substance	*Compartment*	*Solanyl resins*	*%*	*Arboform Resins*	*%*	*PS resins*	*%*
Nickel	Soil	0,027357423	47,79	0,0193697	57,40	0,0078596	57,13296
Propane, 1,2-dichloro-	Water	0,02213464	38,67	0,0093547	27,72	0,0046196	33,58077
Hexane	Water	0,002380107	4,16	0,0027394	8,12	0,0003158	2,29590
Diethylene glycol	Air	0,001595803	2,79	0,0008377	2,48	0,0001927	1,40089
Ethane, 1,2-dibromo-	Water	0,000628136	1,10	0,0005225	1,55	0,0005584	4,05893
Benzaldehyde	Water	0,000818124	1,43	0,0001958	0,58	1,102E-08	0,00008
Pronamide	Soil	0,000709803	1,24	0,0001661	0,49	2,066E-09	0,00002
Diethylene glycol	Water	9,57522E-05	0,17	9,3E-05	0,28	5,871E-06	0,04268
Carbaryl	Water	0,000128979	0,23	7,829E-05	0,23	1,326E-05	0,09638
Mane	Soil	0,000156836	0,27	5,857E-05	0,17	1,276E-05	0,09276
Dibenz(a,h)anthracene	Water	6,48438E-05	0,11	5,538E-05	0,16	9,592E-05	0,69724
t-Butyl methyl ether	Water	0,000210392	0,37	4,933E-05	0,15	3,028E-09	0,00002
Fosetyl-aluminium	Soil	4,10255E-05	0,07	3,43E-05	0,10	3,682E-06	0,02677
Acrylonitrile	Water	0,000102429	0,18	2,566E-05	0,08	4,632E-09	0,00003
Carbaryl	Soil	1,5847E-05	0,03	2,287E-05	0,07	3,616E-08	0,00026
Benzo(a)pyrene	Water	3,05133E-05	0,05	1,689E-05	0,05	4,958E-06	0,03604
Aniline	Air	7,36721E-06	0,01	1,206E-05	0,04	3,498E-06	0,02543
Acetamide	Air	7,1824E-06	0,01	1,037E-05	0,03	1,639E-08	0,00012
Acifluorfen	Soil	0,000113649	0,20	1,028E-05	0,03	1,277E-09	0,00001
Isoprene	Air	1,16918E-05	0,02	8,27E-06	0,02	8,103E-08	0,00059

E.5. Top 20 substances contributing to human toxicity (non-carcinogenic)

Table 35: Substances with most significant contribution to human toxicity (non-carcinogenic).

Non-CARC							
Substance	*Compartment*	*Solanyl resins*	*%*	*Arboform Resins*	*%*	*PS resins*	*%*
Zinc	Soil	0,0068266	41,30	-0,0001109	-1,67	8,975E-06	0,3267944
Nickel	Soil	2,718E-08	0,00016	-1,964E-09	0,00	7,221E-09	0,0002629
Allyl chloride	Water	-2,642E-08	-0,00016	-1,415E-13	0,00	-3,718E-14	-1,354E-09
Ethane, 1,1,1-trichloro-, HCFC-140	Water	1,427E-19	8,635E-16	2,987E-20	0,00	1,828E-21	6,655E-17
Ethephon	Water	7,171E-19	4,339E-15	5,838E-19	0,00	9,79E-22	3,564E-17
Methomyl	Water	1,622E-18	9,814E-15	1,32E-18	0,00	2,214E-21	8,061E-17
Tebuconazole	Water	2,431E-18	1,471E-14	1,979E-18	0,00	3,318E-21	1,208E-16
Chromium III	Soil	0	0	4,257E-18	0,00	0	0
Ethane, 1,2-dibromo-	Water	0	0	5,145E-18	0,00	0	0
Propane, 1,2-dichloro-	Water	0	0	8,818E-18	0,00	0	0

Tebuconazole	Air	1,47E-17	8,897E-14	1,197E-17	0,00	2,007E-20	7,309E-16
Diethyl ether	Air	5,641E-17	3,413E-13	1,348E-17	0,00	1,965E-18	7,153E-14
Hexane	Water	0	0	1,503E-17	0,00	0	0
4-Methyl-2-pentanone	Air	4,618E-17	2,794E-13	4,201E-17	0,00	2,687E-19	9,784E-15
Methomyl	Soil	1,217E-16	7,366E-13	9,911E-17	0,00	1,662E-19	6,051E-15
Ethephon	Air	2,587E-16	1,565E-12	2,106E-16	0,00	3,531E-19	1,286E-14
Anthracene	Air	1,27E-19	7,684E-16	4,157E-16	0,00	2,866E-22	1,043E-17
Pyrene	Air	1,187E-15	7,183E-12	4,473E-16	0,00	6,351E-16	2,312E-11
Pronamide	Soil	5,214E-15	3,155E-11	5,326E-16	0,00	9,719E-18	3,539E-13
Thiodicarb	Soil	1,859E-15	1,125E-11	1,231E-15	0,00	1,433E-17	5,217E-13

Appendix F – Impact results

F.1. The changes for each impact category for Solanyl® and Arboform® resins in comparison to PS.

Table 36: Increase and decrease in impact per impact category for Solanyl and Arboform in comparison to PS. (- indicates a decrease in impact compared to PS while no sign indicates an increase)

Impact category	Solanyl resins	Arboform resins
Global warming	-35%	-47%
Stratospheric ozone depletion	22542%	20843%
Ionizing radiation	5951%	5704%
Ozone formation, Human health	-4%	-52%
Fine particulate matter formation	54%	11%
Ozone formation, Terrestrial ecosystems	-6%	-53%
Terrestrial acidification	54%	1%
Freshwater eutrophication	1623%	1722%
Marine eutrophication	25272%	1962%
Terrestrial ecotoxicity	230%	28%
Freshwater ecotoxicity	316%	145%
Marine ecotoxicity	297%	144%
Human carcinogenic toxicity	22%	-2%
Human non-carcinogenic toxicity	502%	142%
Land use	39228%	60186%
Mineral resource scarcity	714%	604%
Fossil resource scarcity	-64%	-70%
Water consumption	167%	-31%

F.2. Normalized impact results in percentages

Table 37: Externally impact results presented in percentage. The values represent the percentage of the average global impact of one person per year. Orange indicates the values above 0.05%.

Impact category	Solanyl resins	Arboform Resins	PS resins
Global warming	0.03%	0.03%	0.05%
Stratospheric ozone depletion	0.02%	0.02%	0.00%
Ionizing radiation	0.03%	0.03%	0.00%
Ozone formation. Human health	0.03%	0.02%	0.03%
Fine particulate matter formation	0.02%	0.01%	0.01%
Ozone formation. Terrestrial ecosystems	0.04%	0.02%	0.04%
Terrestrial acidification	0.04%	0.02%	0.02%
Freshwater eutrophication	0.14%	0.15%	0.01%
Marine eutrophication	0.06%	0.01%	0.00%
Terrestrial ecotoxicity	0.57%	0.22%	0.17%
Freshwater ecotoxicity	5.72%	3.37%	1.38%
Marine ecotoxicity	9.02%	5.54%	2.27%
Human carcinogenic toxicity	2.68%	2.14%	2.19%
Human non-carcinogenic toxicity	1.65%	0.66%	0.27%
Land use	0.03%	0.04%	0.00%
Mineral resource scarcity	0.00%	0.00%	0.00%
Fossil resource scarcity	0.07%	0.06%	0.19%
Water consumption	0.05%	0.01%	0.02%