Comparative Life Cycle Assessment of Single-Serve Coffee Packaging in Ontario

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Single-serve coffee pods are occupying a growing share in the coffee market. In Ontario, with 14 million people, it is estimated that 2 billion single-serve coffee pods are consumed annually, the consumption of which generates 30,000 tons of landfill waste in Ontario, equivalent to 0.3% of total landfill waste generated in the province in 2014.

Different formats of coffee pods have been introduced, and each addresses the waste problem differently. Two examples are recyclable coffee pods made of aluminum and compostable coffee pods made from biodegradable polymers. In this research, these two coffee pod formats are investigated together with a typical petroleum-based plastic coffee pod, which represents the baseline landfilling scenario. A cradle-to-grave life cycle assessment (LCA) is conducted to quantify and compare the environmental effects of these systems, with a special focus on packaging materials and end-of-life management.

The results show that among the three investigated coffee pods, the recyclable aluminum format has the highest potential environmental effects across nine impact categories. Whereas, the Biodegradable Pod, which is assumed to be composted in 40% of uses, has reduced greenhouse gas emissions and landfill waste generation potential when compared with the petroleum-based plastic coffee pod. After applying a standard LCA weighting, results indicate that human toxicity is the most important life cycle impact assessment indicator result associated with all three of coffee pod formats.

This research is important from both a biodegradable material and a circular economy perspective. From a biodegradable material perspective, this study is the first to compare polylactic acid, a bio-based biodegradable polymer, with polystyrene, a petroleum-based non-degradable plastic. Biodegradable materials enable consumers easily to compost the coffee waste together with the coffee pod, but at the same time, it requires an extra plastic packaging warp for each coffee pod. From a circular economy perspective, the study is important because the results indicate the strength of using compostable biological nutrients over recyclable technical nutrients in the context of small single-use food products. Like all LCA studies, the results are dependent on specific assumptions and scenarios analyzed.

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List of Abbreviations

14DCB	1,4-Dichlorobenzene
Al	Aluminum
ASTM	American Society for Testing and Materials
BPI	Biodegradable Products Institute
CAD	Canadian Dollars
CE	Circular Economy
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTUe	Comparative Toxic Unites for environment
CTUh	Comparative Toxic Unites for human
EMF	Ellen MacArthur Foundation
EOL	End of Life
EPA	United States Environmental Protection Agency
Eq.	Equivalent
EVOH	Ethylene Vinyl Alcohol
FAO	Food and Agriculture Organization of the United Nations
GEO5	Global Environment Outlook 5
GHG	Greenhouse Gases
GWP	Global Warming Potential
HQCF	High-Quality Composting Facility
H_2S	Hydrogen Sulfide
IESO	Independent Electricity System Operator
ISO	International Organization of Standardization
IWM	Integrated Waste Management
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density Polyethylene
MSWM	Municipal Solid Waste Management
NE	New England
NH_3	Ammonia
N_2O	Nitrous Oxide
NZWC	National Zero Waste Council of Canada
ON	Ontario
OPS	Oriented Polystyrene
Pb	Lead
PBS	polybutylene succinate
PCL	Polycaprolactone

PE	Polyethylene
PET	Polyethylene Terephthalate
PLA	Polylactic Acid
PlasticsEurope	Plastics Industry Association in Western Europe
PM	Particulate Matter
PP	Polypropylene
PS	Polystyrene
RPRA	Resource Productivity and Recovery Authority
SBB	Solid Bleached Board
SimaPro	System for Integrated Environmental Assessment of Products
SUB	Solid Unbleached Board
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
UCTE	Union for the Coordination of the Transmission of Electricity
UNEP	United Nation Environment Program
USDA	United States Department of Agriculture
USEIA	United States Energy Information Administration
USEPA	United States Environment Protection Agency
VOC	Volatile Organic Compounds

Chapter 1

Introduction

1.1 Coffee Pods in Ontario

Coffee is the most popular prepared beverage among adult Canadians. According to market research, 67% of adult Canadians enjoy at least one cup of coffee a day with the average at 3.0 cups/day, and 29% of their coffee beverage are brewed by single-serve pod machines (Coffee Association of Canada, 2017). In Ontario, the home of 14 million people (Statistics Canada, 2017), it is estimated that 2 billion single-serve coffee pods are consumed annually. With a large and growing market size, the environmental effects of single-serve coffee pod are necessary to be estimated.

Single-serve coffee pod in this study is a packaging system, which contains a small amount of ground coffee, could be used in a special coffee brewing machine to make a cup of coffee for an individual. Such coffee pod was brought into the market as early as 1976 by the Swiss food and beverage giant, Nestlé (LA Société, 2008). Its development was slow in 1970s and 1980s, because of the high price of a pod and a brewing machine. But in 1997, a new product called K-Cup was invented by Green Mountain Coffee Roasters. This new product used plastics instead of aluminum for the pod body and reduced the cost of the pod (Keurig Green Mountain, 2016). The low priced single-serve coffee pod shocked the coffee beverage market t with its convenience in making a freshly brewed coffee. Since then, the market of single-serve coffee pod has experienced a rapid growth. In the fiscal year of 2016, Keurig Green Mountain (formerly Green Mountain Coffee Roasters) sold 57 billion coffee pods globally (Keurig Green Mountain, 2016), equivalent to CAD 34 billion. Nespresso, a coffee pod brand owned by Nestlé, also reported annual sales of 3 billion Swiss Franc, or CAD 3.85 billion, in 2011 (Nestlé, 2011). In Europe, pod machines have become the second most common preparation method after a filter drip coffee maker by the year of 2011. It is indicated that 23% of German people use pod machines (Brommer, Stratmann, & Quack, 2011.).

However, the coffee pods are not welcomed by everyone. Media has been criticizing the K-Cup for its single-use of petroleum materials and creating landfill waste for years (Oatman, 2014; Hamblin, 2015; Gelles, 2016). The Germen city of Hamburg even banned coffee pods from state-run buildings as part of an environmental drive to reduce waste (BBC News, 2016). In Province of Ontario, the estimated 2 billion coffee pod annual consumption would generate 30,000 tons of waste at 15 g per pods, equivalent to 0.3% of landfilled waste generated in the province in 2014 (Statistics Canada, 2016). Ontario, who declared their ambitions in reducing greenhouse gas emission and being waste-free (Ontario Ministry of Environment and Climate Change, 2016a, 2016b), should be conscious of the environmental burdens of the consumption of single-serve coffee pods.

1.2 Ontario's Environmental Plans

Ontario has the second highest total provincial greenhouse gas (GHG) emissions of any province in Canada, with 166.2 megatons of carbon dioxide equivalent greenhouse gases in 2015 (Environment and Climate Change Canada, 2017). Ontario leads in the volume of waste disposal in Canada, generating 9.2 million tons of waste in 2014 (Statistics Canada, 2016). To decrease GHG emissions and waste generation, the Ontario Ministry of Environment and Climate Change put forward the Ontario's Five-Year Climate Change Action Plan and the Strategy for a Waste-Free Ontario in 2016 (Ontario Ministry of Environment and Climate Change, 2016a, 2016b). In the latter document, building a circular economy was written into a provincial strategy in Canada for the first time.

1.2.1 Five Year Climate Change Plan

Ontario's people and businesses are already feeling the effects of global warming and paying the price. Climate change has damaged the environment and has caused extreme weather events such as flooding and drought, and has hurt the ability to grow food in some regions (Ontario Ministry of Environment and Climate Change, 2016). Ontario's Five-Year Climate Change Action Plan ("Action Plan") stressed climate change as a grave concern, and highlighted the actions required for the next five years (2016-2020) to address climate change, reduce greenhouse gas pollution and help move us to a prosperous low-carbon economy (Government of Ontario, 2016).

According to Ontario's Climate Change Update 2014, transportation and industry remain to be the two largest GHG emitting sectors in Ontario since 1990. However, the industrial sector succeeded in reducing emissions by 14% compared to 1990, whereas transportation sector has an 11% higher emission (Government of Ontario, 2014). The Action Plan sees reducing the emissions from transportation sector as the most important target. Approaches that are put forward in the Action Plan associated with transportation include promoting lower-carbon fuels and electric vehicles, supporting cycling and walking, increasing the use of low-carbon trucks and buses, and developing public transits (Ontario Ministry of Environment and Climate Change, 2016a). The Action Plan also emphasizes other action areas, such as buildings and homes, land-use planning, and industry and business. As conclusion, the Action Plan emphasizes public involvement and mobilizes all stakeholders to act together to fight climate change.

1.2.2 Waste-Free Ontario

At the same time when the Action Plan was released, the Ontario Ministry of Environment and Climate Change was also drafting the Strategy for a Waste-Free Ontario Building the Circular Economy ("The Strategy"). The goals of The Strategy are to achieve a zero waste Ontario and zero greenhouse gas emission from the waste sector, and to achieve a transformation to a circular economy (Ontario Ministry of Environment and Climate Change, 2016). To achieve a waste-free

Ontario, The Strategy puts forward four functional objectives and a series of actions to attain them, these objectives are

- To enhance provincial direction and oversight
- To enable efficient and effective recovery systems
- To increase waste reduction and improve resource productivity, and
- To create conditions for sustainable end-markets.

Among the actions, “waste diversion” and “resource recovery” are two keywords that are brought up multiple times.

The current research is expected to help waste diversion and resource recovery by providing a case study on coffee pod packaging systems. As a single-use product that has a high sales volume, coffee pods are generating 30,000 tons of packaging waste (2 billion pods multiplied by 15g per pod) every year in Ontario. Different pod formats on the market are made from different materials and therefore fall under different waste management approaches. In this study, the comparison between different coffee pods formats can identify the one that has higher possibility and value to be diverted from landfill and may provide a generalizable reference for design of other single-use product.

Chapter 2

Literature Review

2.1 Single-Serve Coffee Pod

2.1.1 Waste Problem

The popularity of single-serve coffee pods in Europe and North America could not be overstated, but its inefficient usage of packaging materials has created a waste problem. Take a common coffee pod in the market, for example, the K-cup is made of 2.41 g of composite plastic, 0.22 g of aluminum foil and 0.31 g of paper, and packaged in 2.88 g of cardboard on average. A total amount of 5.77 g materials is used for the package of 9.81 g of coffee. On the other hand, a bulk package system using a traditional stand-up pouch requires 2.57 g of materials to package the same amount of coffee (Humbert et al., 2009). The plastic composite and the structure of a coffee pod make it impossible to be recycled in most municipal and industrial recycling facilities. It turns out that billions of coffee pods end up being buried in the landfills or incinerated across the world (Humbert et al., 2009). Media criticized that used K-Cups in 2013 were enough to wrap around the equator 10.5 times (Oatman, 2014). Although recyclable coffee pods are available in the market, but they are also criticized for their low recycling rate (Gelles, 2016; Bali, 2017)

Sustainability of coffee cultivation and coffee product systems have been an academic topic of interest (Chayer & Kicak, 2015; Dubois, Humbert, & Margni, 2011; Jaffee, 2014; Manezes, Finzer, & Oliveira, 1998), because of their large consumption volume in developed countries and socio-economic implications of its production in developing countries (Hassard, Couch, Techa-Erawan, & Mclellan, 2014). 8 million metric tons of coffee beans were consumed globally in 2016, half of which were produced in Brazil and Colombia (International Coffee Organization (ICO), 2017). Efforts have been made to quantify the energy use and other environmental burdens of the life cycle of coffee products. A full life cycle inventory of Brazilian green coffee bean agriculture (Coltro, Mourad, Oliveira, Baddini, & Kletecke, 2006) has been an important basis for many life cycle assessment studies of coffee beverages (Büsser & Jungbluth, 2009; Chayer & Kicak, 2015; Dubois et al., 2011; Humbert, Loerincik, et al., 2009). Most of the available coffee beverage studies focused on traditional coffee brewing methods, i.e. a filter drip coffee maker. Their results show that coffee bean cultivation and use stage are the two main sources of greenhouse gas (GHG) emission. Coffee bean cultivation relies on nitrogen fertilizer which causes the emission of a strong greenhouse gas, nitrous oxide (N_2O) (Büsser & Jungbluth, 2009; Chayer & Kicak, 2015; Hassard et al., 2014). Heating water and keeping coffee warm in use stage is responsible for half of the life-cycle energy consumption, which also causes GHG emission (Büsser & Jungbluth, 2009; Dubois et al., 2011; Haas, Krausmann, Wiedenhofer, & Heinz, 2015; Humbert, Loerincik, et al., 2009). These studies also indicated that packaging is not an influential stage in a bulk package scenario. However, other studies comparing between a single-serve brewing system and a drip filter brewing system indicated that packaging materials and their production play more important roles in the life cycle of a single-serve coffee pod, because more packaging materials required for small amount of coffee (Brommer et al., 2011; Chayer & Kicak, 2015; Dubois et al., 2011).

2.1.2 Innovations for Coffee Pod Packaging

The coffee pod industry is looking for a solution to handle the waste problem and to increase resource efficiency. Developing recyclable or compostable pods are two potential strategies. As early as 1991, Nespresso launched the world's first capsule recycling system in Switzerland. Nespresso provides two options for customers to recycle their used pods. They can either take the used pods back to the Nespresso Boutique, where the recycler will collect the pods and send them to a recycling facility, or the consumers can separate ground coffee from the used pod, and put the aluminum shell into their household recycling bin for municipal recycling service. By 2013, Nespresso had reached 75% global recycling capacity, achieved with the help of some 14,000 dedicated capsule collection points operational around the world (Nespresso, 2017). However, recycling capacity does not ensure recycling rate in practice. Although Nespresso has set up a complete pod recycling route and has made continuous effort to encourage their customers to recycle used pods, only 24% of their used pods were recycled in 2016 (Nestlé Nespresso S.A., 2017). According to environmental authority of Ontario, municipal recycling facilities in Ontario don't accept an enclosed Nespresso pod as recyclable waste (Ren, 2017). Additionally, the distribution of Nespresso Boutique in Ontario is less intensive than Europe, consumers tend to buy the capsules online. It is rational to believe that the Nespresso recycling rate in Ontario is lower than global average. In this study, it is assumed that its recycling rate in Ontario is 14%. Bali (2017), an informant from the coffee pod industry, indicated that low recycling rate of Nespresso overall is because consumers prefer single serve pods rather than bulk coffee as they are convenient and time-saving, but recycling the pods takes coffee consumers extra time.

Compostable pod is another direction that the industry is working on. In 2016, a new product, called PURPOD100™, was launched in the market by a coffee roaster company based in Ontario. According to information disclosed by the National Zero Waste Council of Canada (NZWC), the main materials used for PURPOD100™ are polylactic acid (PLA) and other compostable biobased polymers (NZWC, 2017). This pod is claimed to be "100% compostable" and "the first coffee pod to earn certification from the Biodegradable Products Institute (BPI)" (Club Coffee, 2016). The producer claims that this coffee pod can break down in twelve weeks in well-managed municipal composting facilities (Club Coffee, 2016). In the US, PURPOD100™ is accepted as compostable waste by many municipal composting facilities, but in Ontario, it has not been accepted in any of the composting facilities yet (Recycling Today, 2016). It is reported that the situation in Ontario can be improved if the funding for municipal composting facilities is increased (Club Coffee, 2016; Mckillop, 2017; Ren, 2017).

Recyclable and compostable pods are both available in the Ontario market. In this study, a typical petroleum plastic coffee pod, representing a traditional landfilling scenario, is used as the baseline for the comparison between a recyclable aluminum pod and a compostable biobased polymer pod.

2.2 New Polymers

Polylactic acid (PLA) and other biobased polymers are used as raw materials in PURPOD100™. The term biobased, according to the definition from European Bioplastics and the U.S. Department of Agriculture (USDA), means that the material is (partly) derived from biomass, or produced from living organisms (European Bioplastics, 2017; Golden, J; Handfield R; Daystar, J; McConnell, 2015). USDA further defined biobased polymers as polymers that produced by living organisms that form long chains by the interlinking of repeating chemical blocks (Golden et al., 2015). Biobased polymers can be natural or synthetic. Cellulose and starch are two examples of biobased polymers that are abundant in nature. The history of artificial synthesis of biobased polymer dates back to 1860s, when celluloid was invented, and since then, many other biobased polymers have been developed (Dodiuk & Goodman, 2013).

2.2.1 Biodegradability

Biodegradability is another term that is commonly referred to when people talk about new polymer materials. But being biodegradable and biobased are not the same (Ellen MacArthur Foundation (EMF), 2016). Being biodegradable means a material is capable of being decomposed by biological agents (Golden et al., 2015). Not all biodegradable polymers are biobased: polycaprolactone (PCL) and most polybutylene succinate (PBS) are petroleum based, but they can be degraded by microorganisms. Vice versa, biobased polymers are not necessary to be biodegradable, e.g. biobased polyethylene and Nylon 11 (Tokiwa, Calabia, Ugwu, & Aiba, 2009).

The interest in the development and production of biodegradable polymers arose in 1990s in response to problems associated with plastic waste and its effect on the environment (Poirier, Nawrath, & Somerville, 1995). The difficulty in recycling highly contaminated plastic, and the high (energy) cost have limited the effect of mechanical recycling. Generation of dioxins and other toxic products has made incineration unwelcomed by municipal residences. When neither mechanical recycling nor incineration provides a complete solution to the problem of plastics wastes, biodegradation becomes an attractive ecological alternative to locking away polymer wastes in expensive landfills. (Scott, 2002)

The application of biodegradable polymers is the most common in food packaging (Pawar & Purwar, 2013; Siracusa, Rocculi, Romani, & Rosa, 2008) and medicine (Dash & Konkimalla, 2012; Reed & Gilding, 1981). Biodegradable polymers are preferable to the non-degradable in food packaging because the package is often contaminated by foodstuff and biological substance and difficult to recycle, but contamination does not bother degradation (Siracusa et al., 2008). The medical use of biodegradable polymer has a long history (Gilding & Reed, 1979). Because a series of biodegradable polymers can be degraded and absorbed by human body, and is harmless, they were first used in bone surgeries later in drug delivery and tissue engineering (Dash & Konkimalla, 2012; Reed & Gilding, 1981).

2.2.2 Polylactic Acid (PLA)

Polylactic acid (PLA) is a highly versatile linear aliphatic thermoplastic polyester that is both biobased and biodegradable (Drumright, Gruber, & Henton, 2000; Martin.O, 2001; Tokiwa & Calabia, 2006). Enantiomerically pure PLA is semi-crystalline polymer with a glass transition temperature of about 55 ℃ and melting point of about 180 ℃, and soluble in chlorinated or fluorinated organic solvents, dioxane, dioxolane, and furan (Södergård & Stolt, 2002). The mechanical properties of PLA are comparable to polystyrene (PS) and polyethylene (PE) (Tokiwa & Calabia, 2006). But the physical, chemical and mechanical properties of PLA composites can be varied to a large extent according to the lactic acid chiral molecular structures (D-Lactide, L-Lactide or meso-lactide) and the use of additives (Ellen MacArthur Foundation (EMF), 2016; Martin.O, 2001; Södergård & Stolt, 2002).

The commercial production of PLA from corn starch started in 1994 by a company called Cargill Inc., who used and is still using the technology of ring-opening polymerization of lactides (Vink et al., 2003, 2015). Nowadays, PLA is used in a wide range of applications, including food service ware; films and sheet; rigid, thermoformed packaging; fibers and nonwovens; three-dimensional printing; and durable products (Vink & Davies, 2015).

The production of PLA can use starch derived from different feedstocks. The choice of starch feedstock depends on the local availability in the production locations, for example corn in the USA (Vink & Davies, 2015), sugarcane in Thailand (Groot & Borén, 2010), and rice in Japan (Fukushima, Sogo, Miura, & Kimura, 2004). Considering the availability, the current research assumes that PLA in PURPOD100 are sourced from a facility in Blair, Nebraska, USA, which is owned by NatureWorks, owned by Cargill Inc. NatureWorks, who named their PLA polymer as Ingeo, published a cradle-to-polymer factory gate life cycle inventory data for PLA production every couple years since 2003 (Vink et al., 2003, 2007, 2010, 2015). According to the latest report (Vink & Davies, 2015), the production of 1 kg Ingeo (PLA) uses the starch fraction of 2.67kg corn (15% moisture) or the starch from 400,500 t of corn if running the Ingeo production plant at full capacity. This represents the starch from 0.11% of total 2014 US corn production and 0.04% of world corn production. And for other corn product markets, e.g. corn oil, gluten feed and gluten meal markets would remain unaffected. The feedstock from corn, sugarcane or rice, is categorized as 1st Generation of feedstock, which is defined as biomass from plants that are rich in carbohydrates and that can be used as food or animal feed, by EMF, who envisions the use of plants that are not suitable for food or animal feed (2nd Generation) and biomass derived from algae (3rd Generation) as feedstock (Ellen MacArthur Foundation (EMF), 2016).

Food packages made from PLA are usually compared with those made from petroleum plastics in terms of environmental impacts with life cycle assessment (LCA) (Datzel & Krüger, 2006; Gironi & Piemonte, 2009; Suwanmanee et al., 2013). Datzel & Krüger (2006) and Gironi & Piemonte (2009) compared clam shell food containers and water bottles made from NatureWorks PLA produced in the U.S. against those made from petroleum plastics (e.g. polypropylene (PP), oriented polystyrene (OPS), and polyethylene terephthalate (PET)). Both of their results showed that PLA system has advantages compared to petroleum plastic systems in the categories of Fossil Resource Consumption, Global Warming and Smog, while it has disadvantages in Acidification, Terrestrial Eutrophication, Human Toxicity and Land Use. Their results are consistent with Weiss et al. (2012) who reviewed 44 LCA studies that cover about 60 individual biobased materials. However, when Suwanmanee et al. (2013) compared boxes made from PLA granules, which is produced in Thailand, with PS boxes from cradle to factory gate, PLA boxes have much higher GHG, acidification and smog emissions. The contrast between PLA produced in the U.S. and Thailand is caused by the Thai electricity grid mix, in which 94% generation is from fossil fuel power plants (Suwanmanee et al., 2013). Producing PLA from starch consumes a large amount of electricity, which therefore enlarges the impact of electricity grid mix.

2.2.3 Industrially Compostable Product

PURPOD100™ is certified as an industrially compostable product by BPI with compliance to American Society for Testing and Materials (ASTM) D6868 "Standard Specification for Labeling of End Items that Incorporate Plastics and Polymers as Coatings or Additives with Paper and Other Substrates Designed to be Aerobically Composted in Municipal or Industrial Facilities" (BPI, 2016; ClubCoffee, 2016). The Compostable Logo provided by BPI, as a prove of certification, is printed on the exterior package of PURPOD100™.

BPI is a not-for-profit association of key individuals and groups from government, industry and academia, which promotes the use, and recycling of biodegradable polymeric materials (via composting). BPI provides a certification for products onto which compostability testing was conducted and was demonstrated compliance with ASTM D6400 or ASTM D6868 (BPI, 2017). ASTM standards are set by ASTM International. ASTM International, organized in 1898, is one of the world's largest international standards developing organization. The types of standard set by ASTM International covers test method, specification, guide, practice, classification and terminology (ASTM International, 2017a). ASTM D6400 and D6868 standard defines industrially compostable plastics and product in North America (EMF, 2016)

A product is compostable, according to ASTM D6400 and D6868 standard, meets the following requirements:

- *Disintegration During Composting* – after twelve weeks (84 days) in a controlled composting test, no more than 10% of its original dry weight remains after sieving on a 2.0-mm sieve.

- *Biodegradation* – 90% of the organic carbon in the whole item or for each organic constituent shall be converted to carbon dioxide within a 180 days period at 58°C (±2°C).
- *Support Plant Growth* – the end item shall have concentrations of heavy metals less than 50%, and the germination rate and the plant biomass of the sample composts shall be no less than 90% of blank composts. (ASTM International, 2012, 2017b)

2.3 Circular Economy

It is evident that the concept of circular economy (CE) has recently gain importance for academia, policymakers and companies (Geissdoerfer, Savaget, Bocken, & Jan, 2017; Ghisellini, Cialani, & Ulgiati, 2016). CE, as alternative to a traditional take-make-dispose linear economic system (Bocken, Olivetti, Cullen, Potting, & Lifset, 2017), has inspired the administration of Ontario. In the Waste-Free Ontario Strategy, building a circular economy was written into a provincial strategy in Canada for the first time (Ontario Ministry of Environment and Climate Change, 2016). Although CE is still a developing concept, it provides conceptual framework for Ontario to build a more eco-efficient and sustainable future.

2.3.1 Evolvement and Definition

The concept of CE has been evolving since the late 1970s (EMF, 2013). Ghisellini et al. (2016) stressed in their review on the development of CE that the concept of CE was initially inspired by Boulding (1966), whose idea of economy as a circular system is seen as a prerequisite for the maintenance of the sustainability of human life on Earth. Ghisellini et al. (2016) credited Pearce & Turner (1990) as scholars who primarily introduced the concept of CE based on Boulding's (1966) idea, and explained the shift from the traditional open-ended economic system to the circular economic system as a consequence of the law of thermodynamics that dictate matter and energy degradation, and identify economic functions of the environment as: provision of resources, life support system, and sink for waste and emissions.

McDonough & Braungart (2002) inspected the cradle-to-grave production system emerged since industrial revolution, and propagated a cradle-to-cradle system. McDonough & Braungart (2002) also introduced how products and materials circulate in a cradle-to-cradle system, and put forward the concept of biological nutrients and technical nutrients. Biological nutrients are materials, which can safely be returned to the biosphere, should flow within a biological metabolism; and technical nutrients, which cannot be broken down and safely absorbed by biological systems, should flow in the technical metabolism (Brennan, Tennant, & Blomsma, 2013; McDonough & Braungart, 2002). The biological and technical nutrient framework was further illustrated by EMF (2013) with their famous "butterfly figure", and the figure has been instrumental in visualizing a hierarchy of circularity strategies (reuse, repair, refurbishment, remanufacturing, repurpose, and recycling) (Bocken et al., 2017).

The definitions of CE vary from different academic studies or policy documents. In the current study, CE is defined as an economic system in which material flows are either made up of biological nutrients designed to re-enter the biosphere, or materials designed to circulate within the economy through reuse or recycle. This definition is in line with the framework from McDonough & Braungart (2002) and EMF (2013), and is in line with the definition in The Global Environment Outlook 5 (GEO5) written by United Nation Environment Program (UNEP) (Haas et al., 2015; United Nations Environment Programme, 2012).

2.3.2 Implementations

CE has wide scope of implementation, and it happens at micro, meso and macro level (Ghisellini et al., 2016). Implementing CE at micro level guides the behavior of a single company or consumer. For a company, the application of CE covers areas from business model (Bocken et al., 2016; Lieder & Rashid, 2016), product design (Brennan et al., 2013; den Hollander, Bakker, & Hultink, 2017), cleaner production (Hicks & Dietmar, 2007; Shi, Peng, Liu, & Zhong, 2008), and product recycling and reuse (Cooper & Gutowski, 2015). CE is implemented among consumers by promoting the purchase and use of sustainable products and services. Functional instruments for green consumers are specific information and labelling systems covering food, non-food products, as well as services (Ghisellini et al., 2016).

CE implementation at the meso level usually refers to the development of eco-industrial parks and industrial symbiosis districts (Ghisellini et al., 2016; Su, Heshmati, Geng, & Yu, 2013). In these industrial systems, industries that traditionally work as separate entities, become engaged in complex interplays of resource exchange, forming a system called "industrial symbiosis" (Chertow, 2000). In an industrial symbiosis system, like the one located in Kalundborg, Denmark, waste from a company is used as a resource by others (Symbiosis Center Denmark, 2015).

The macro level implementation can be identified in circular economic legislation and planning for a city, province or country (Ghisellini et al., 2016). Since the 1990s, several countries have implemented more or less complex versions of CE (International Reference Centre for the Life Cycle of Products (CIRAIG), 2015). Germany passed the "Closed Substance Cycle and Waste Management Act" in 1994, which marks the starting point of CE legislation (Su et al., 2013). In 2002, The Basic Law for Establishing a Recycling-based Society came into force in Japan, showed the commitment of Japanese government to develop a comprehensive legal framework for moving towards a recycling-based society (Morioka, Tsunemi, Yamamoto, Yabar, & Yoshida, 2005). In China, CE has been introduced as a new development model to help China leapfrog into a more sustainable economic structure (Su et al., 2013)

For further implementation of CE, indicators for circularity quantification are critical. Currently, some circularity indicators for macro, meso or micro level are available. For example, material flow analysis (MFA) is used for national or eco-industrial park circularity measurement (Sendra, Gabarrell, & Vicent, 2007). For micro level, EMF, co-operating with GRANTA, built up Material Circularity Indicator that estimates the circularity of a product based on the fraction of recycled content of a product after use (EMF, 2015). Other product circularity indicators include Circular Economic Index developed by Di Maio & Rem (2015), which emphasizes the economic value of recycled materials, and Circular Economy Performance Indicator by (Huysman, De Schaepmeester, Ragaert, Dewulf, & De Meester, 2017), which compares quality of virgin material over recycled material. But existing micro-level indicators focus on recyclable materials, fail to evaluate the circularity of biological nutrients.

2.4 Municipal Solid Waste Management

This section makes a brief introduction of development of municipal solid waste management (MSWM) in North America, and its current trends. Three waste management methods associated with coffee pod wastes are also introduced in the context of Ontario: landfilling, recycling and composting.

2.4.1 Development and Trends

Waste management can be defined as the organized collection, transportation, processing, recycling or disposal of waste in ways that minimizes potential ruinous effects on the environment and human health (Squire, 2012). MSWM is a waste management service provided by municipalities to manage the solid waste generated by the residential, commercial, institutional, construction and demolition activities in their jurisdictions (Kreith & Tchobanoglous, 2002). During the middle of 19^{th} century, it was realized for the first time that municipal solid waste management practice has an impact on public health. Industrialization and growing populations in cities led to excessive accumulation of wastes, which would essentially cause diseases if not properly managed (Zavodska, 2000). During the 1890s, major cities in North America realized the necessity to better manage their sewage and solid wastes. At that time land application was the most popular method for the disposal of municipal refuse, followed by farm use and dumping in water (Louis, 2004).

From the 1920s to 1960s, MSWM was strongly characterized as engineering-based management in North America (Chen, 2008; Louis, 2004). Along with technological progress, sanitary landfilling, incineration, recycling, and other alternative methods emerged, which significantly strengthened the capacity for waste treatment and safe disposal (Chen, 2008). During that period, landfilling and combustion were still the main waste management approaches. Resource recovery from waste and environmental impacts were typically not considered (Kollikkathara, Feng, & Stern, 2009; Mader, 2011).

An important shift in attitude emerged in the 1970s, where the focus gradually shifted to recycling, and material and energy recovery rather than simply burying or burning the municipal waste (Louis, 2004). One reason of the shift was urbanization. The population concentrated in urban areas created higher and higher pressures on the landfill sites, and locations for landfill became harder to find. City planners needed better methods to manage the wastes (Manaf, Samah, & Zukki, 2009). The shift was also attributed to legislation hat encouraged recycling and recovery and set up guidelines for operation and monitoring at state/provincial and federal/national level (Chen, 2008). Since the implementation of U.S. Resource Conservation and Recovery Act in 1976, the MSW recycling and composting rate in the United States has grown from 7.5% in 1975 to 34.6% in 2014 (USEPA, 2016).

Since the early 1990s, sustainability has gradually become a concern in MSWM, waste management planning has been required to consider its economic, social and environmental impacts. As Haight (1991: ix) stated, "owing to the complex and variable nature of municipal solid waste and the various evaluation criteria, it can be difficult to identify the optimal option for a particular community." Because of this complexity, the Integrated Waste Management (IWM) approach evolved and attained its popularity in North America (Kollikkathara et al., 2009; Tchobanoglous, Theisen, & Vigil, 1993; Van De Klundert, 1999). IWM is a systematic approach that considers all methods of waste prevention, waste collection, resource recovery and disposal and chooses the best combination of methods to achieve the specific waste management goals of a community (Morrissey & Browne, 2004). The IWM approach considers the environmental, energy, socio-economic and political impacts of waste management techniques and seeks to incorporate options with the potential to cause less harm (Tchobanoglous et al., 1993). Currently, municipalities in North America are still committed to further implementation of IWM. It helped Canada and the U.S. achieve 36.1% and 34.6% municipal solid waste diversion rate respectively in 2014 (Statistics Canada, 2017; USEPA, 2016). European Union promotes guidelines on waste prevention under a IWM infrastructure (European Commission, 2012). The benefit of IWM does not limit to diverting resources from waste, it also reduced the GHG emissions from the waste sector, due to using less incineration and more recycling and composting (Habib, Schmidt, & Christensen, 2013).

However, several features limited the promotion of IWM in developing countries. Implementing IWM emphasizes on public participation and demands for substantial financial, technical and human resources (Furedy, 1992; Squire, 2012). Furthermore, the IWM approach requires effective coordination and partnership among various agencies (Squire, 2012).

2.4.2 Landfilling

Landfilling involves the controlled deposit of waste in a designated space and covering such wastes with top-cover as a means of minimizing and preventing pollution (Cointreau-Levine, 1999; Squire, 2012). Landfilling has advantages in being simple, versatile and relatively inexpensive, and it offers final disposal route for other waste management options (Cheremisinoff, 2003). However, landfilling also threatens environment and human health with its leachates and landfill gas emission. Leachate from landfills contains pollutants such as dissolved organic matter, inorganic macro components, heavy metals and xenobiotic organic compounds (Koerner & Daniel, 1997). Landfills generate gases that can contribute to global warming including methane, carbon dioxide (CO_2), hydrogen sulfide (H_2S) and volatile organic compounds (VOC), oxygen, nitrogen, benzene and vinyl chloride. Other issues like land occupation and post-closure maintenance also bother municipalities and their residences.

The current standards for new landfill designs in Ontario were effective on August 1, 1998, under Regulation 232/98 (Government of Ontario, 2012). The regulation covers issues such as waste fill area and leachate collection system design requirements, mandatory air emissions control, water condition assessment and monitoring, leachate contingency plan and post closure care (Government of Ontario, 2012). Leachate collection and landfill gas control are mandatory for landfills in Ontario, which effectively reduce pollution from the landfills. It is reported that there are 805 active landfill sites across Ontario, with the total remaining capacity of 127.3 million tons in 2014 (Ontario Waste Management Association, 2016).

2.4.3 Recycling

Recycling involves the conversion of post-usage products into new useful products through physical, chemical or biological processes (Cunningham & Cunningham, 2012; Oskamp, 1995). Usually, recyclables are collected through buy-back, drop-off and/or curb-side programs and sent to recycling plants for conversion (Squire, 2012). In addition to reducing landfill use and extending the useful life of landfills, recycling as a waste management method has other significant benefits. Those benefits includes saving natural resources for a sustainable development, reducing energy use, pollution, GHG emission for new material production, and creating jobs (Oskamp, 1995). But not all products or materials will be recycled because the value of the recycled products are sometimes not enough to cover the cost of collecting, sorting, transporting, processing and packaging (Cunningham & Cunningham, 2012). In this study two materials, aluminum and cardboard, are considered recyclable. Electricity is the main energy input for aluminum recycling, whose electricity consumption is 5% that of producing primary aluminum from primary oxides (Green, 2007). Cardboard recycling is a mature and widespread industry, and it is beneficial from energy consumption and wastewater emission perspectives (Villanueva & Wenzel, 2007).

Municipalities in Ontario are running a series of recycling activities to help residence to recycle their recyclables, according to the Resource Productivity and Recovery Authority (RPRA) (2017) the activities are:

- Blue Box printed paper and packaging
- Waste Electrical and Electronic Equipment;
- Municipal Hazardous or Special Waste;
- Other recyclables (e.g., scrap metal); and
- Used tires

The Ontario RPRA (2017) also indicated that the overall provincial residential waste diversion rate in Ontario is 47.7% in 2015, and recycling activities contributed 60% of diverted waste with the balance comprising organic diversion, including compositing.

2.4.4 Composting

Composting is defined as the controlled biological decomposition of organic material with the aid of air, moisture, temperature, fungi and bacteria (Epstein, 2011; Haug, 1993). The composting process produces compost as end product, which is defined as a stabilized organic soil conditioner devoid of human and plant pathogens that is beneficial to plant growth (Haug, 1993). Compost is used primarily as a soil amendment or mulch by farmers, horticulturalists and households as nutrients that enable plant growth (Squire, 2012).

Aerobic composting and anaerobic digestion are the two techniques for composting. Aerobic composting is defined as the bacterial process of decomposition or rotting occurring in the presence of oxygen (Haug, 1993). In the presence of oxygen, bacteria would rapidly consume organic matter and convert it into carbon dioxide. While anaerobic digestion is a process in which microorganisms break down organics and generate methane in the absence of oxygen, anaerobic digestion is typically a slower procedure than aerobic composting, and produce less heat during reaction (Squire, 2012). A certain level of moisture content is required by both processes, while aerobic composting needs high temperature to accelerate the decomposition. Both aerobic composting and anaerobic digestion are available in Ontario, but in this study, the composting of used coffee pod is modelled as the aerobic composting process, because the decomposition of PLA is much faster in a high temperature environment (Tokiwa et al., 2009). There are three major types of aerobic composting processes including the “windrow”, “aerated static pile” and ‘in-vessel’ systems, with the former and latter most dominant (Komilis & Ham, 2004). With a cold climate in Ontario, aerobic composting is usually conducted in an in-vessel system, in which composting takes place in an enclosed vessel with air pumped into the organic piles (City of Guelph, 2017).

Benefits of composting as a waste management method include diverting waste from landfills and incinerators, generating compost, and provision of renewable natural gas in anaerobic digestion (Tokiwa et al., 2009). However, there are some challenges associated with composting. Large scale composting facilities are expensive to run and can be labor intensive. There is also a danger of leachate pollution in areas where large scale composting is carried out. The release of ammonia gas during composting can contribute to devaluing the quality of compost and may also cause a myriad of environmental problems (O’Leary, 1999).

2.4.5 Incineration

Incineration involves a regulated thermal destruction process that converts combustible materials into non-combustible residue or ash (Squire, 2012), producing heat, water vapor, particulate matter, products of incomplete combustion, nitrogen, carbon dioxide and oxygen (Carter- Whitney, 2007).

There are many types of incineration systems including grate burners, fluidized bed burners and more recently, pyrolysis and gasification (Porter, 2010). Incinerators are typically fed mixed waste containing low levels of hazardous substances such as heavy metals and chlorinated organic chemicals (Carter- Whitney, 2007). These substances can be transformed by incineration into forms that are likely to be more toxic (Franchini, Rial, Buiatti, & Bianchi, 2004). Depending on the nature of the waste being incinerated, other compounds may be produced, including hydrogen chloride, hydrogen fluoride, nitrogen oxides, sulphur dioxide, volatile organic carbons, dioxins and furans, heavy metals, etc. (Williams, 2005).

As a waste management option, incineration has several benefits. It can reduce the volume and toxicity of solid, liquid and gaseous residue by as much as 80-90%, imposing a lesser demand for land in comparison to landfilling (Squire, 2012). Further, incineration technology is capable of generating electricity and energy for heating purposes. On the other hand, the most worrying disadvantage of incineration is the discharge of dangerous dioxins and furans into the atmosphere causing significant levels of air pollution (Squire, 2012). Additionally, incineration is critiqued for contributing to the retardation of recycling efforts (Carter- Whitney, 2007). The disposal of incinerated ash in landfills may also cause pollution of surface, ground and drinking water (Enger, Smith, & Bockarie, 2000).

Currently, Emerald Energy From Waste Inc. located in Brampton is the only operating municipal waste incinerator in Ontario, and the opening of Durham-York Energy Centre in Clarington has been postponed since December, 2014 (Carter- Whitney, 2007; Javed, 2016). The fact that only one incineration facility is in full operation in Ontario shows how hesitant municipalities have been to them as a management option. Based on the fact that incineration is only available for a small proportion of Ontario, this research does not consider incineration as one of the waste management option in Ontario. Other energy-from-waste options (like anaerobic digestion) were not considered as options for municipal waste processing, and for coffee pod waste specifically.

2.5 Summary of Literature Review

This research investigates three single-serve coffee pod systems, compares their potential environmental effects and waste generation in the context of Ontario. The three coffee pods are primarily made from petroleum-based plastics, aluminum, and biobased polymers, respectively. And therefore, fall under different waste management approaches, i.e. landfilling, mechanic recycling, and composting. Biobased polymers are attracting more attention from the academia and industry, because they, as alternatives of petroleum based plastics, can reduce fossil resource consumption and GHG emissions, and have more and more applications.

Since the concept of circular economy appeared, it has been closely connected to substituting landfilling with other waste management approaches like recycling and composting, and recovering resources from wastes. In the last decade, the conceptual framework of CE has been applied by more and more regional or national governments to guide their sustainable development in Asia and Europe. The Province of Ontario followed their steps by enacting the Waste-Free Ontario Act and Five-Year Climate Change Plan in 2016. In these documents, Ontario set targets in building a circular economy, increasing waste diversion rate and reducing GHG emissions. This case study of a single-use product with high sales volume can provides more insights of biobased materials versus traditional materials, and waste management approaches, therefore, help Ontario to attain its targets.

Chapter 3

Methodology and Data

3.1 Investigating Packaging Systems

Three brands of single serve coffee pods are considered in this study, named as Polystyrene Pod, Aluminum Pod and Biodegradable Pod, respectively. Life cycle assessment (LCA) is used as a method to assess and compare the potential environmental effects of three selected brands of coffee pods over their life cycle. Polystyrene Pod is the most popular coffee pod product in North American market, it is therefore chosen as the baseline scenario for this LCA study. Polystyrene Pod has a cup-shaped polyethylene and polystyrene composite shell that is sealed with an aluminum foil lid. Inside the shell, there is an abaca fiber filter holding some ground coffee. Aluminum Pod is a hemispherical aluminum capsule with an aluminum foil lid. There is not a filter inside Aluminum Pod. Biodegradable Pod is consisted of three parts, a cotton mesh that serve as filter and the container for ground coffee, a paper lid and a biobased polymer ring that holds the mesh and the lid together. For secondary package, both Polystyrene Pod and Aluminum Pod are airtight, only a cardboard box is necessary. But Biodegradable Pod is not airtight, and therefore a low-density polyethylene (LDPE) overwrap is necessary for each pod before putting in a cardboard box. The cardboard box for the pods are made from different materials. Boxes for Polystyrene Pod and Biodegradable Pod use solid unbleached board, while boxes for Aluminum Pod are made from solid bleached board. Figures 1, 2 and 3 show the images of packaging systems for Polystyrene Pod, Aluminum Pod and Biodegradable Pod, respectively. Table 1 indicates the packaging materials used in each packaging system.

Figure 1 Image of Polystyrene Pod

Figure 2 Image of Aluminum Pod system

Figure 3 Image of Biodegradable Pod system

Table 1 Packaging materials of investigated coffee pods

Coffee Pod #	Components	Materials	Mass (g)	Data source
Polystyrene Pod	Abaca filter	Abaca fiber	0.202	(Chayer & Kicak, 2015)
		Softwood	0.0224	
		Polyethylene (PE)	0.056	
	Aluminum lid	Aluminum foil	0.0692	
		Polyethylene terephthalate (PET)	0.034	
		PE	0.144	
	Shell	Polystyrene (PS)	2.52	
		Ethylene vinyl alcohol (EVOH)	0.0428	
		PE	0.115	
	Cardboard box	Solid unbleached board (SUB)	2.83	Measurement
	Coffee ground		9.81	
	Total		15.85	
Aluminum Pod	Aluminum lid	Al foil	0.042	Measurement and assumption
		PET	0.020	
		PE	0.087	

	Shell	Al alloy	1.81	
	Cardboard box	Solid bleached board	4.47	
	Coffee ground		12.92	
	Total		19.35	
Biodegradable Pod	Paper lid	Kraft paper	0.288	Measurement and assumption
		Polylactic acid (PLA)	0.032	
	Ring	PLA	1.82	
		Coffee chaff	0.46	
	Mesh	PLA	0.24	
	Wrapping bag	PE	1.23	
	Cardboard box	SUB	4.95	
	Coffee ground		10.46	
	Total		19.48	

A Quantis LCA report (Chayer & Kicak, 2015), which compares single-serve coffee and bulk coffee brewing, has provided a comprehensive life cycle inventory of a single-serve coffee pod that is identical to Polystyrene Pod. Primary data on material used in Chayer & Kicak (2015) was collected directly from Mother Parkers Tea & Coffee, a coffee pod manufacturer. The coffee pod assembly takes place in Waterbury, Vermont, the United States. Inventory data on Polystyrene Pod's component, material and mass, and transportation distance are derived from Chayer & Kicak (2015).

Inventory data of Aluminum Pod and Biodegradable Pod are empirical data collected through weighing the component of coffee pods. The weighing was carried out on a scale with an accuracy of 0.1g. For each measurement, ten identical products were disassembled into components listed in Table 1, each component was weighed respectively. The same component of ten products were weighted together to assure accuracy. The results were then divided by ten to generate the mass of each component. The materials in each component were not possible to be extracted for weighing separately, nor were they available from reliable sources. Therefore, the mass of materials was converted from mass of components based either on information provided by producer or from assumptions. The material of aluminum lid in Aluminum Pod was assumed to be 57.9% PE, 28.5% Al foil and 13.6% PET. This assumption was based on the material assumption of aluminum lid in Polystyrene Pod in Chayer & Kicak (2015). According to the Biodegradable Pod producer, the biobased polymer ring of Biodegradable Pod is made from a composite with 80% polylactic acid and 20% coffee chaff by mass, and the paper lid is made of kraft paper with PE membrane (Personal communication, 2017).

For clarification, Polystyrene Pod and Biodegradable Pod are usable in the same brewing machine, but Aluminum Pod is only usable in its specially-designed machine. These two different brewing machines may consume different amount of energy in use stage. However, this study focused only on the environmental effects of the coffee pods' packaging systems. All other aspects regarding the manufacturing and use of the brewing machines are beyond the scope of this study.

3.2 Goal and Scope

3.2.1 Goal

By comparing the environmental effects of three single-serve coffee pod packaging systems

- Polystyrene Pod: a petroleum plastic coffee pod with aluminum lid and paper filter,
- Aluminum Pod: an aluminum coffee pod,
- Biodegradable Pod: a biobased polymer coffee pod that made of polylactic acid and kraft paper,

The objectives of this case study are:

1. To quantify the environmental hotspots of each coffee pod packaging system,
2. To compare global warming potential (GWP) between the systems, and to identify tradeoffs in other life cycle impact categories,
3. To estimate the landfill waste generated by the consumption of the coffee pods under current waste management system in Ontario.

The ultimate goal of this research is to evaluate and compare different packaging options that may contribute to achieve a circular economy.

The results of this study are intended to inform at least three groups of audiences who could make efforts towards a more circular economy,

1. The government of the Province of Ontario who is seeking to cut down wastes and greenhouse gas(GHG) emission. Ontario has issued two environmental documents in 2016 (Ontario Ministry of Environment and Climate Change, 2016, 2016) .The first one is Strategy for a Waste Free Ontario: Building the Circular Economy, in which diverting more waste from landfill is an important part of their plan. The second one is Ontario's Five-Year Climate Change Action Plan 2016-2020, which encourages industries and business to reduce GHG emission. This study provides insights into efficiency of waste reduction programs, GHG reduction and other environmental effects of replacing petroleum plastics with aluminum and biobased polymers.
2. The producers of single serve coffee pods who are aware of the heavy environmental burdens of their products, are looking forward to improve their products to avoid the burdens and reduce GHG emission. Recyclable pods and compostable pods are two potential methods to solve the waste problem of the coffee pods. The results of this study are possible to provide some information for their improvement.
3. To consumers of the single-serve coffee pod, this research illustrates the environmental effects of the selected coffee pod formats, and provides supporting information for consumer decision making regarding which coffee pod to buy and how to manage wastes after use.

3.2.2 The Function and Reference Unit

According to the instruction of the brewing machines, for a single use of a Polystyrene Pod or Biodegradable Pod, it is capable of providing a 6oz, 8 oz. or 10 oz. cup of coffee drink, and an Aluminum Pod can provide a cup of 8oz (Keurig Green Mountain Inc., 2016; Nespresso, 2016). This study assumes that every use of a coffee pod provides 8 oz. of coffee beverage. The functional unit of the study is packaging required to deliver coffee product sufficient for providing 8 oz. of coffee beverage. The reference flow is 1000 units of single-serve coffee pods used for coffee beverage brewing, which is a reasonable quantity for a small household in one year.

3.2.3 Spatial and Temporal Scope

Although the coffee pods are produced in different parts of the world (Polystyrene Pod in Waterbury, Vermont, the United States, Aluminum Pod in Orbe, Switzerland, and Biodegradable Pod in Toronto, Canada), it is assumed that the three types of coffee pods in this study are used and managed after use within the Province of Ontario.

All activities in this study were modeled on the temporal base of 2016, for the reason that the newest background data available are 2016 data, for example electricity generation mix (IESO, 2017; USEIA, 2017). As for the pre-existing datasets derived from EcoInvent v. 2.2, most of which were built up with data collected before 2010, it is assumed that those production and processing technologies have not experienced major evolutions, and the datasets are still reflecting current situation.

3.2.1 System boundary

This comparative LCA study considers cradle-to-grave full life cycles of three types of coffee pods, from extraction and process of all raw materials through the end-of-life of all product components. The following flow diagrams (Figure 4, 5 and 6) show the system of petroleum plastic coffee pod, aluminum coffee pod and biobased polymer coffee pod, respectively.

The analysis covered all of the identified materials used for the coffee packaging systems, including the coffee pods and their secondary package. In this study, it is assumed that the coffee ground contained in the three systems are from the same source and undergoes identical roasting and grinding processes. Although the average coffee contents vary from 9.81 to 12.92 g/capsule, in this LCA study, coffee cultivation and its following processing procedures are excluded from the system boundary. Because this study focused on the packaging system and their end-of-life management, the retail and use phase were excluded, also excluded were the manufacture and use of the brewing machines which the coffee pods are put in to brew coffee.

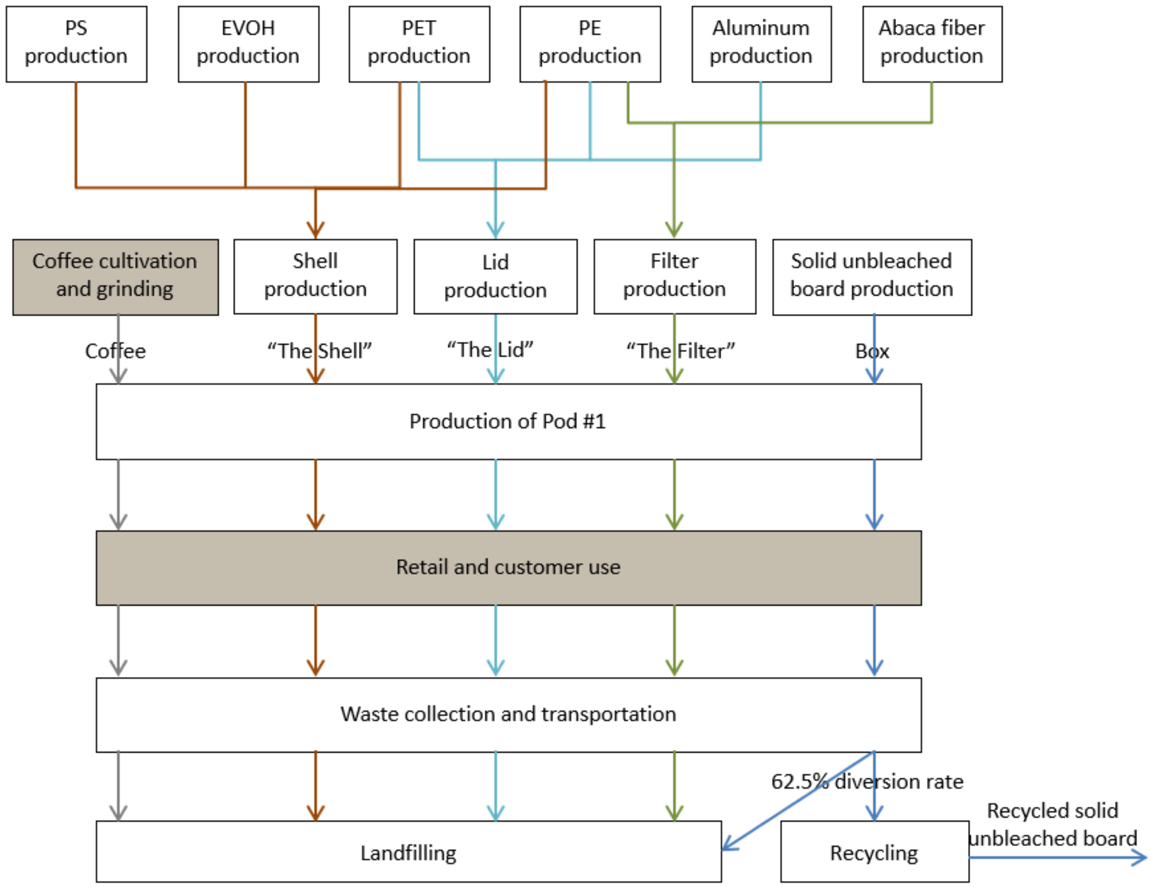

Figure 4 Life cycle flow diagram of Polystyrene Pod. Coffee cultivation and processing, and coffee pod use are excluded from the system boundary of this LCA study. After use, all Polystyrene Pods are landfilled together with the coffee wastes, whereas 62.5% of the cardboard boxes are recycled.

Polystyrene Pod was chosen as the baseline for the comparison of environmental impact categories between the three coffee pods, because it is the most common form of single-serve coffee pod in the market. The pod consists of three parts, a cup-shape plastic cell, a paper filter containing ground coffee and an aluminum lid. There are 12 pods packed in one solid unbleached cardboard box. After use, the whole pod is assumed to be landfilled with ground coffee inside, while 62.5% of the cardboard box is assumed to be recycled in a municipal recycling facility according to the U.S. paper and paperboard recycling rate in 2013 (USEPA, 2016).

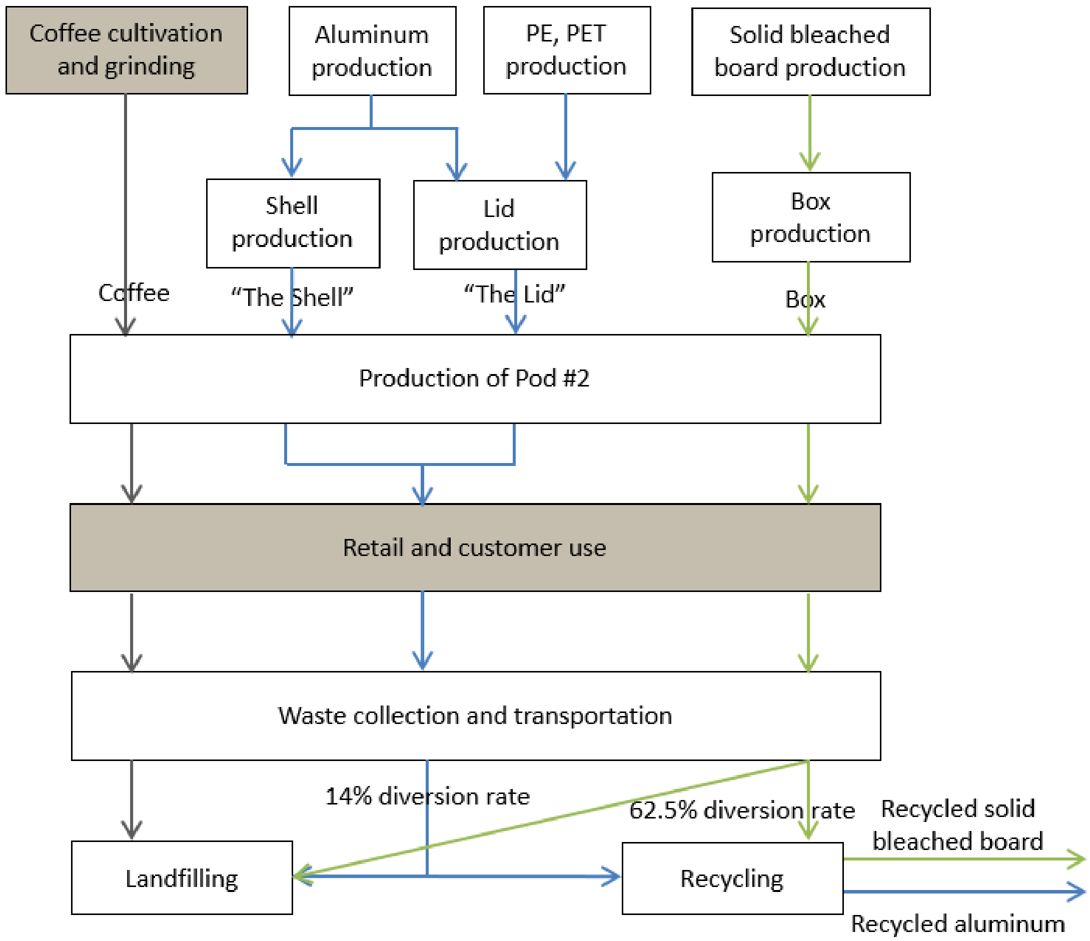

Figure 5 Life cycle flow diagram of Aluminum Pod. After use, 14% of the Aluminum Pods and 62.5% of the cardboard boxes are recycled. The coffee wastes contained in the recycled pods are composted.

Aluminum Pod is fully made of aluminum, whose shell is colored by aluminum anodizing from the outside. A solid bleached board box will contain 10 pieces of this pod. The end-of-life scenario designed for Aluminum Pod is an aluminum recycling scenario. According to the producer, 24% of the used pods were recycled in 2016 (Nestlé Nespresso S.A., 2017). However, considering the less intensive distribution of recycling spots in Ontario than in European nations, this study assumed that 14% of the used pods are collected for recycling via the recycling system established by the pod producer in Ontario. For those pods that are assumed be recycled, the coffee ground contained inside is diverted and sent for aerobic composting. The rest of the used pods will be landfilled with the coffee ground contained inside. The same as Polystyrene Pod, 62.5% of the cardboard boxes are assumed to be recycled.

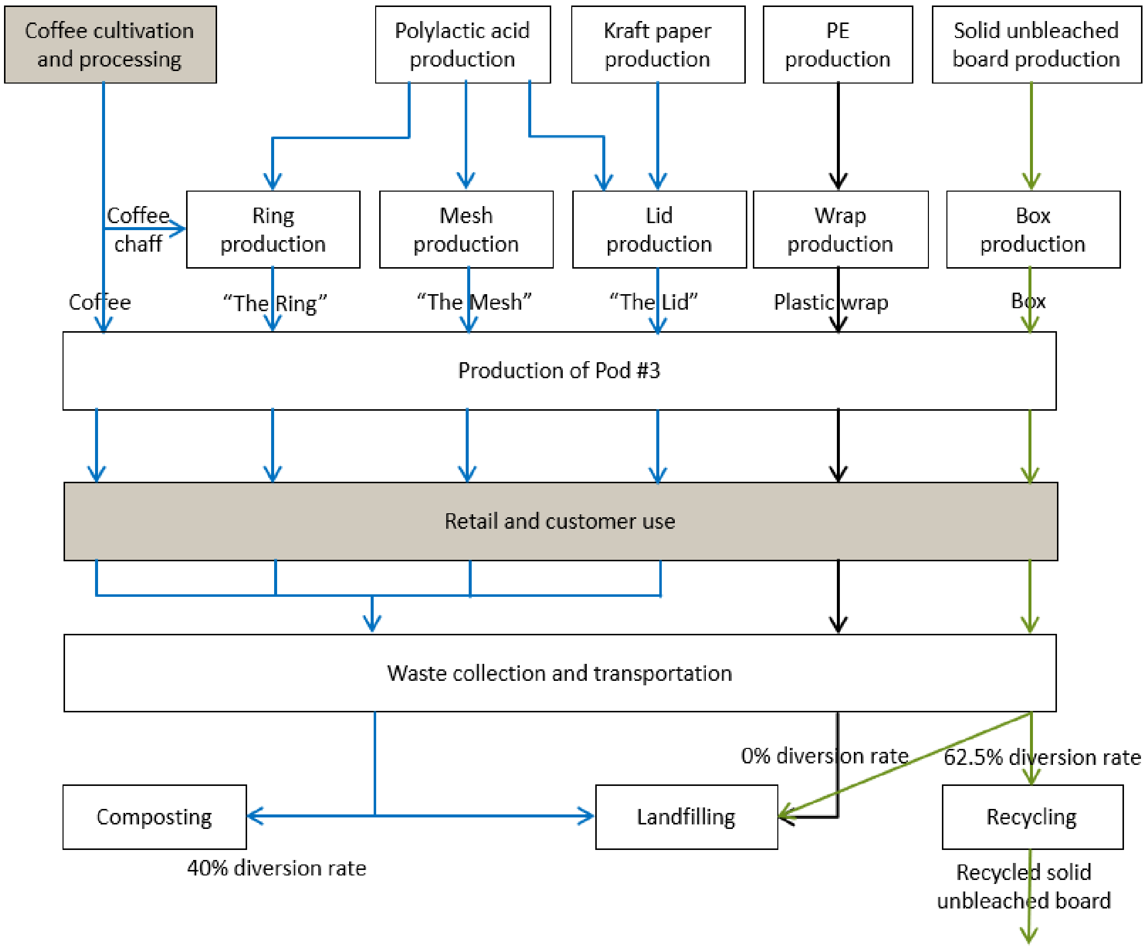

Figure 6 Life cycle flow diagram of Biodegradable Pod. After use, 40% of the Biodegradable Pods are aerobic composted with their coffee wastes, and 62.5% of the cardboard boxes are recycled.

Biodegradable Pod consists of three parts, a filter mesh that contains ground coffee, a biobased polymer ring that holds the mesh and a paper lid. Unlike the other two products, each Biodegradable Pod is wrapped individually in a polyethylene (PE) bag. For this brand, 20 pods will be packed in one solid unbleached board box. The end-of-life scenario for Biodegradable Pod is partially composting scenario, 40% of the used pods are sent to industrial composting facility, along with the ground coffee contained inside, for aerobic composting. The rest 60% will be sent to a landfill. However, all of the PE bags are assumed to be landfilled and 62.5% of the cardboard boxes are assumed to be recycled.

3.2.2 Allocation Procedures

Coffee chaff, a by-product of coffee roasting process, is used as one of the raw material for Biodegradable Pod. For most cases, coffee chaff has no utility value, and is a problematic waste to deal with (The Roasterie, 2013). The coffee roasting procedure produce both valuable roasted coffee beans and valueless coffee chaff. According to an economic allocation method, neither the environmental burden of coffee cultivation, nor of coffee roasting should be carried on by coffee chaff, but by roasted coffee beans. Therefore, coffee chaff is treated as an emission-free raw material input in the ring production of Biodegradable Pod consistent with established LCA practice (Baumann & Tillman, 2004; Guinée, Heijungs, & Huppes, 2004).

In this study, aluminum in Aluminum Pod and cardboard boxes were considered to be recycled at a recycling rate of 14% and 62.5%, respectively (USEPA, 2016). To avoid allocation in modelling recycling, a system boundary expansion approach was used, meaning that the recycled materials were modelled as they contribute to avoiding the production of virgin materials (Chayer & Kicak, 2015; ISO, 2006).

3.2.3 Assumptions

Critical assumptions of this study are:

1. It is assumed that the material processing technologies used in coffee pod manufacture, including plastic film calendaring, extrusion forming and cardboard box production, are identical in Europe and North America. This assumption is important because the modeling of the same process applied in different countries are based on the same dataset from EcoInvent.
2. It is assumed that coffee itself can be excluded from the comparison of packaging systems. In this study, it is assumed that the three coffee pod companies sourced their coffee bean from the same region, and roasted and grinded them with similar technology. Although slightly different amount of coffee grounds, varying from 9.8g to 12.9g per capsule, are contained in different coffee pods, coffee bean cultivation and processing are excluded from the system boundary in order to emphasize the effects of packaging system.
3. To prevent coffee oxidation, nitrogen is injected into single-serve coffee pods (Chayer & Kicak, 2015). But because of the lack of reliable data source, it is assumed that the amount nitrogen injected into each capsule are similar and limited, and generates insignificant amount of emissions. The nitrogen injection process is excluded from the system boundary. For the same reason, the compressing process, in which a small amount of electricity is consumed to combine different components to produce a coffee pod, is assumed to be insignificant and excluded from the system boundary.
4. Different road transportation vehicles may be used for different cargoes or in different regions. To simplify the model, it is assumed that all the raw material, finished product and waste are transported by diesel fueled lorries which have a maximum capacity of 16 metric ton and meet Euro 5 emission standard. The USEPA Tire 3 Standard, which is the functioning standard in the U.S. and Canada, has a higher requirement than the Euro 5 standard in terms of nitrogen oxides and total hydrocarbon emission (Blumberg & Posada, 2015). The difference between the standards increased uncertainty of the study. As for marine transportation, transoceanic freight ships are assumed to be the carrier.

Other assumptions applicable for a specific coffee pod modeling in the study, will be explained in the life cycle inventory section (3.2).

3.3 Life Cycle Inventory

Life cycle inventory Data from Chayer & Kicak (2015) was used for the material used and material transportation distances of Polystyrene Pod. Primary data was collected for the mass of the components of the Aluminum Pod and Biodegradable Pod through direct measurement. Data for the material transportation distances of Aluminum Pod was converted from Dubois, Humbert, & Margni (2011), in which an LCA study was conducted on a coffee capsule that was manufactured in the same site as Aluminum Pod located in Orbe Switzerland. Material transportation distance data of Biodegradable Pod were results of assumptions and estimations.

LCA software SimaPro (version 7.3.0), created by PRé Consultants, was used for the unit process modeling and calculation in this study. SimaPro has been the leading LCA software package for 25 years. It is trusted by industry and academics in more than 80 countries (Long Trail Sustainability, 2017; Boureima, Sergeant, & Wynen, 2007).

3.3.1 Unit Processes

Although different datasets for one material may be available from different databases, all background life cycle inventory data were derived from EcoInvent Database Version 2.2, which is the main source for secondary LCI data. More importantly, EcoInvent shows higher completeness and transparency, and a wider coverage of material and process variety than any other databases that available in SimaPro. Using datasets from the same database for different modules helps to maintain data quality. But most of the datasets in EcoInvent were generated in Europe and representing European industrial conditions. Therefore, the datasets were modified in terms of electricity source mix according to the location of the production sites to increase geographical correlation. A dataset of medium voltage electricity generation of Ontario is created based on the Ontario's supply mix extracted from the Independent Electricity System Operator (IESO) website (IESO, 2017).

Material loss happens in most processing procedures, and the percentages of material loss in plastic processing are documented in EcoInvent datasets (PRé Consultants, 2013). The current research considers the plastic losses in the LCA modeling, and increased the quantities of relevant material input. But material losses smaller than 2% were considered insignificant and ignored. The ignored losses occur in rigid sheet calendering (0.3%) and injection molding (0.6%). On the other hand, losses occur in film extrusion (2.6%) and thermoforming (2.3%) were calculated.

3.3.1.1 Production of Polystyrene Pod

Life cycle inventory data on the production of 1000 pieces of Polystyrene Pod were converted from Chayer & Kicak (2015). Material inputs and processing methods are listed in Table 2. Since the production site of Polystyrene Pod is located in Waterbury, Vermont, United States of America, the datasets from EcoInvent related to Polystyrene Pod were adapted by replacing the European electricity grid mix with an Vermont mix.

Table 2 Process datasets for modeling the production of 1000 pieces of Polystyrene Pod

Product (1,000p)	Component		Dataset (Source: EcoInvent)	Value	Unit
Polystyrene Pod	Shell	Materials	Polystyrene, expandable, at plant/RER U	2.64	kg
			Polyethylene, LDPE, granulate, at plant/RER U	0.121	kg
			Ethylene vinyl acetate copolymer, at plant/RER U	0.0449	kg
		Processes	Extrusion, plastic film/RER U (New England (NE.) electricity mix)	2.68	kg
			Thermoforming, with calendering/RER U (NE. electricity mix)	2.68	kg
	Lid	Materials	Aluminum, primary, at plant/RER U	0.0692	kg
			Polyethylene terephthalate, granulate, amorphous, at plant/RER U	0.035	kg
			Polyethylene, LDPE, granulate, at plant/ RER U	0.148	kg
			Printing color, offset, 47.5% solvent, at plant/RER U (NE. electricity mix)	0.038	kg
		Processes	Calendering, rigid sheets/RER U (NE. electricity mix)	0.178	kg
			Extrusion, plastic film/RER U (NE. electricity mix)	0.178	kg
			Sheet rolling, aluminum/RER U (NE. electricity mix)	0.0692	kg
	Filter	Materials	Kraft paper, bleached, at plant/RER U (NE. electricity mix)	0.224	kg
			Polyethylene, LDPE, granulate, at plant/RER U	0.057	kg
		Process	Extrusion, plastic film/RER U (NE. electricity mix)	0.056	kg
	Secondary package	Material	Solid unbleached board, SUB, at plant/RER U (NE. electricity mix)	2.83	kg
		Process	Production of carton board boxes, offset printing, at plant/CH U (NE. electricity mix)	2.35	kg
	Transportation		Transport, lorry 7.5-16t, EURO5/RER U	8.31	t-km
			Transport, transoceanic freight ship/OCE U	5.05	t-km

Note: About 70% of the electricity in Vermont is supplied by the New England grid and Canada, in this study the New England grid is used as a proxy for the electricity supply for the production of Polystyrene Pod.

3.3.1.1.1 Shell Production

The outer shell of Polystyrene Pod is made from a petroleum plastic composite of polystyrene (94.1% in mass), polyethylene (4.3%) and ethylene-vinyl acetate copolymer (1.6%). The composite is extruded, via a melt-down or spun-bounded process, into a continuous sheet that is then rolled and shipped for thermoforming.

Polystyrene (PS)

PS is the most important raw material for Polystyrene Pod, making up 77.7% of each capsule by mass. For the modeling of PS production, the expandable PS EcoInvent dataset was used. The dataset was originally from the Eco-profiles of the European plastics industry (PlasticsEurope), covering 21 European production sites which produce PS with suspension polymerization out of benzene and ethylene (Hischier, 2010). Although the PS used for production of Polystyrene Pod was produced in the United States, European based data were used. It is assumed that the technology used in American production sites are similar to that used in Europe.

Polyethylene (PE)

PE is another important plastic material for Polystyrene Pod, in addition to the shell, PE also plays roles in its lid and filter. For its wide-use as a packaging material, low-density polyethylene (LDPE) was found in the material lists of all three coffee pods under investigation. LDPE is a thermoplastic made from monomer ethylene with a density range from 0.910-0.940 g/cm^3. For the modeling of LDPE production, a pre-existing EcoInvent dataset for LDPE granulate production was used. The data are also from Plastics Europe, representing 27 European production sites (Hischier, 2010). Polystyrene Pod, Aluminum Pod and Biodegradable Pod contain LDPE from different origins respectively, but the same dataset was used for their modeling, because the origins of the plastics are uncertain.

Ethylene vinyl alcohol (EVOH)

EVOH is a copolymer of ethylene and vinyl alcohol, which is commonly used as an oxygen barrier in food packaging (Premium Pack, 2017). The dataset used for EVA modeling is for ethylene-vinyl acetate copolymer production process, which the only available dataset for EVA production. This dataset represents the technology of producing EVA from ethylene and vinyl acetate by emulsion polymerization (Hischier, 2007).

Processing

Two datasets were used for modeling the processes applied on the plastic composite to form the shell. The plastic film extrusion dataset modeled the first stage where resin is extruded into a continuous sheet. And dataset of thermoforming with calendering modeled the process in which the sheet in formed into a pod shape. Both of the datasets were modified in terms of electricity mix, from an original European mix into an American one.

3.3.1.1.2 Lid Production

The lid of Polystyrene Pod is produced from aluminum that undergoes sheet rolling process to obtain an aluminum foil sheet. The sheet is coated with a heat-sealing adhesive on one surface, and is printed with the brand name and logo of the relevant company on the other. A thin layer of sealant is applied over the printing to protect the image. The sheet is then cut into the right shape and dimensions to fit the capsules (Chayer & Kicak, 2015).

Primary Aluminum Production

The lid of Polystyrene Pod, as well as the shell and lid of Aluminum Pod, are produced out of primary aluminum. Primary aluminum originates from bauxite, the ore from which aluminum oxide compound, also known as alumina, is extracted. Then, the alumina is smelted into pure aluminum metal. The modeling of primary aluminum production used the pre-existing EcoInvent primary aluminum process dataset in SimaPro. This dataset includes input and output data of cast aluminum ingot production, transportation of materials to the plant and the disposal of the wastes (Althaus, 2003).

Polyethylene Terephthalate (PET)

PET is used for the coating of the lid. An amorphous PET granulate production dataset from EcoInvent was used for its modeling in this study. This dataset represents average data for the production of amorphous PET out of ethylene glycol and purified terephthalic acid (Hischier, 2003).

Offset Printing Color

The logo of the coffee brand is printed on one surface of the lid via offset printing, the printing color is also included in the system as one of the raw materials. This printing is applied on both Polystyrene Pod and Biodegradable Pod. The printing ink is included in the model as one of the materials and an EcoInvent dataset of 47.5% solvent offset printing color is used for its modeling. The dataset includes material inputs (solvents, binders, pigments and fillers) and energy consumption, but doesn't include emission to air or water (Hischier, 2003).

Processing

In the analyzing model, three EcoInvent datasets were modified in electricity mix and employed to model the processes applied upon the production of aluminum lid. In addition to the dataset of aluminum sheet rolling, the datasets of rigid sheets calendering and plastic film extrusion were used for the modeling of sheet coating processes. Note that die cutting is also one of the process that the lid undergoes, but because of the absence of a pre-existing dataset and the information of power consumption, the modeling of die cutting was not included in the system.

Both of the lid of Polystyrene Pod and Aluminum Pod are a piece of circular aluminum membrane that covered by plastic film on each side. It is assumed that the production of both lid used the same materials and underwent identical processes except for colored printing. However, the modeling of Aluminum Pod used original EcoInvent datasets, as its production site locates in Orbe, Switzerland.

3.3.1.1.3 Filter Production

According to Chayer & Kicak (2015), the paper filter sealed inside a Polystyrene Pod is made from abaca fiber, a natural plant fiber grown in Philippines and Ecuador. Since Philippines produces 83% of global abaca (FAO, 2010), it is assumed that the filter in Polystyrene Pod uses Philippine abaca fiber as raw material. After harvested in Philippines, the abaca is pulped and sent to the filter production facility, which is assumed to be located in Lydney, UK. The process of production of bleached kraft paper was used as a proxy for the wet laid process, which is similar to paper production except that it is made from synthetic fibers blended with the natural fibers (EDANA, 2008). Thus, the processes for paper production would account for the abaca filter step. The bleached kraft paper EcoInvent dataset was adapted to approximate the abaca portion of the filter (Chayer & Kicak, 2015).

After abaca fiber is made into a continuous, thin sheet of filter material, it will be shipped to fluted and cut into filter form. Heat-sealable abaca filter material is coated with a thin layer of PE around the top of the filter, where it will be sealed onto the side of the outer hard shell. The processes used to cut and attach the paper are still unknown (Chayer & Kicak, 2015). Therefore, only the process of PE coating was included and modeled with a modified EcoInvent plastic film extrusion dataset.

3.3.1.1.4 Solid Unbleached Board Production

Solid unbleached board (SUB) box is used as the secondary package for Polystyrene Pod and Biodegradable Pod product systems, but their mass varies because of different box sizes. SUB is made mainly of unbleached chemical pulp. To achieve a white surface, it is coated with mineral pigments (Stora Enso Renewable Packaging, 2013). The pre-existing SUB EcoInvent dataset used for the modeling of the cardboard production, and another dataset of carton board boxes production modeled the cutting, folding and printing of the boxes. Per kg of used cardboard, 0.83 kg of box production module is needed (PRé Consultants, 2013). Both datasets origin from European producers, and is used as European average data (Hischier, 2011). Since cardboard producers are universally distributed, in this study, it is assumed that the cardboard was sourced from producers that is close to the pod production sites, therefore the datasets were altered in the aspect of electricity mix according to the locations of the coffee pods' production sites.

3.3.1.2 Production of Aluminum Pod

The materials used for production of Aluminum Pod are aluminum, solid bleached board and a small amount of petroleum plastics. The aluminum in Aluminum Pod was assumed to be 100% primary aluminum produced from bauxite ores. But according to its producer, a small amount of the pod is produced from recycled pods, and the number is possible to increase(Nestlé Nespresso S.A., 2017). The assumption of primary aluminum fraction will undergo a sensitivity analysis to evaluate its impact on results and conclusions. Aluminum could be found in both the shell and the lid of Aluminum Pod, which underwent different processes before they were put together. Aluminum for the shell was cut into the required dimensions and extruded into the right shape, and then anodized for exterior coloring and corrosion prevention. On the other hand, treatments on the aluminum lid were assumed to be identical as the lid of Polystyrene Pod, including aluminum sheet rolling and plastic film coating, but offset printing was not applied on Aluminum Pod. The lid production model, cardboard box production model, and plastic model have been introduced in 3.2.1.1.

Table 3 Process datasets for modeling the production of 1000 pieces of Aluminum Pod

Product (1,000p)	Component		Dataset (Source: EcoInvent)	Amount	Unit
Aluminum Pod	Lid	Materials	Aluminum, primary, at plant/RER U	0.042	kg
			Polyethylene terephthalate, granulate, amorphous, at plant/RER U	0.02	kg
			Polyethylene, LDPE, granulate, at plant/RER U	0.089	kg
		Processes	Sheet rolling, aluminum/RER U	0.042	kg
			Calendering, rigid sheets/RER U	0.107	kg
			Extrusion, plastic film/RER U	0.107	kg
	Shell	Materials	Aluminum, primary, at plant/RER U	1.81	kg
		Processes	Anodizing, aluminum sheet/RER U	4.71	m^2
			Cold impact extrusion, aluminum, 1 stroke/RER U	1.81	kg
	Exterior package	Material	Solid bleached board, SBB, at plant/RER U	4.47	kg
		Process	Production of carton board boxes, offset printing, at plant/CH U	3.71	kg
	Transportation		Transport, lorry 7.5-16t, EURO5/RER U	4.99	t-km
			Transport, transoceanic freight ship/OCE U	89.38	t-km

3.3.1.2.1 Shell Processing

Extrusion Shaping

Impact extrusion is a type of specialty cold forming used for larger parts with hollow cores and thin wall thickness (Metal Forming Industries, 2017). A one-stroke cold impact extrusion is used to approximate the shaping process of the aluminum shell. The 1-stroke cold impact extrusion dataset from EcoInvent is used for the modeling of the extrusion shaping process. This dataset encompasses the electricity consumption of the machine as well as common pre- and post-treatments. Furthermore, machine as well as factory infrastructure and operation are considered as well (Steiner, 2007). The aluminum loss during the extrusion process is unclear in the dataset, it is assumed that such loss is insignificant in this study.

Anodizing

Anodizing is the procedure to increase corrosion resistance and allow dyeing on the surface of aluminum alloys (Davis, 1993). The anodizing dataset used in this study is from EcoInvent, which includes mechanical surface treatment, degreasing, pickling, anodizing and sealing processes.

3.3.1.2.2 Solid Bleached Board Production

Another character that distinguishes packaging system of Aluminum Pod from the other two is the use of solid bleached board (SBB) box instead of solid unbleached board box. SBB is a virgin fiber grade of paperboard, which is made purely from bleached chemical pulp and usually has a mineral or synthetic pigment (Stora Enso Renewable Packaging, 2013). The modeling of SBB production used pre-existing European based EcoInvent dataset.

3.3.1.3 Production of Biodegradable Pod

The use of bio-based polylactic acid (PLA) as a substitution petroleum plastic is a significant difference between Biodegradable Pod and traditional coffee pods similar to Polystyrene Pod. The materials that make up Biodegradable Pod are a composite of coffee chaff and plant-based resins which formed the ring, PLA which made up the filter, and PLA coated kraft paper which making up the lid (NZWC, 2017). Injection molding is applied to shape the composite into the ring. The coffee pod is wrapped by a polyethylene bag to avoid direct exposure to air and light, before it is put into a cardboard box. Based on the appearance of the inner side of the cardboard box, the box for Biodegradable Pod was made of solid unbleached box, which is different from the box of Polystyrene Pod and Aluminum Pod. But the process that fold and print the box is the same as those for the other two pods.

Note that the datasets used for the Biodegradable Pod model were modified by replacing the European electricity mix with an Ontario mix to adapt to the situation that Biodegradable Pod is produced in Ontario, Canada. The Ontario's electricity grid mix will be introduced in a later part of this chapter.

Table 4 Process datasets for modeling the production of Biodegradable Pod

Product (1,000p)	Component		Dataset (Source: EcoInvent)	Amount	Unit
Biodegradable Pod	Lid	Materials	Kraft paper, unbleached, at plant/RER U (ON. electricity mix)	0.288	kg
			Polylactide, granulate, at plant/GLO U	0.033	kg
		Processes	Extrusion, plastic film/RER U (ON. electricity mix)	0.032	kg
			Calendering, rigid sheets/RER U (ON. electricity mix)	0.032	kg
	Ring	Material	Polylactide, granulate, at plant/GLO U	1.82	kg
		Process	Injection molding/RER U	2.28	kg
	Mesh	Material	Polylactide, granulate, at plant/GLO U	0.25	kg
		Process	Extrusion, plastic film/RER U (ON. electricity mix)	0.24	kg
	Plastic wrap	Material	Polyethylene, LDPE, granulate, at plant/RER U	1.26	kg
		Process	Thermoforming, with calendering/RER U (ON. electricity mix)	1.23	kg
	Secondary package	Material	Solid unbleached board, SBB, at plant/RER U (ON. electricity mix)	4.95	kg
		Process	Production of carton board boxes, offset printing, at plant/CH U (ON. electricity mix)	4.11	kg
	Transportation		Transport, lorry 7.5-16t, EURO5/RER U	4.16	t-km

The Biodegradable Pod is produced in Ontario; therefore, the datasets were modified by replacing the original electricity input with an Ontario electricity grid mix.

3.3.1.3.1 Ring Production

Based on the technology developed by the University of Guelph, the bioplastic ring of Biodegradable Pod is made from a composite of coffee chaff and plant-based resins, and may contain other additional additives, such as reinforcing agents and/or compatibilizers (Mohanty, Misra, Rodriguez-Uribe, & Vivekanandhan, 2015). The plant-based resins that mixed with coffee chaff are not disclosed, but are assumed to be PLA based. The name and mass of additional additives are also unknown. It is assumed that PLA and coffee chaff dominate the fraction of the composite by weigh, and the environmental effects of the additives are insignificant.

Polylactic Acid (PLA)

PLA is produced from lactic acid by ring-opening polymerization through the lactide intermediate (Datzel & Krüger, 2006). In this study, PLA production is modeled with the polylactide granulate production dataset in EcoInvent database. The dataset is based on data from the world largest PLA plant which uses corn starch as raw material. The inventories include the LCI data from the report of the producer NatureWorks (Stettler, 2007). The dataset covers corn growing, corn wet milling, lactic acid production as well as lactide and polylactide production.

Coffee chaff

Coffee chaff, the outer shin of a coffee bean, is usually a waste product of the roasting process of coffee beans (The Roasterie, 2013). Coffee chaff is mixed with PLA resins to form the ring of Biodegradable Pod, making up 20% of the ring by mass. It is claimed to reduce the consumption of PLA and increase toughness and heat distortion temperature. For the production of 1,000 pieces of Biodegradable Pod, 0.29 kg of coffee chaff is used. Since coffee chaff is a waste product from the coffee bean roasting process without an economic value, it was not included in the life cycle assessment model as a raw material according to the economic value based allocation method

Injection molding

Injection molding is the processing technology used for the formation of bioplastic composite ring. The EcoInvent database provides the only injection molding process dataset in SimaPro. It is assumed that the technology used in the ring production site matches the one in the dataset.

3.3.1.3.2 Lid Production

Unlike Polystyrene Pod and Aluminum Pod, which have an aluminum lid, the lid of Biodegradable Pod is a kraft paper sheet coated with a transparent PLA film on one surface, and is printed with the brand name and logo on the other. The PLA film is produced via an extrusion process and stick onto the kraft paper sheet via calendering. The sheet is cut into the right shape and dimensions to fit the base ring. The modeling of extrusion, calendering and offset printing are similar to those in the model of Polystyrene Pod, except that they use an Ontario electricity mix instead of an American one.

Kraft paper

Kraft paper is produced from sulfuric pulp, which is stronger than that made by other pulping processes. Bleaching is commonly used for kraft paper production to attain white color (Paper Shipping Sack Manufactures Association, 2017), but the original color of the unprinted area shows that the lid is made from unbleached kraft paper. A modified EcoInvent dataset for unbleached kraft paper production is used in the analyzing model. The module includes the European production of unbleached kraft paper in an integrated mill – including transports to paper mill, wood handling, chemical pulping, paper production, energy production on-site and internal waste water treatment. To fit into the Canadian production context, the unbleached kraft paper dataset uses an Ontario electricity mix instead of the original European mix.

3.3.1.3.3 Filter Production

The filter of Biodegradable Pod is a PLA mesh according to the information disclosed by the National Zero Waste Council (NZWC, 2017). Plastic film extrusion is assumed to be the processing method applied to form the mesh. Both of the modeling of PLA production and extrusion process have been introduced in this chapter (3.2.1.3.1 and 3.2.1.1.1), except that the extrusion modeling dataset is modified with an Ontario electricity mix.

3.3.1.3.4 Plastic Warp

Unlike Polystyrene Pod and Aluminum Pod, which are air-tight with their sealed shell and lid, Biodegradable Pod doesn't have a shell that blocks air and sunlight and keeps the coffee fresh. Therefore, Biodegradable Pod needs an extra plastic warp to ensure air-tightness. The plastic wrap is made from LDPE and underwent a thermoforming process with calendering. The modeling of LDPE production and thermoforming process are the same as those in Polystyrene Pod (3.2.1.1.1), except the electricity mix use. After use, the PE wrapping bag is landfilled in the end-of-life scenario.

3.3.1.4 Transportation

Transportation data used in this study are based on existing LCA studies of coffee pods (Chayer & Kicak, 2015; Dubois et al., 2011) and estimations. Transportation distance was calculated in kilometers (km), after the transportation distance was multiplied by material mass, their results were entered in the models in ton-kilometer (t-km).

Chayer & Kicak (2015) provided cradle-to-gate transportation data of Polystyrene Pod, which includes the abaca fiber transportation from farm to processing site and transportation of all components from suppliers to Polystyrene Pod production site. Both road transport and marine transport were calculated. But transportations from producer to retailer, from retailer to end-user and waste collection were not included (Chayer & Kicak, 2015). In this study, all the coffee pods are assumed to be transported from production sites to Toronto, Ontario for retail and consumption. The road transport distance from Polystyrene Pod's production site in Waterbury, Vermont is 730 kilometers. It is assumed that waste collection trucks travel 50 km to deliver waste to the treatment sites. There are 8.31 t-km road transport and 5.05 t-km marine transport for the life cycle of 1,000 pieces of Polystyrene Pod in total.

Transportation data of Aluminum Pod was calculated based on assumptions and information provided in Dubois et al., (2011). It is assumed that all packaging materials used for Aluminum Pod were produced in Switzerland and transported by truck for 100 km on average from material production site to the pod manufacture site. Dubois et al., (2011) suggested that the empty pod is transported for 250 km from the manufacture site to the filling center in Orbe, Switzerland, where the finished product will be distributed for retail (Nestlé Nespresso S.A., 2015). To transport form Orbe to Toronto, coffee pods will be trucked to Marseille, France, then shipped to Toronto in a transoceanic freight ship. The accumulated transportation value is 4.7 t-km road transport and 89 t-km marine transport.

Table 5 Material transportation distance of Aluminum Pod

Material	Route	Transport mode	Distance (km)
Aluminum and plastics	Material production site to pod manufacture site	Truck (7.5-16t)	100
Empty pod	Pod manufacture site to filling center	Truck (7.5-16t)	250
Solid bleached board	Material production site to filling center	Truck (7.5-16t)	100
Finished product	Orbe, Switzerland to Marseille, France	Truck (7.5-16t)	550
Finished product	Marseille, France to Toronto, Canada	Transoceanic freight ship	13,900

Transportation data of Biodegradable Pod is based on the assumption and estimation. PLA was assumed to be supplied by NatureWorks, a major vender of PLA located in Blair, Nebraska, the USA. Cardboard and kraft paper were assumed to be produced in a paper mill in southern Ontario. LDPE was assumed to be sourced from a plastic producer in Ontario. Biodegradable Pod is manufactured and packaged in Toronto, the transportation distance from manufacturer to retail is assumed to be small and insignificant. Total transportation value for Biodegradable Pod is 4.3t-km route transport, marine transport was not identified.

Table 6 Material transportation of Biodegradable Pod

Material	Route	Transport mode	Distance (km)
PLA	Blair, Nebraska, USA to Toronto, Canada	Truck (7.5-16t)	1,600
Kraft paper and cardboard	Material production site to pod manufacture site	Truck (7.5-16t)	50
LDPE	Material production site to pod manufacture site	Truck (7.5-16t)	250

3.3.1.5 Electricity Generation

Electricity is an important source of energy for most, if not all, of the industrial processes. The generation mix of electricity consumed in any stage in the life cycle of a product, process, or industrial sector has a significant effect on the associated inventory of emissions and environmental effects because of large differences in the power generation method used (Marriott, Matthews, & Hendrickson, 2010).

Polystyrene Pod is produced in Waterbury, Vermont, USA. About 70% of the electricity in Vermont is supplied by the New England grid and Canada (U.S. Energy Information Administration, 2017). To simulate the context of Vermont, the New England electricity generation mix dataset was built according to the information provided by ISO New England (2016).

Table 7 Vermont electricity generation mix by fuel type (ISO New England, 2016)

Gas	Nuclear	Hydro	Waste	Wood	Coal	Wind
49%	31%	7%	3%	3%	2.4%	2.4%

Based on the 2016 Yearly Energy Output by Fuel Type of Ontario data provided by the Independent Electricity System Operator (ISIE), an Ontario medium voltage electricity mix dataset was created to simulate Ontario's electricity generation status. This electricity mix dataset is used to modify the EcoInvent datasets associated with the Ontario-based production of Biodegradable Pod, except for PLA production.

Table 8 Ontario electricity generation mix by fuel type (IESO, 2017)

Nuclear	Hydro	Gas/Oil	Wind	Biofuel	Solar
61%	24%	9%	6%	<1%	<1%

Datasets associated with the production of Aluminum Pod used the original electricity mix in the module as they occurred in Europe. Most of them used the UCTE mix, which represents the average electricity mix consumed in Western Europe through the highly interconnected electricity grid (Dubois et al., 2011).

3.3.2 End-of-Life Scenarios

Because of the different packaging materials, each of the coffee pods is designed for different EOL management methods. To be specific, Polystyrene Pod does not have any option other than landfilling, a portion of Aluminum Pod is recycled, the remained is landfilled, while a portion of Biodegradable Pod is composted, the remained is landfill. However, in present situation, not all of these coffee pods go through their ideal EOL route. To estimate the environmental impacts associated with the EOL management of the coffee pods, EOL scenarios were created for each pod format, according to baseline diversion rates.

A landfilling scenario was built up for Polystyrene Pod. In this scenario, all used pods are thrown into waste bin after brewing, with the coffee waste inside. The used coffee pod is then sent to a landfill together with other solid waste. Because there is only one fully operational in Ontario (Carter- Whitney, 2007), which is serving a small proportion of the population and processing a small amount of wastes, incineration is not considered as an available waste management option in Ontario and is not included in the EOL scenarios of the coffee pods.

A recycling scenario is applicable to Aluminum Pod, in which the aluminum pod is opened, and ground coffee is taken away from the pod, so that the aluminum alloy can be thrown to the blue bin to recycle. In additional to disassembling the pod by the customers, the producer of Aluminum Pod provides used pod collection service to their customers. They can bring the used pods back to the retailer shops, and recycling companies will finish the sorting and recycling. Assumption is that sorting either by consumers or by recyclers creates equal amount of environmental impacts. It is assumed that Aluminum Pod has 14% recycling rate in Ontario. The recycling rate of Aluminum Pod is converted as 14% of the aluminum in 1,000 pieces Aluminum Pod will be recycled in the EOL scenario.

A composting scenario is applicable to Biodegradable Pod. In this scenario, Biodegradable Pod is thrown into household green bin for organic waste and collected by curbside organic waste collection truck, and sent to an industrial composting facility with the ground coffee inside. In a composting facility, the coffee pod is treated along with other organic wastes. It is claimed that the coffee pod could be turn into usable compost in 12 weeks in a well-managed facility (Club Coffee, 2017). Biodegradable Pod is assumed to go through an aerobic composting progress as part of the municipal organic waste. But the LDPE wrap of Biodegradable Pod will be landfilled. According to the information disclosed in Waste-Free Ontario Act, Ontario currently has an organic diversion rate at about 40% (Ontario Ministry of Environment and Climate Change, 2016), therefore, it is assumed that 40% of used Biodegradable Pods are diverted and composted.

Although single-serve pods could be landfilled, recycled or composted, the exterior packaging box was assumed to be recycled at a rate representing the average North American residential rate, while the rest is landfilled. A recycling rate of 62.5% was used to represent cardboard based on average US and Canadian rates (EPA, 2011). Notably, the coffee ground is still excluded from the EOL stage of the LCA analysis. Table 9 shows detailed EOL treatments for each component of the investigated products.

Table 9 End-of-life scenarios for coffee pods

Product	Material	EOL treatment	Diversion rate
Polystyrene Pod	Plastics	Landfilled	0%
	Aluminum alloy		
	Filter paper		
	Solid unbleached board	Recycled	62.5%

<table>
<tr><td rowspan="3">Aluminum Pod</td><td>Aluminum alloy</td><td>Recycled</td><td>14%</td></tr>
<tr><td>Plastics</td><td>Landfilled</td><td>0%</td></tr>
<tr><td>Solid bleached board</td><td>Recycled</td><td>62.5%</td></tr>
<tr><td rowspan="5">Biodegradable Pod</td><td>PLA</td><td rowspan="3">Composted</td><td rowspan="3">40%</td></tr>
<tr><td>Coffee chaff</td></tr>
<tr><td>Paper</td></tr>
<tr><td>LDPE warp</td><td>Landfilled</td><td>0%</td></tr>
<tr><td>Solid unbleached board</td><td>Recycled</td><td>62.5%</td></tr>
</table>

The modeling of waste landfilling used a pre-existing municipal solid waste dataset with 22.9% waste disposal to sanitary landfill in EcoInvent. This dataset includes waste-specific short-term emissions to air via landfill gas incineration and landfill leachate, burdens from treatment of short-term leachate in wastewater treatment plant and long-term emissions from landfill to groundwater (EcoInvent, 2003).

The recycling of packaging materials is analyzed using the system expansion principle, in which all avoided burden is credited as a function of recycling. System expansion is a method used to avoid coproduct allocation by expanding the boundary of the system investigated to include the alternative production of exported functions (Humbert, Rossi, Margni, Jolliet, & Loerincik, 2009). In any EOL scenario, solid paper board, either bleached or unbleached, has a recycling rate of 62.5%, which means 1.46kg, 2.31 and 2.554kg of solid paper board input is avoided in the production on 1,000 pieces of Polystyrene Pod, Aluminum Pod and Biodegradable Pod, respectively. While in the recycling scenario, 0.24kg of primary aluminum input is avoided in the production of 1,000 pieces of Aluminum Pod, based on the 14% recycling rate.

3.3.2.1 Composting Model

Different composting facilities in Ontario use different composting technology, for example anaerobic composting that produce methane in addition to compost is available for residences in Toronto, while composting facilities in Hamilton and Guelph use aerobic composting technology (Toronto Environmental Alliance, 2017; City of Guelph, 2017; AIM Environmental Group, 2006). According to the certification information disclosed by BPI, the Biodegradable Pod is certified to be aerobically compostable based on the ASTM D6868 Standard (BPI, 2016). Therefore, only aerobic composting is considered as composting option for Biodegradable Pod waste. The composting process is modeled as those happen in an aerobic composting with a windrow composting system, based on a secondary life cycle inventory (LCI) of municipal solid waste windrow composting in the US (Komilis & Ham, 2004).

Komilis & Ham (2004) built up an LCI for low quality and high quality MSW composting facility and yard waste composting facility respectively. A low quality MSW composting facility is characterized by undergoing a short (4 weeks) composting period and producing a final product that can be used as landfill cover or can be directly landfilled in a "zero emission" landfill. While on the other hand, it takes a high-quality composting facility (HQCF) 8 weeks for composting stage and another 4 weeks for curing stage to produce compost for use as a soil amendment. And a yard waste composting facility only accepts yard waste and also produces compost as a soil amendment product (Komilis & Ham, 2004).

The 12-week composting procedure in a HQCF is assumed to be the procedure Biodegradable Pod waste undergoes. This assumption is based on that fact that the 12-week timeframe meets the time requirement claimed by the producer of Biodegradable Pod, and is the same as that in the composting facilities in Guelph and Hamilton (City of Guelph, 2017; AIM Environmental Group, 2006).

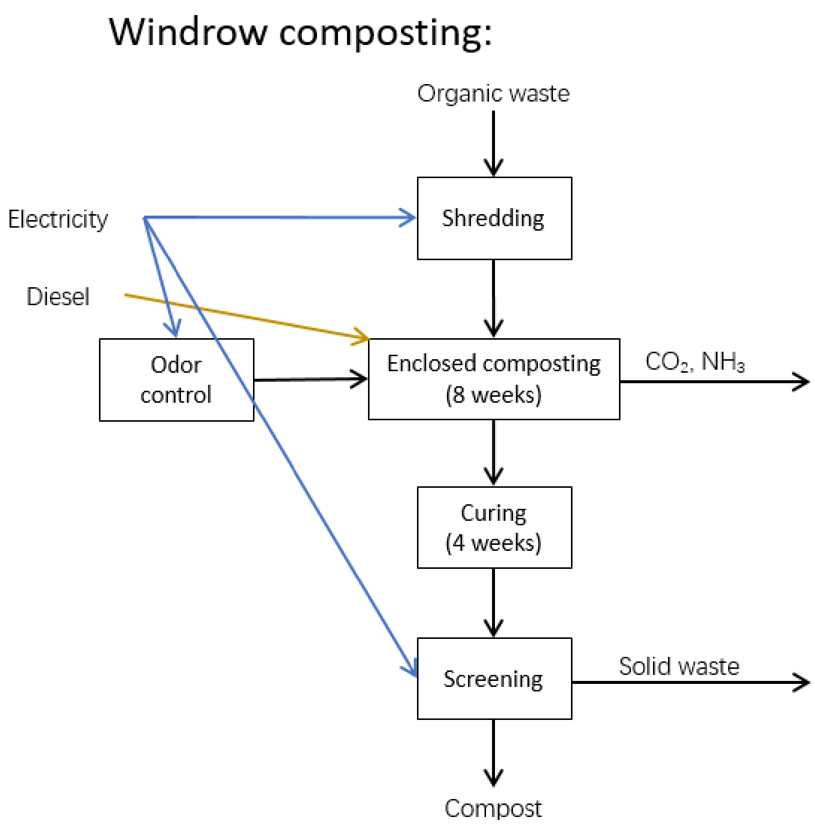

Figure 7 Flow diagram for high quality composting facility

In such composting facility, organic waste diverted from source is first shredded by a hammermill before being sent to the enclosed composting pad. Inside the pad, the composting pile will go through an 8-week composting stage, and will be turned over 3 times a week, an odor control system will run 24 hours / day to draw odor from the enclosed pad. Composting stage is followed by a 4-week curing stage, after which the compost will go through a trammel screen to filter out the remained solid waste from final compost product. Approximately, 1 wet t of organic waste will produce 0.8 t of wet compost product (Komilis & Ham, 2004). Diesel is used as the fuel for front end loader and windrow turner, and electricity is powering the hammermill, odor control and trammel screen. Table 10 indicates the life cycle input and output of composting 1 t of organic waste in a high-quality composting facility. Carbon dioxide and ammonia generated during decomposition is the main environmental output.

Table 10 Life Cycle Inventory (LCI) for High-quality Composting

Materials	Input/output	Value
Energy Input		
Diesel (L/t)	Input	2.2
Electricity (kWh/t)	Input	76
Emission to air (kg/t)		
PM_{total}	Output	6.0E-02
NO_X	Output	2.9E-01
HC (non CH_4)	Output	5.9E-02
SO_x	Output	3.1E-01
CO	Output	1.2E-01
$CO_{2\ biomass}$	Output	3.9E+02
$CO_{2\ fossil}$	Output	3.7E+01
NH_3	Output	5.0E-01
Pb	Output	2.8E-09
CH_4	Output	2.3E-04
HCl	Output	3.0E-07
Emission to water (kg/t)		
Dissolved solids	Output	2.6E-02
Total suspended solids	Output	2.4E-05
BOD_5	Output	2.6E-05
COD	Output	1.3E-04
Oil	Output	3.3E-04
H_2SO_4	Output	2.5E-02
Fe	Output	6.3E-03
NH_3	Output	3.6E-06
Cr	Output	6.9E-09
Pb	Output	3.8E-09
Zn	Output	5.7E-08
Solid waste (miscellaneous)	Output	4.3E+00

Compost is widely used in gardening and agriculture for soil amendment. Because the chemical composition of compost depends heavily on the organic waste source, compost is usually mixed with chemical fertilizers to ensure the agronomic performance, but in general, the use of compost could significantly reduce the use of chemical fertilizer (Baldi et al., 2010; Jayathilake & Fernando, 2016). To evaluate the environmental benefits of the compost final product from Biodegradable Pod composting, the compost production is credited as avoided ammonium nitrate phosphate as N source for crops. It is assumed that 1kg of compost is capable of replace 0.8 kg of ammonium nitrate phosphate fertilizer.

3.4 Life Cycle Impact Categories

A midpoint oriented LCIA methodology, the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2 v 4.00), was used in this study to convert the input and output data into environmental performance indicators and impact categories. The TRACI 2 methodology was developed by the U.S. Environmental Protection Agency specifically for the USA using input parameters consistent with U.S. locations (Bare, 2011). Since this study is conducted in Ontario, which has similar environmental and geographic situations with the U.S., and in terms of environment and technology, the method is used here. Other commonly used methods, such as CML 2001 and Eco-Indicator, are based on European conditions. TRACI 2 involves eight impact categories (table 11), but it does not apply normalization or weighting which are important to understand better the relative magnitude for each indicator result (ISO, 2006)

Table 11 Impact categories in TRACI 2 methodology

Impact category	Unit
Ozone depletion	kg CFC-11 equivalent (ep.)
Global warming	kg CO_2 eq.
Smog	kg O_3 eq.
Acidification	mol H^+ eq.
Eutrophication	kg N eq.
Carcinogenics	Comparative Toxic Unites for human (CTUh)
Non carcinogenics	CTUh
Respiratory effects	kg Particulate Matter (PM) 10 eq.
Ecotoxicity	Comparative Toxic Unites for environment (CTUe)

In order to provide further insight into the impact potential, a second method was employed that incorporates normalization and weighting. ReCiPe is an LCIA method that integrate 'problem oriented approach' and 'damage oriented approach', and has both midpoint and endpoint impact categories. The midpoint characterization factors are multiplied by damage factors, to obtain the endpoint characterization values. Listed in Table 12 are 18 midpoint impact categories and 3 endpoint categories that are addressed in ReCiPe. (PRé Consultants, 2014)

Table 12 Midpoint and Endpoint impact categories in ReCiPe

Midpoint level	
Impact category	Unit
Ozone depletion	year/kg CFC-11 eq.

Human toxicity and ecotoxicity	yr/kg 1,4- dichlorobenzeen (14DCB)
Radiation	yr/kg Uranium 235 eq.
Photochemical oxidant formation	yr/kg Non-methane volatile organic compound
Particulate matter formation	yr/kg PM_{10} eq.
Climate change	yr/kg CO_2 eq.
Agricultural and urban land occupation	m^2.yr
Natural land transformation	m^2.yr
Marine eutrophication	yr/kg N to freshwater eq.
Freshwater eutrophication	yr/kg P to freshwater eq.
Fossil fuel and minerals depletion	kg oil eq.
Minerals depletion	kg Iron (Fe) eq.
Freshwater depletion	m^3
Endpoint level	
Impact category	Unit
Human Health	years
Ecosystems	years
Resources surplus costs	2000US$

In the current research, ReCiPe version 1.0.6 method was employed with a normalization/weighting set of World ReCiPe E/A, referring to the normalization values of the world with the average weighting set (PRé Consultants, 2013). The environmental effects of the coffee pods are presented in midpoint impact categories. Their weighting results are converted into a single score for each pod system, which enables easy comparison between different systems and expresses the relative importance of the impact categories. But the score is prone to subjectivity, since the chosen weighting factors can influence the results.

Chapter 4

Results

This chapter shows the cradle-to-grave LCA results for the reference unit of 1,000 pieces of each coffee pod formats. Polystyrene Pod refers to the petroleum-based plastic pod, Aluminum Pod is the aluminum pod, and Biodegradable Pod is made from biobased polymers.

Overall LCA results generated by TRACI 2 and ReCiPe methods are both presented, in order to make a more comprehensive comparison between the three systems. The global warming potential (GWP) impact category is broken down to identify the main source of greenhouse gases (GHG). Although coffee bean cultivation and roasting processes are excluded from the system boundary, but different packaging formats provide the used coffee ground with different EOL management approaches. A second comparison between the packaging systems was conducted with a consideration of used coffee grounds into the waste management scenarios.

In the last section of the chapter, a series of sensitivity analyses were conducted on primary aluminum fraction in Aluminum Pod and the EOL scenarios to evaluate how these assumptions impact the LCA results.

4.1 Overall LCIA Results

4.1.1 Characterization Results from TRACI 2

Figure 8 shows the comparison on the characterization results generated by TRACI 2 method. The highest value in each environmental impact category is presented as 100%, and the lower values in that category are presented as percentages corresponding to the highest value. According to Figure 8, Aluminum Pod has the highest value in all of the environmental impact categories, whereas Polystyrene Pod and Biodegradable Pod have similar values in most categories except for ozone depletion. It indicates that the Aluminum Pod has potential to create relatively higher effects in all the considered impact categories. The difference is the greatest in carcinogenics, in which Aluminum Pod has a value ten times as high as Biodegradable Pod's. While comparing Polystyrene Pod and Biodegradable Pod, the biobased polymer pod performs better in the impact categories of global warming, smog, acidification, and respiratory effects, but worse in the others.

In the following paragraphs, the characterization results of each pod will be broken down by life cycle stages.

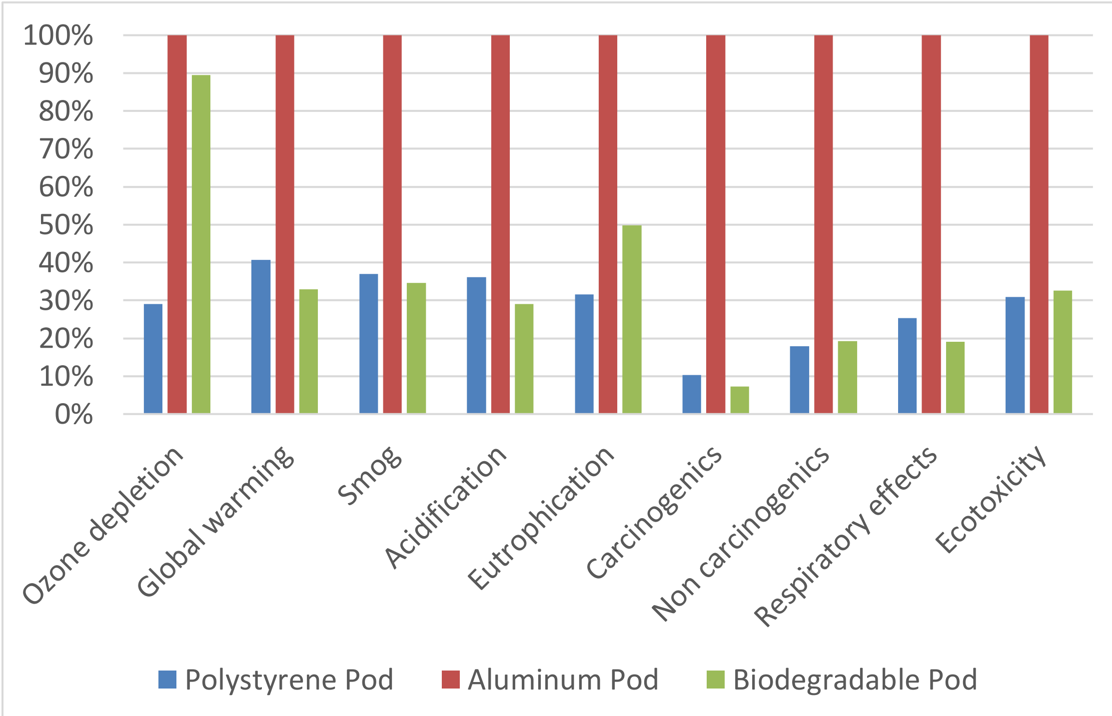

Figure 8 Characterization result comparison between the three pod formats. The highest indicator value in each impact category is presented as 100%, the others are presented as a fraction of it.

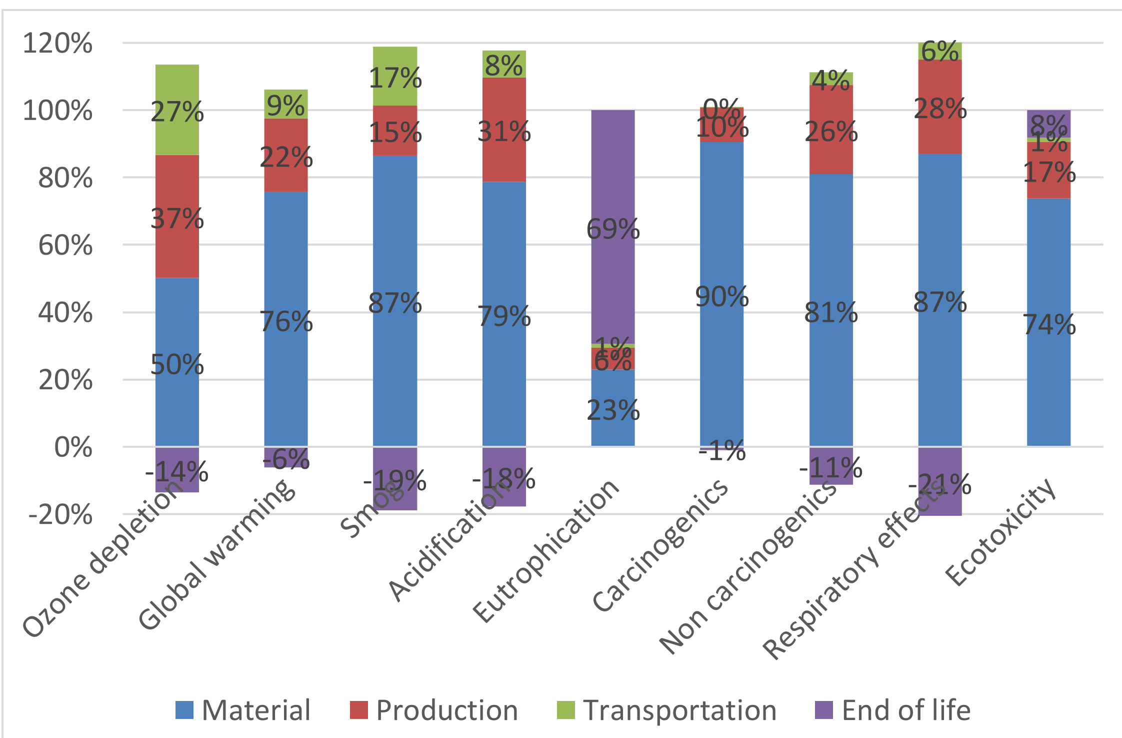

Figure 9 Characterization results of Polystyrene Pod. In each impact category, the percentages represent the fraction of the emissions generated from each life cycle stage relative to the total

emissions from the system. The percentages in each category add up to 100%.

Figure 9 shows that the material phase of Polystyrene Pod dominates the source of effect in all categories except for ozone depletion and eutrophication. Production is the second largest contributor to impact categories after material. Because of the recycling of solid unbleached board (SUB), end-of-life stage has negative values in most of the impact categories. However, the high percentage in eutrophication shows that the landfilling of 1,000 plastic pods has a high emission of N containing nutrients. Transportation plays a less important role in most of the categories except ozone depletion.

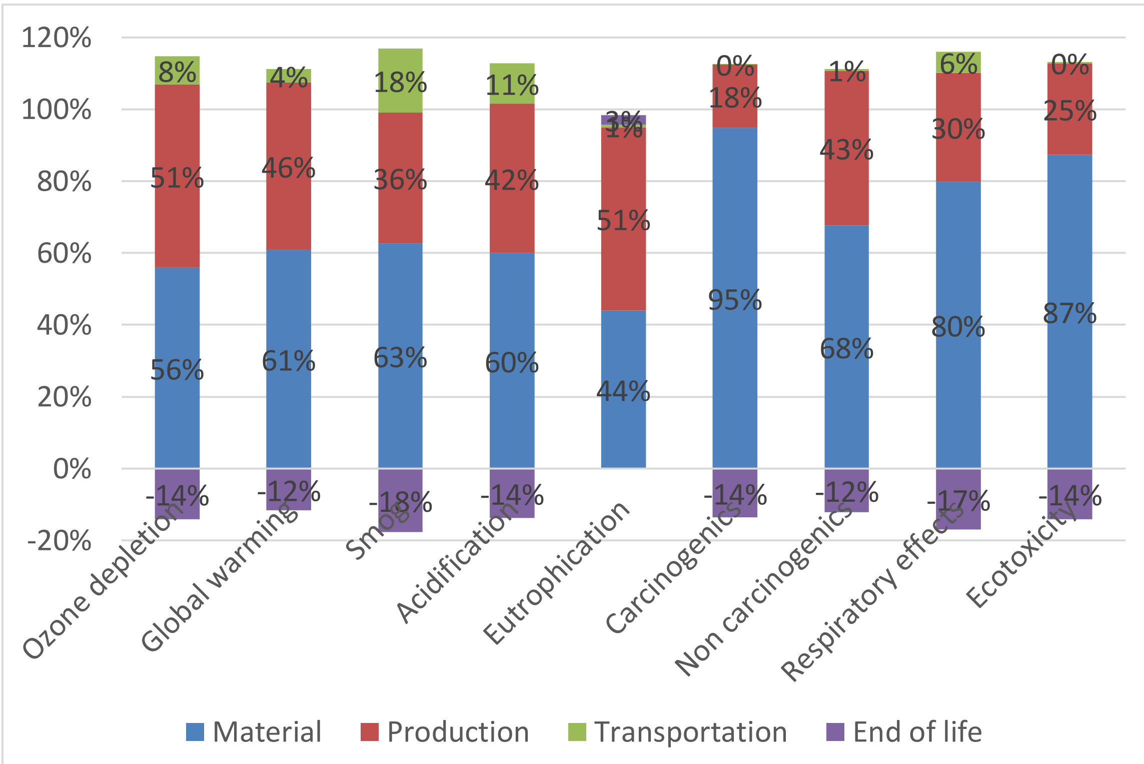

Figure 10 Characterization results of Aluminum Pod

According to Figure 10, material phase of Aluminum Pod takes critical responsibility in carcinogenics (83%), non carcinogenics (60%), respiratory effects (72%) and ecotoxicity (77%). These percentages indicate the extraction and refining of primary bauxite, significantly increasing the Aluminum Pod's potential of harming human health and ecosystem quality.

The use of aluminum not only shows high effects from materials phase, but also reveals the increasing effects generated by production of aluminum that requires some impactful processing technologies. Production phase takes a large burden in ozone depletion (52%), eutrophication (51%) and global warming (46%). This is a situation that has not been identified in the other two systems. Transportation stage also plays a less important role here, even though the transportation distance is larger for Aluminum Pod case.

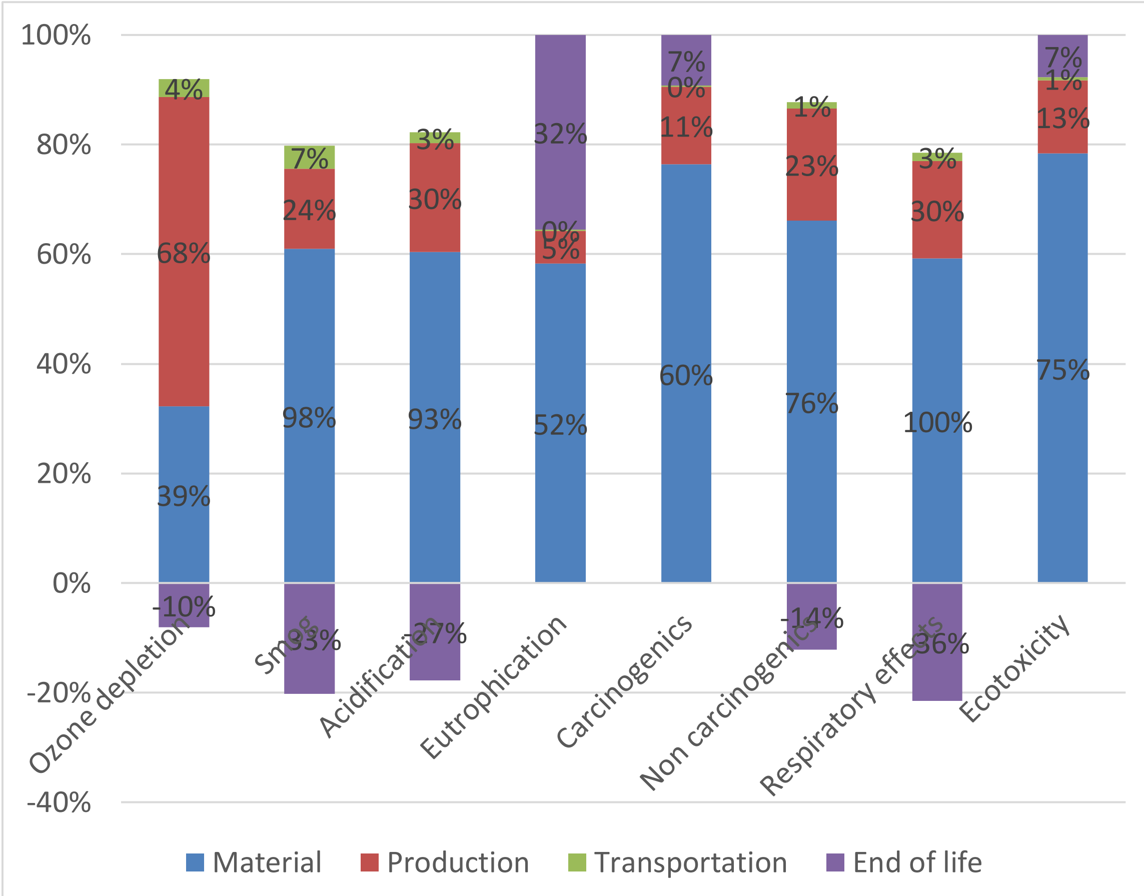

Figure 11 Life cycle analysis results of Biodegradable Pod

Based on Figure 11, production dominates the ozone depletion category. Material phase, more specifically, the production of PLA, is responsible for more than 50% of the effect for the rest of the impact categories. Similar to Polystyrene Pod, the EOL phase plays an important role in eutrophication effect. It shows that the decomposition of nitrogen-rich organic waste, either happening in a landfill or a composting facility, could increase the risk of aquatic eutrophication.

4.1.2 Weighting Results from ReCiPe

Although Aluminum Pod has high indicator values compared with those of Polystyrene Pod and Biodegradable Pod (see Figure 8), and some of their differences are large, the importance of these effects cannot be illustrated by the characterization results. Therefore, the weighting results, generated by ReCiPe LCIA method with a world average weighting set, was added up and presented as single score to show the importance of potential effects from the coffee pod systems.

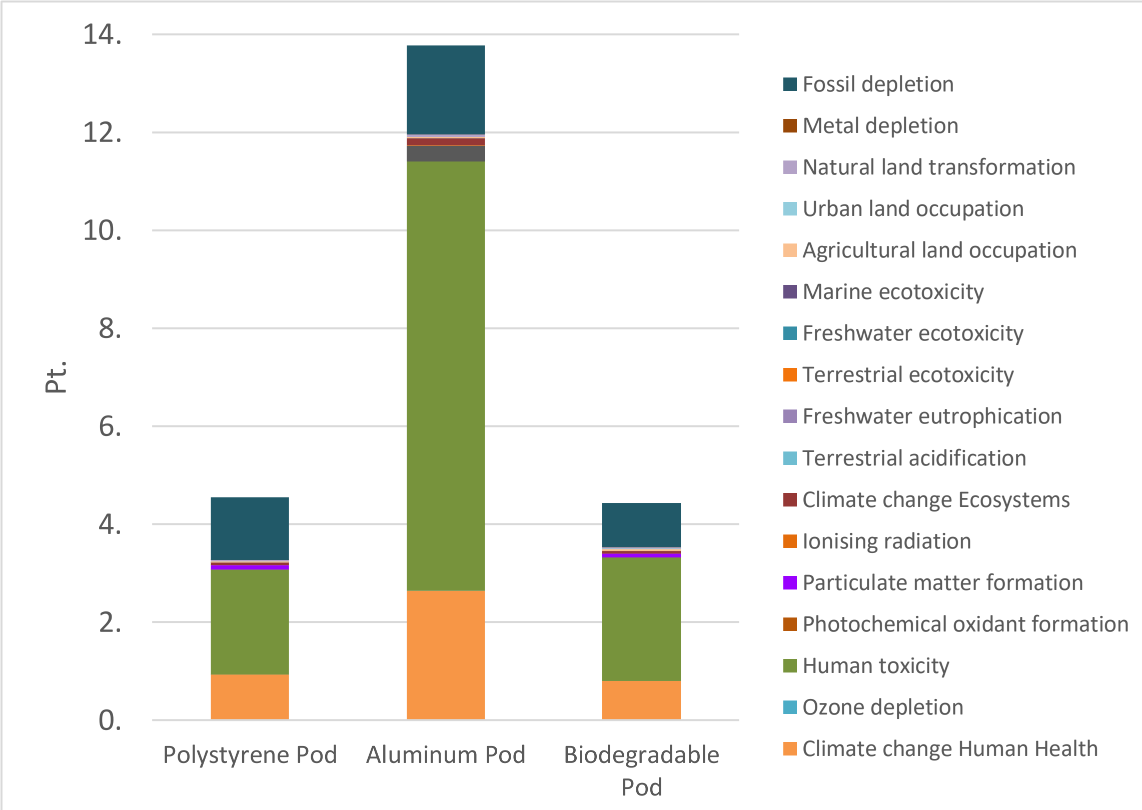

Figure 12 Weighting results generated by ReCiPe in midpoint impact categories.

In the weighting results, three impact categories are of higher importance than the others, namely human toxicity, climate change and fossil depletion. The smaller weighting results of other indicators show that although the difference of the analyzed systems in these indicators may be large, but the indicator values themselves are too small to create significant effects.

Comparing the weighting results of the coffee pods, Aluminum Pod still has the highest total score, Polystyrene Pod and Biodegradable Pod have similar score and shared patterns in weighting results. The comparison is consistent with the characterization results from TRACI 2. Among all 17 impact categories, human toxicity has made the most significant contribution to the total scores. Human toxicity in ReCiPe aggregates carcinogenics and non-carcinogenics emissions (National Institute for Public Health and the Environment of Netherlands, 2011). The difference of the three systems is also great in human toxicity. This disparity is in line with the characterization results. Another important category identified in weighting is climate change, which will be broken down and discussed in detailed in the following section. Fossil depletion is a category with high indicator value in ReCiPe that failed to be evaluated in TRACI 2. ReCiPe identified the largest fossil depletion in Aluminum Pod, followed by Polystyrene Pod, with the smallest in Biodegradable Pod.

4.2 Global Warming Potential

Figure 13 shows the life cycle assessment results for the global warming potential (GWP) of the three coffee pod packaging systems, in the unit of kg CO_2 eq./ 1,000 pieces.

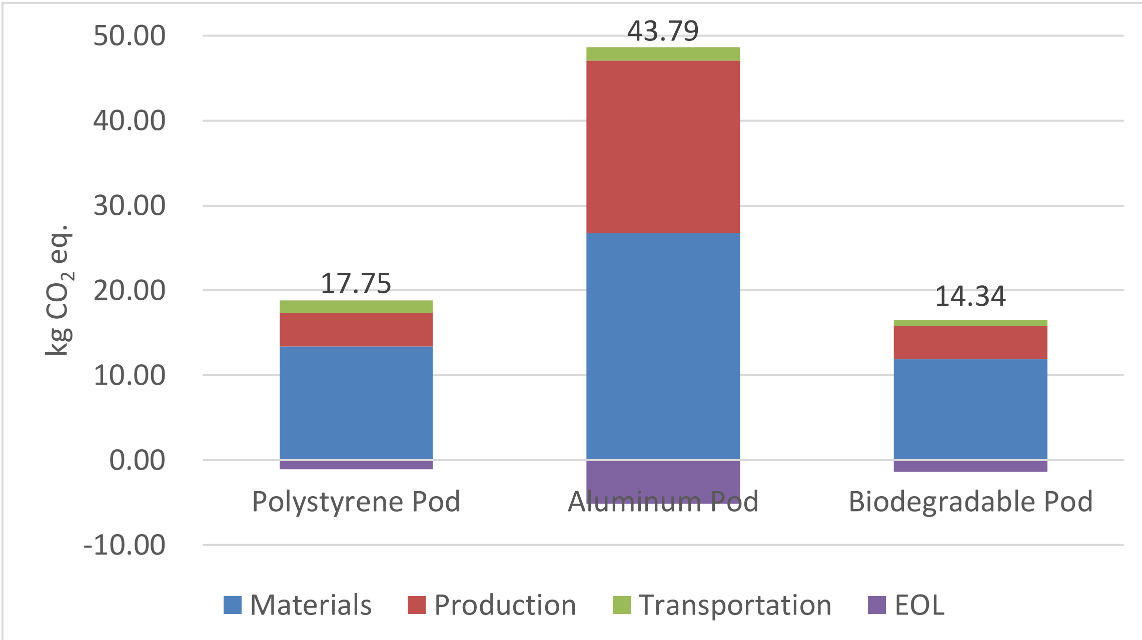

Figure 13 Global warming potential comparison

For all of the packaging systems, raw material extraction, being the major contributor, is responsible for more than half of their global warming potential. The production phase, which includes shaping and coloring, is the next important source of the greenhouse gas emission. The EOL stage has an overall positive GWP output because of the credits of recycled materials and compost product. Transportation, including transportation of raw materials to production site and transportation of finished product to retailing shops, is relatively insignificant in Aluminum Pod and Biodegradable Pod, but accounts for 7% of GWP for Polystyrene Pod.

In comparison, Biodegradable Pod has the lowest GWP, which is 14.34 kg CO_2 eq./ 1,000 p, which is 19% lower than Polystyrene Pod (17.73 kg CO_2 eq./ 1,000p). Aluminum Pod, with a figure of 43.79 kg CO_2 eq./ 1,000p, is the highest, 247% higher than Polystyrene Pod and 305% higher than Biodegradable Pod. When the three coffee pods are compared by their life cycle stages, Aluminum Pod not only has larger GHG emission in raw material extraction, but also significantly larger in production stage than the other two pods.

The following part of this section will present detailed GWP results for each coffee pod, categorized in components. In this way, the GWP hotspots will be revealed.

4.2.1 GWP of Polystyrene Pod

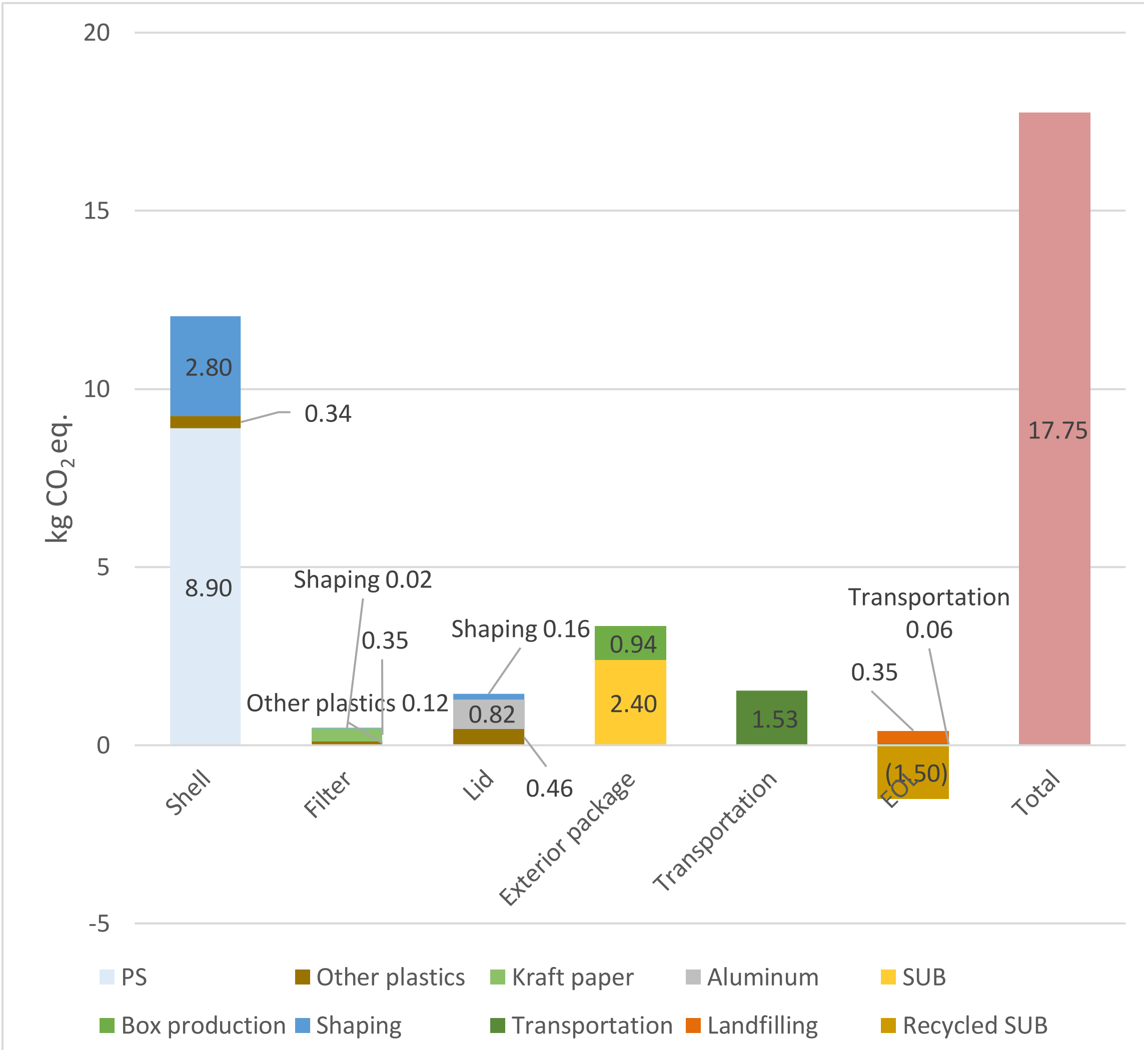

Figure 14 Global warming potential breakdown of Polystyrene Pod. Each column includes the GWP from the materials and the production of one packaging component. EOL includes GWP from transportation for waste collection, landfilling and credits from recycled materials.

Figure 14 shows the breakdown of global warming potential effect by different components and processes involved in Pod # 1 system. It indicates that the major part of GHG comes from the production of pod shell, which takes up half of the packaging system by mass. The polystyrene, used as the main material of the shell, is responsible for 50% of the GHG emission. Whereas shaping the shell, including extrusion and thermoforming, is responsible for another 16%. Another important contributor is the use of solid unbleached board box as the secondary package, causing 19% of the total GWP, however, the recycling of solid unbleached board is effective in reducing the burden of it.

4.2.2 GWP of Aluminum Pod

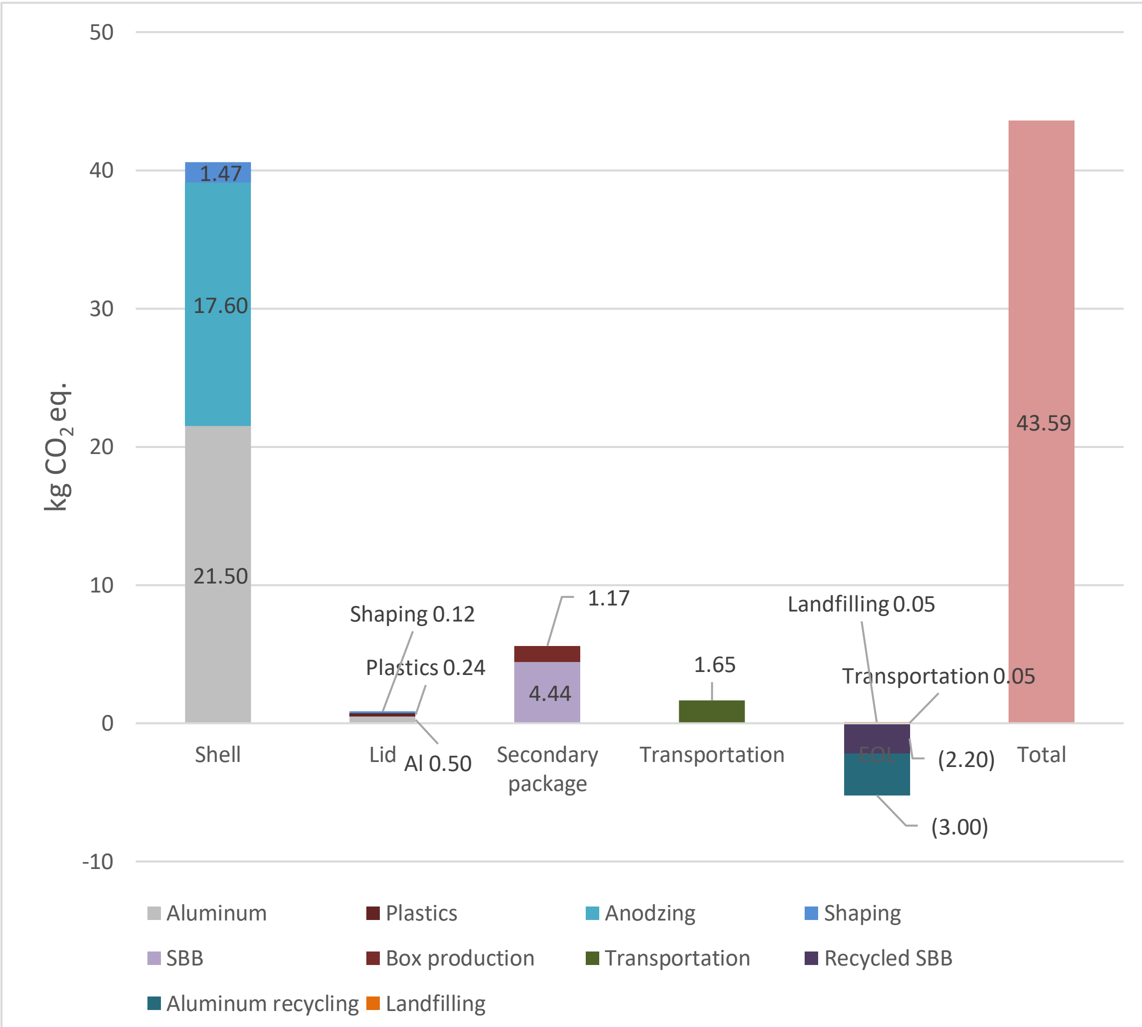

Figure 15 Global warming potential breakdown of Aluminum Pod

Figure15 indicates that the aluminum shell of Aluminum Pod dominates the source of GHG emissions, accounting for over 90% of total GWP. Half of the GHG emission is caused by the extraction and refinery of bauxite to produce primary aluminum. Whereas anodizing, the processing technology applied to prevent oxidation and to color the shell, also has a high emission because of its high consumption of heat and electricity. The recycling of aluminum, at a 14% recycling rate, does not have a major impact on reducing GWP. The secondary package, which used solid bleached board, has higher emission than the unbleached board boxes in the other two systems. Because aluminum is stable in a landfill environment, the GHG emission regarding landfilling is notably lower in Aluminum Pod

4.2.3 GWP of Biodegradable Pod

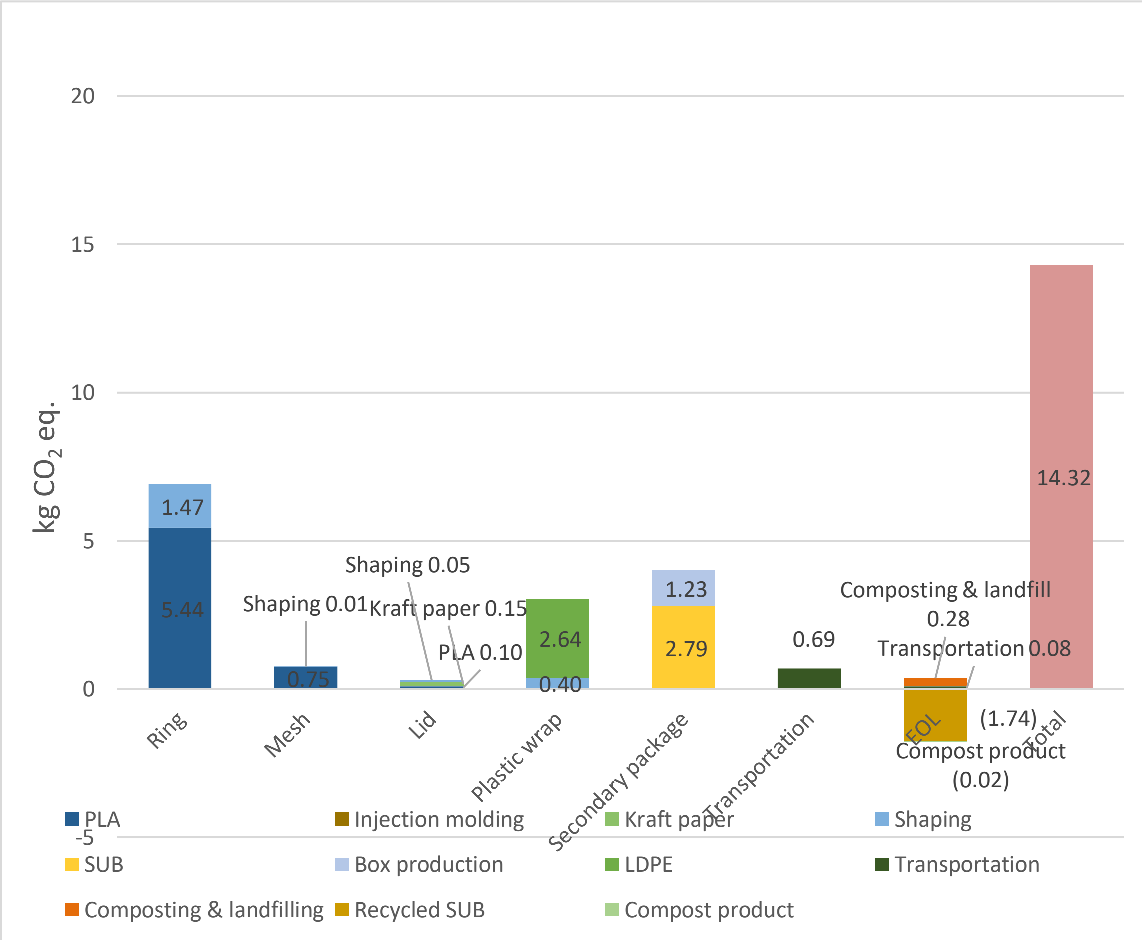

Figure 16 Global warming potential breakdown of Biodegradable Pod

Figure 16 shows that PLA, as the most important packaging material, accounts for 44% of the total GWP. The ring-based design of Biodegradable Pod has reduced the use of PLA, but it requires a plastic wrap to prevent coffee oxidation. Being made from LDPE, the plastic wrap is responsible for 19% of the total GWP. Biodegradable Pod has the heaviest secondary package box among the three systems. But because solid unbleached board has a smaller GWP than bleached board per kilogram (Hischier, 2010), the overall GWP associated with secondary package of Biodegradable Pod is smaller than Aluminum Pod

From a component stand point, the base of a coffee pod, namely the shell of Polystyrene Pod and Aluminum Pod, and the ring of Biodegradable Pod, is the most significant source of their GWP. Both raw material extraction and production of this part carry heavy GWP burdens. Another GWP hotspot is the secondary packaging box. Although an effective cardboard recycling system can avoid a fraction of GWP from the cardboard box, the GWP associated with the cardboard box could be much higher in areas without a sound recycling system.

4.3 Effect of Coffee Ground EOL Approach

Although coffee bean cultivation and roasting are excluded from the system boundary, different packaging formats provide the used coffee ground with different EOL management approaches. Specifically, for the landfilling of Polystyrene Pod, coffee grounds contained inside will also end up in landfill. For the 14% of Aluminum Pod, which are assumed to be recycled, their coffee ground will be diverted from the pod to be composted, with the remaining being landfilled. As for Biodegradable Pod, 40% will be composted with the pod, and 60% will be landfilled. Table 13 shows the total and diverted amount of coffee ground in each pod system. A second comparison between the packaging systems was conducted with the consideration of used coffee grounds into the waste scenarios. In the LCA model, coffee ground waste is simulated untreated wood waste with 20% moisture.

Table 13 Total amount of coffee grounds in each pod and their EOL approaches (unit: kg/1,000 p)

Coffee pod #	Total amount of coffee	EOL approach	Treated amount
Polystyrene Pod	9.81	Landfilling	9.81
Aluminum Pod	12.92	Landfilling	11.11
		Composting (14%)	1.81
Biodegradable Pod	10.46	Landfilling	6.28
		Composting (40%)	4.18

In Figure 17, the EOL scenario, from which coffee ground is excluded, is compare with the EOL scenario that includes coffee ground in five impact categories. These five impact categories are GWP, eutrophication, carcinogenics, non-carcinogenics, and ecotoxicity. They are identified to have significant differences in overall LCA results when coffee waste is (not) considered in the EOL stage of the coffee pods.

Except for global warming potential, the largest changes before and after coffee ground was included in the EOL scenario are identified in Aluminum Pod. This can be explained by that aluminum, as a mineral, does not reacts with microorganisms in the landfills, and has very small, if there is any, emission. On the other hand, Biodegradable Pod has the smallest changes, which illustrates that composting has smaller emissions than landfill in the listed impact categories. When it comes to global warming potential, coffee landfilling is responsible for about 1.5 kg CO_2 eq., this is similar to another LCA study conducted on this format of coffee pod (Chayer & Kicak, 2015). The smaller changes in Aluminum Pod and Biodegradable Pod are due to the credits from compost product.

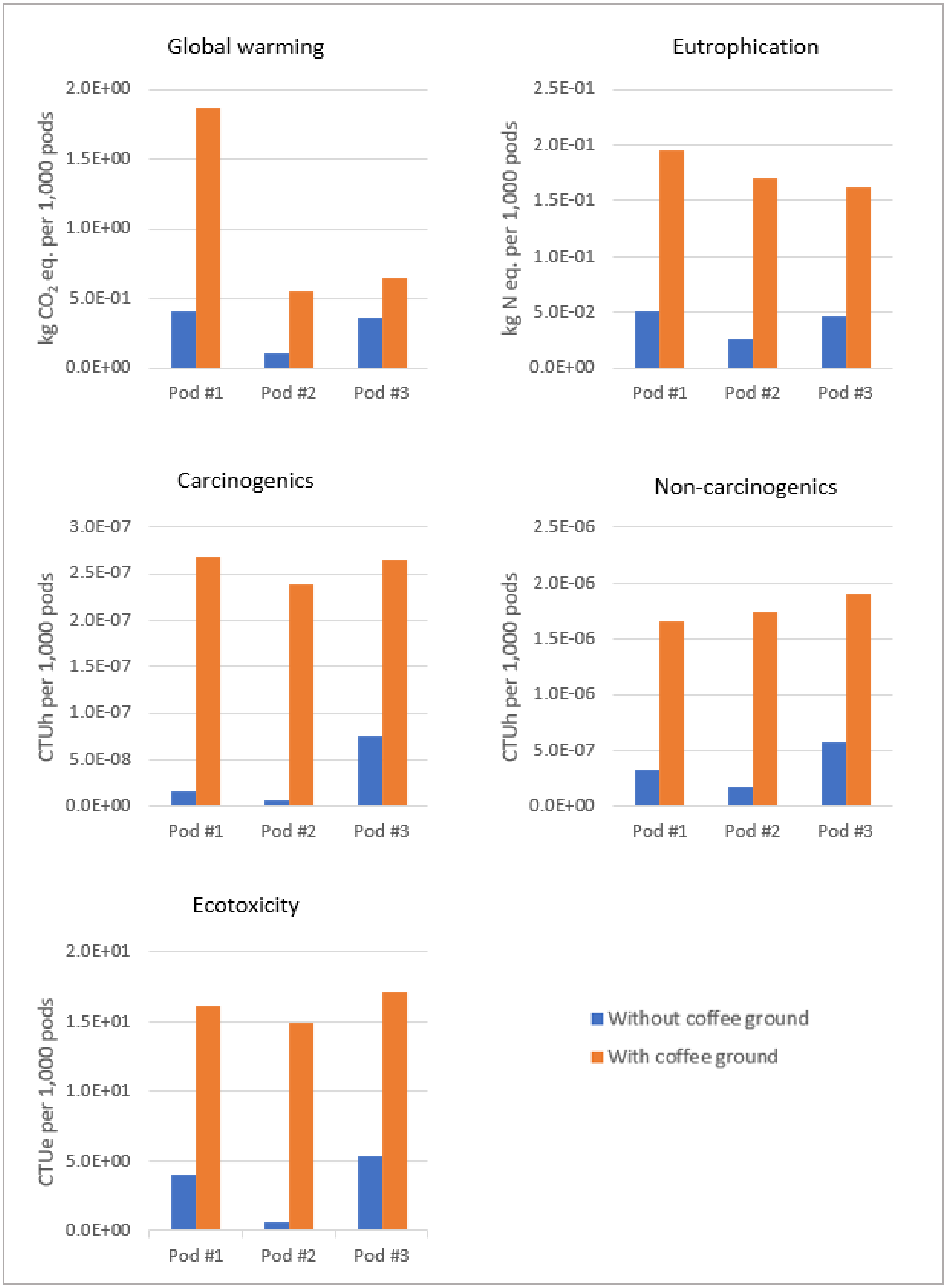

Figure 17 EOL stage contribution with and without coffee ground in five categories.

4.4 Sensitivity Analysis

The objective of the sensitivity check is to assesses the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results (ISO, 2006). Sensitivity analyses were carried out to evaluate how the LCA results would be influenced by three critical assumptions: the fraction of primary aluminum contained in the aluminum of Aluminum Pod, the recycling rate of Aluminum Pod, and the composting rate of Biodegradable Pod. As suggested by international practice standard, with the assumption varied by ±25%, if the results have a change for more than ±10%, the changes will be identified as significant (ISO, 2006).

4.4.1 Primary Aluminum Fraction of Aluminum Pod

The aluminum metal used in Aluminum Pod was assumed to be 100% primary aluminum in the original model. For sensitivity analysis, a ratio of 75% was used for comparison. Table 14 shows the comparison between original analysis results and the sensitivity analysis results.

Table 14 Sensitivity analysis results and percentages of change for primary aluminum fraction of Aluminum Pod

Impact category	Unit	Original (100% primary)	Variation (75% primary, 25% secondary)	Change
Ozone depletion	kg CFC-11 eq	3.94E-06	3.54E-06	-10.1%
Global warming	kg CO2 eq	4.38E+01	3.84E+01	-12.2%
Smog	kg O3 eq	2.11E+00	1.90E+00	-9.6%
Acidification	mol H+ eq	1.09E+01	9.70E+00	-10.9%
Eutrophication	kg N eq	2.15E-01	1.99E-01	-7.3%
Carcinogenics	CTUh	6.33E-06	4.89E-06	-22.6%
Non carcinogenics	CTUh	7.17E-06	6.43E-06	-10.4%
Respiratory effects	kg PM10 eq	6.13E-02	5.16E-02	-15.8%
Ecotoxicity	CTUe	8.16E+01	6.63E+01	-18.8%

For most of the impact categories, characterization results of sensitivity analysis are more than 10% lower than the original results, showing that the primary aluminum fraction has significant influence on LCA results of Aluminum Pod. However, if the GWP result of sensitivity analysis (38.4 kg CO_2 eq.) is compared with the results for Polystyrene Pod (20.6 kg CO_2 eq.) and Biodegradable Pod (16.7 kg CO_2 eq.), the conclusion that Biodegradable Pod has the lowest global warming potential remains valid.

4.4.2 Recycling Rate of Aluminum Pod

A low recycling rate (0%) and a high recycling rate (39%) of Aluminum Pod are used for sensitivity analysis comparing with the original 14% recycling rate. The sensitivity analysis results are shown in Table 15. In the lower recycling rate situation, carcinogenics and ecotoxicity have more evident changes. With the higher recycling rate, all changes are significant except smog formation and eutrophication. However, when the GWP result in the 39% recycling scenario is compared with the GWP of Polystyrene Pod and Biodegradable Pod in their base scenario, Aluminum Pod in its high recycling rate scenario is the highest.

Table 15 Sensitivity analysis results and percentages of change for recycling rate of Aluminum Pod

Impact category	Unit	Original (14% recycling rate)	0% recycling rate	Change	39% recycling rate	Change
Ozone depletion	kg CFC-11 eq	3.94E-06	4.16E-06	5.6%	3.54E-06	-10.0%
Global warming	kg CO2 eq	4.38E+01	4.66E+01	6.5%	3.87E+01	-11.7%
Smog	kg O3 eq	2.11E+00	2.22E+00	5.2%	1.91E+00	-9.4%
Acidification	mol H+ eq	1.09E+01	1.15E+01	5.9%	9.73E+00	-10.6%
Eutrophication	kg N eq	2.15E-01	2.24E-01	4.3%	1.99E-01	-7.7%
Carcinogenics	CTUh	6.33E-06	7.08E-06	11.9%	4.98E-06	-21.3%
Non carcinogenics	CTUh	7.17E-06	7.68E-06	7.1%	6.26E-06	-12.7%
Respiratory effects	kg PM10 eq	6.13E-02	6.65E-02	8.4%	5.20E-02	-15.1%
Ecotoxicity	CTUe	8.16E+01	9.00E+01	10.3%	6.66E+01	-18.4%

Table 16 Sensitivity analysis results and percentages of change for composting rate of Biodegradable Pod

Impact category	Unit	Original (40% composting rate)	15% composting rate	Change	65% composting rate	Change
Ozone depletion	kg CFC-11 eq	3.43E-06	3.43E-06	0.0%	3.43E-06	0.0%
Global warming	kg CO2 eq	1.67E+01	1.67E+01	0.0%	1.67E+01	0.0%
Smog	kg O3 eq	8.30E-01	8.30E-01	0.0%	8.29E-01	0.0%
Acidification	mol H+ eq	3.85E+00	3.86E+00	0.1%	3.85E+00	-0.1%
Eutrophication	kg N eq	1.20E-01	1.21E-01	0.4%	1.20E-01	-0.4%
Carcinogens	CTUh	5.71E-07	5.72E-07	0.2%	5.70E-07	-0.2%
Non-carcinogens	CTUh	1.55E-06	1.56E-06	0.5%	1.54E-06	-0.5%
Respiratory effects	kg PM10 eq	1.42E-02	1.42E-02	0.0%	1.42E-02	0.0%
Ecotoxicity	CTUe	2.85E+01	2.86E+01	0.3%	2.84E+01	-0.3%

4.4.3 Composting Rate of Biodegradable Pod

For Biodegradable Pod, 40% of the used coffee pods were diverted from landfill waste to composting in the original model. In the sensitivity analysis, such diversion rate was both increased to 65% and decreased to 15%. As showed in Table 16, changes of the indicator values are small when the composting rate of Biodegradable Pod is increased or decreased for 25%. Considering the fact that environmental effects from coffee pod EOL stage is rather small comparing to the full life cycle, this is a reasonable outcome. However, the contribution of composting the coffee wastes is not considered in this LCA study. With coffee waste management included in the EOL scenario, the impact of different composting rate is expected to be greater.

Chapter 5

Discussion

In this chapter, the objectives of this study will be revisited. The life cycle impact assessment will help us to identify the coffee pod with the lowest GHG emission and its environmental tradeoff, and the landfill waste generated by each coffee pod system will be added up for comparison. In addition to the findings, this chapter discusses the practical and theoretical implications of the study and its limitation. In the end, the research will be wrap up with future research directions and conclusion.

The discussion needs to address synthesis of the findings, the practical and theoretical implications, the strengths and limitations of the research, and the future research directions.

objectives:

1. To quantify the environmental hotspots of each coffee pod packaging system,
2. To compare GWP between the systems, and to identify tradeoffs in other life cycle impact categories,
3. To estimate the landfill waste generated by the consumption of the coffee pods under current waste management system in Ontario.

5.1 Key Findings

5.1.1 Environmental Hotspots

This life cycle assessment study reveals that for the three coffee pod packages, material stage is the most important contributor to the overall life cycle effects, while coffee supply and use stage are not considered. In addition to the pod materials, materials for secondary packages and plastic wraps also made an important contribution to the results. Production stage also plays an important role, especially for Aluminum Pod. Transportation of materials and distribution of finished products do not have significant impacts on the LCA results, while end-of-life stage has a positive overall effect in most categories with the credit of recycled materials.

While comparing aluminum pods with traditional plastic pods, it is not an environmentally wise choice to promote aluminum pods over petroleum-based plastic pod. Considering that aluminum recycling consumes much less electricity than producing aluminum from its primary orcs, the amount of recycled aluminum is increasing over time (Green, 2007). But in the case of aluminum coffee pod, the used pod cannot be recycled in a municipal recycling system because of the coffee remain. The inconvenient recycling route resulted in a lower recycling rate than other aluminum package (according to USEPA (2016), the recycling rate for aluminum packaging in the U.S. was

39% in 2014). Moreover, as indicated by sensitivity analysis results, the conclusion remains the same, even when the recycling rate of aluminum pod is increased to a higher level (40%). This illustrated that primary aluminum production generates much higher impacts than PS and PLA.

Also, electricity system choice is a long-standing and controversial discussion in aluminum LCAs (Liu & Müller, 2012). The EcoInvent dataset for primary aluminum production uses a special global average grid mix for aluminum industry, in which 53% is hydropower electricity (Frischknecht, 2007). The electricity mix for anodizing dataset is the mix of UCTE (Union for the Coordination of the Transmission of Electricity, substituted by the European network of transmission system operators for electricity, or ENTSO-E, in 2009), in which nuclear power plays an important role (Tuchschmid, 2007). Both of them are relatively clean power mixes. The results could be worse if the processes are powered by fossil-dependent grid.

5.1.2 Low GHG Emission Pod

The characterization results show that a bio-based polymer coffee pod has evident advantages in global warming potential, acidification, and respiratory effects in comparison with a petroleum plastic pod. On the other hand, disadvantages are identified in ozone depletion and eutrophication. This conclusion is in line with earlier LCA studies that compare bio-based polymer products with petroleum based plastic products (Datzel & Krüger, 2006; Gironi & Piemonte, 2009). Weiss et al. (2012) who conducted a literature review on forty-four LCA studies that compared bio-based materials and petroleum materials, also put forward similar conclusions. However, the weighting results presented in section 4.1.2 indicate that the difference between the two coffee pod packaging systems is limited. The bio-based polymer coffee pod system incorporates other materials, like LDPE warp and cardboard box, which may result in some inconsistency against other bio-based material LCA studies. But from both a CE and a landfill waste generation point of view, the promotion of bio-based polymer coffee pod should be supported, because the compostable materials can re-enter the biosphere as biological nutrients (UNEP, 2012), and enable coffee ground to be composted after use. With coffee waste considered in the EOL stage, the coffee waste in the aluminum pod and the bio-based polymer pod generate less GHG. The benefits from coffee waste management increase the advantage of the bio-based polymer pod in GHG emission.

5.1.3 Landfill Waste Generation

LCA is capable of estimating various categories of environmental effects, but it does not reveal how much landfill waste is generated by a system directly. To fulfill the objective of waste generation estimation, a manual calculation is required.

In this part, the mass of landfill waste generated by the use of 1,000 pieces of the three coffee pods will be calculated. The calculation includes the coffee grounds, coffee pods and their secondary packages, but does not include coffee waste generated during roasting or grinding, due to lack of information. Although coffee cultivation and processing were excluded from the LCA system boundary, used coffee ground is calculated in waste generation. Because different packaging systems not only provide different end-of-life approaches for the packaging materials, but also change the patterns of coffee ground EOL treatments. For the Aluminum Pod diverted for recycling, the coffee ground will be sent for composting after the coffee ground were separated from the pod by the recycling company, instead of being landfilled. For coffee Pods Biodegradable Pod diverted from landfill, the coffee ground will be composted together with the pod. The calculation is based on the EOL scenarios introduced in section 3.2.2 (see Table9).

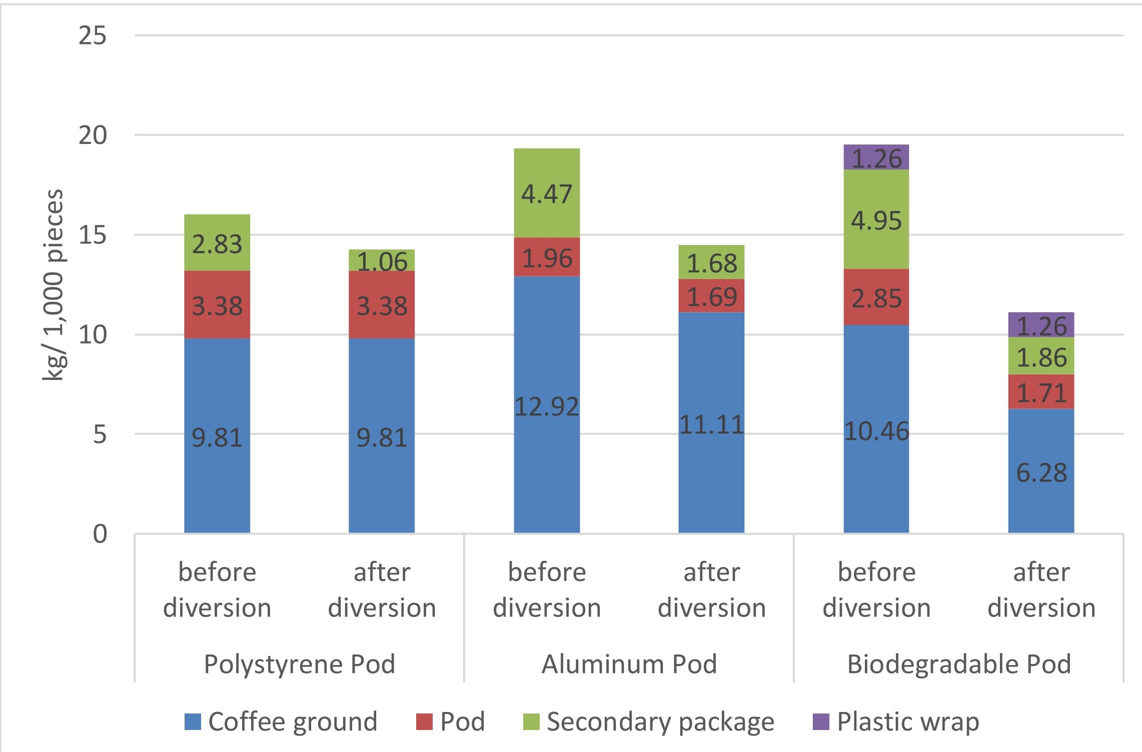

Figure 18 Amount of waste before and after diversion (unit: kg/1,000 pieces). For all coffee pods 62.5% of secondary package is diverted. For Aluminum Pods, 14% of the pods and coffee ground are diverted. For Biodegradable Pod, 40% of the pods and coffee ground are diverted

As shown in Figure 18, coffee ground accounts for more than 50% of the mass of any coffee pod systems, hence diverting coffee waste can highly contribute to the overall waste reduction. Notably, secondary packages produce equivalent or even more waste than the coffee pod itself before diversion. It is indicated that the diversion of secondary packages and the plastic wrap of Biodegradable Pod is influential to reducing the landfilled waste generation.

Before diversion, Biodegradable Pod generated the largest amount of total waste (19.52 kg/ 1,000 pieces), closely followed by Aluminum Pod (19.35 kg/ 1,000 pieces). Polystyrene Pod is the smallest with a mass of 16.02 kg/ 1,000 pieces. After diversion, the rankings are totally different. Biodegradable Pod, with 40% of the pod and coffee diverted, has the smallest amount of waste (11.11 kg/ 1,000 pieces). Polystyrene Pod and Aluminum Pod have similar amount of waste remaining after diversion, adding up to 14.25 and 14.48 kg/ 1,000 pieces respectively. If the consumers switch from Polystyrene Pod to Biodegradable Pod for their daily coffee consumption, more than 6,000 tons of landfill waste can be avoided, equivalent to the annual landfill waste generation of 9,000 people (The Conference Board of Canada, 2016).

What is not considered in the landfilled waste generation is coffee chaff – the waste product of the coffee bean roasting process. Roasting 1 kg of wet coffee bean generates about 0.18 kg of coffee chaff (Humbert, Loerincik, et al., 2009). The producers of Polystyrene Pod and Aluminum Pod will treat the coffee chaff as organic wastes, but the producer of Biodegradable Pod is using the coffee chaff as one of the raw materials to produce the coffee pod. Using the coffee chaff, they are not only reducing the wastes from the coffee bean roasting process, but also reducing the use of bio-based polymers. Since coffee bean processing is not included in the system boundary of this study, the benefit of using coffee chaff in Biodegradable Pods is not quantified.

5.2 Practical Implications

5.2.1 Implications for Policy Makers

1. From both a greenhouse gas emission perspective and a landfill waste generation perspective, consumers should be encouraged to switch from Polystyrene Pod to a Biodegradable Pod for single-serve coffee pod consumption. Consumers should also be discouraged to the use of Aluminum Pod.
2. The bio-based polymer system outweighs petroleum-based plastic system in GHG emission and landfill waste generation in this study. It shows bio-based material's potential in reducing emissions in these two categories. Considering Ontario's ambition regarding GHG and landfill waste reduction, support should be offered to further research in bio-based material development and application.
3. By being compostable, Biodegradable Pod not only provides better EOL management approach to its coffee ground, but also generates the least GHG. Benefits of composting include providing an ideal EOL management approach to contaminated food packages, diverting waste from landfill and incinerators, and generating compost (Tokiwa et al., 2009). However, currently industrial composting is not available to residents in every municipality in Ontario. The government should support the composting programs. Consumer behavior will have significant impact on waste diversion. Education should be provided to the residents to take part in organic waste diversion.

5.2.2 Implications for Industry

1. For the single-use product industries, packaging material could play an important role in reducing the life cycle environmental effects of a single-use product. Inspired by the bio-based polymer coffee pod, using light weight packaging design and choosing packaging material wisely can effectively reduce the environmental effects. Recycling is more efficient on contaminated materials, for food package that is usually contaminated by food residue, composting is a more appropriate waste management approach. More generally speaking, it is important to design a product from a life-cycle engineering stand point, and to consider not only financial, but also environment, health and safety throughout its life cycle (Fava, Brady, Young, & Saur, 2000).
2. For the coffee pod industry, the use of aluminum as pod material is questionable. As indicated in the LCIA results, producing and processing aluminum are much more impactful than its substitutes. In the case of aluminum, life cycle stewardship options to source more sustainable aluminum (ASI 2017) and certified metals (Young, Zhe, Dias 2014) should be emphasized to improve the life cycle of aluminum products. Given that, consumers are often not motivated to take part in the recycling program. On the other hand, the producer of compostable pod is supposed to find a replacement for the plastic wrap, which is currently unrecyclable and contributes to relatively high GHG emissions.
3. In addition to improving their products, the coffee pod producers should also cooperate with municipalities to promote the diversion of the pods wastes via consumer education. There is a need to educate consumers how to better manage their used pods.

5.2.3 Implication for Consumers

The results of this research suggest that the Biodegradable Pod is a better option for single-serve coffee pod consumption regarding landfill waste generation and GWP. However, to achieve these benefits, it requires the consumers to actively take part into the diversion of used pods. Considering the fact that the Biodegradable Pod is not accepted by all municipal composting facilities in Ontario, it is suggested that the consumers should consult to their local composting facility before using the Biodegradable Pod. In the case of which Biodegradable Pods are not accepted as compostable organic wastes, Polystyrene Pod and Biodegradable Pod are considered interchangeable. In either case, Aluminum Pod is not suggested.

5.3 Theoretical Implications

5.3.1 Waste Problem and Material Innovations

Unlike other studies on the sustainability of coffee beverages, which focused on coffee bean supply and coffee brewing (Coltro et al., 2006; Humbert, Loerincik, et al., 2009; Manezes et al., 1998), the current research focuses on packaging formats and EOL treatment options of single-serve coffee products. The conclusion that packaging material is identified as the largest source of effects after coffee bean cultivation and coffee brewing, is in line with other LCA studies on single-serve coffee pods (Chayer & Kicak, 2015; De Monte, Padoano, & Pozzetto, 2005; Dubois et al., 2011).

The innovative elements of this LCA study are: it is the first available LCA study on the PLA based compostable coffee pod, and it compares three formats of coffee pod packaging systems made from different materials and fall under different EOL treatment approaches. The results show that the PLA based compostable pod outweighs other coffee pods in terms of global warming potential, fossil depletion and waste generation. This study provides information to help the Province of Ontario to attain their goals in waste reduction and GHG emissions reduction, and to help the coffee pod industry to design pods that generates less environmental effects.

The current research is a case study of single-serve coffee pods, but does not limit to coffee pods. Waste problems are common, since single-use products are everywhere and the world is getting more and more populated. In order to avoid the continuous accumulation of non-biodegradable plastics, the development of biodegradable plastics is of higher importance. PLA used in Biodegradable Pod is among the expending list of biodegradable plastics. The implementation of PLA and other biodegradable plastics is getting more common and covers a wider range of application (Tokiwa et al., 2009). This LCA study, along with many earlier LCA studies (Datzel & Krüger, 2006; Gironi & Piemonte, 2009; Suwanmanee et al., 2013), compares the environmental performance of biodegradable plastics and their products with traditional petroleum-based plastics. PLA is not only a biodegradable material, but also a bio-based polymer (Vink et al., 2003). Being bio-based emphasizes its source from biomass, and the biodegradable emphasizes its capability to be decomposed by microorganisms (Golden, J; Handfield R; Daystar, J; McConnell, 2015). Similar to other materials that are both bio-based and biodegradable (Weiss et al., 2012), an environmental tradeoff is identified in this LCA study related to PLA based product. As indicated by the characterization results, the use of PLA has benefits in global warming potential, fossil depletion and waste generation, but disadvantages in other impact categories like ozone depletion and eutrophication. However, the weighting results in this study support the use of bio-based materials by indicating that the ozone depletion and eutrophication have less important global effects.

Bioplastics is a fast-developing field, new materials come out every now and then. In order to make the most of them, future studies are required to better understand the new materials from both an environmental and engineering perspective.

5.3.2 Circular Economy

The current literature on circular economy tends to be focused on circulating technical nutrients in the economy by recycling or reusing than using biological nutrients. Key words like "recycling", "reusing" and "remanufacturing" occur much more often in CE literatures than key words like "composting" or "biodegrading" (Lieder & Rashid, 2016; Stindt & Sahamie, 2014). In this research, the aluminum pod system falls under the category of "technical nutrients", and the PLA system is categorized as "biological nutrients". Both of them are substitutions for the petroleum based pod system, which can be considered as a representative of the "linear economy". Surprisingly, the results show that the PLA format is preferable in any of the impact categories. When production of primary aluminum is compared with production of PLA, aluminum refining, smelting and casting are more energy intensive procedures than PLA production (Tan & Khoo, 2005; Vink & Davies, 2015). Seemingly, aluminum recycling is an efficient way to recover post-consumer aluminum, but as for small single-use products like a coffee pod, the efficiency depends on public participation. In the case of aluminum coffee pod, only one fourth of the consumers are willing to participate in the recycling program. As a result, the recycling rate remains at a low level (Nestlé Nespresso S.A., 2017). The compostable pod, on the other hand, is easier to be diverted from landfilling in Ontario, where curbside organic collection programs are available to the residents (Stauch, 2012), and do not require extra effort to disassemble the pod by the consumers.

The results of this study indicate that to employ a circular economic product design, it is critical to consider the easy-access and the motivation of public participation. Ghisellini et al. (2016) also emphasized the importance of public participation in implementing CE at micro level, and indicated that the promotion of consumers' responsibility is crucial for enhancing the purchase and use of more sustainable products and services.

5.3.3 Municipal Solid Waste Management

In 2015, the Province of Ontario had an overall residential waste diversion rate of 47.7% (RPRA, 2017), while the Industrial, Commercial, and Institutional (IC&I) sector, which generated 60% of all of the waste in Ontario, had a waste diversion rate plateaued at 13% in 2012 (Halton Region, 2013). The overall waste diversion rate in Ontario according to these figures is at around 22%. In the Waste-Free Ontario Act, the Government of Ontario outlined a goal of 30% diversion rate by 2020 (Ontario Ministry of Environment and Climate Change, 2016). If Ontario wants to achieve this goal, the province should engage and motivate every stakeholder to implement their plan.

The municipalities should adhere to employ an Integrated Waste Management system. To achieve the 30% diversion rate, organic waste must be diverted effectively. Curbside organic collection programs should be developed in more municipalities, experience and lessons learned from curbside organic collection should be shared among municipalities. Moreover, both the provincial government and municipalities should focus on the IC&I sector, in which there is a low diversion rate. Municipalities should set up regulations to guide waste diversion in IC&I sector, and at the same time provide integrated waste management service to them.

5.4 Limitations

Like most LCA studies, this study is based on many assumptions and has its limitations. It should be considered that these limitations may have influence on the implementation of the results and conclusions from this study. Limitations identified in this study are:

1. This study is limited by data quality. Data for Polystyrene Pod is from secondary source. Data for Aluminum Pod and Biodegradable Pod rely heavily on assumptions. Material composition data for Biodegradable Pod is from unverified source. Moreover, the LCA model used pre-existing European based datasets, which is in a different geographical context from Polystyrene Pod and Biodegradable Pod. Different locations may have different production technologies and conditions that cause uncertainty in the results.
2. Coffee supply was assumed to have similar contribution to the environmental effects of the three coffee pods, and thus excluded from the LCA system boundary. However, the amount of ground coffee varies from brand to brand. In 1000 pieces of the investigated products, the average amounts of coffee are:
   - Polystyrene Pod: 9.81 kg/1000 pieces
   - Aluminum Pod: 12.92 kg/1000 pieces
   - Biodegradable Pod: 10.46 kg/1000 pieces.

   Earlier studies indicated that coffee supply dominates the environmental emissions of many coffee products (Brommer et al., 2011; Dubois et al., 2011; Humbert, Rossi, et al., 2009). While including the coffee supply into the LCA, the difference in coffee amount may lead to a different conclusion in some indicators.
3. The transportation distance was not fully calculated. The origins of the materials for Aluminum Pod and Biodegradable Pod are based on assumptions, and their transportation between different production facilities was not considered. Also, extra package is necessary to protect the products during their distribution, for example corrugated boxes or plastic film wrapping, but they are not included in the models.
4. The results generated by this study are dependent on the selection of EOL scenarios. In the selected scenarios, the diversion rates may not accurately represent the relative material diversion situation in Ontario. Take the composting rate of Biodegradable Pod for example, the 40% composting rate is taken from the Waste-Free Ontario Act referring to the total organic waste composting rate, which includes the highly diverted yard wastes. As a matter of fact, Biodegradable Pod have not been accepted by all of the composting facilities in Ontario.
5. This study was conducted in a geographical background of Ontario, Canada. The geographical background decides transportation distances, waste management scenarios and electricity grid mix. Differences in these areas should be considered while conclusions are implemented in different regions.
6. Selection of impact categories also limited the study results. Nine life cycle impact categories were used to assess the environmental performance of the packaging systems. However, studies of bio-based materials pointed out that land use should be considered while comparing bio-based materials with traditional materials (Datzel & Krüger, 2006; Weiss et al., 2012; Zah et al., 2007). This study did not include land use as one of the impact categories.

5.5 Future Research Directions

1. This LCA study compares bio-based polymer (PLA) coffee pod with petroleum-based plastic (PS) coffee pod and aluminum coffee pod, and identified some advantages and disadvantages of bio-based polymer. There is a large variety of bio-based materials that can replace the use of petroleum-based and mineral materials. Future LCA studies can be conducted on these materials and their applications to compare their environmental effects with petroleum-based and mineral materials.
2. From a CE point of view, biological nutrients and technical nutrients are compared in this research. Conclusion is that biological nutrients have better environmental performance in the context of small single-use products. Future studies can compare large durable products that are made from biological nutrients and technical nutrients.
3. This case study of coffee pod did not include coffee cultivation and coffee brewing into system boundary, it actually investigated the life cycle of coffee package. Future studies can include coffee supply and brewing, and investigate the coffee pod as a coffee beverage.

5.6 Conclusions

This research made a comparison between three coffee pod packaging systems, and revealed the environmental effects generated over their life cycles. The results recognized the bio-based polymer coffee pod's advantages in greenhouse gas emission and waste generation. Moreover, it is indicated that bio-based materials and organic waste composting have potential in helping Ontario to achieve the GHG emissions reduction and waste-free targets.

In addition to the comparison between bio-based materials and petroleum-based materials, a comparison between biological nutrients and technical nutrients is discussed in this research. However, one case study is far from enough to draw a general conclusion. To draw any of determined conclusions on whether bio-based materials, petroleum materials or mineral materials are more sustainable than other materials, or whether biological or technical nutrients are more favorable in CE, extensive research and more case studies are required in future.

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Appendixes

Appendix A Characterization Results of Polystyrene Pod

Title: Analyzing 1,000 p 'Polystyrene Pod landfilling'
Method: TRACI 2 V4.00
Indicator: Characterization

Impact category	Unit	Total	Polystyrene, expandable, at plant/RER U	Polyethylene, LDPE, granulate, at plant/RER U	Ethylene vinyl acetate copolymer, at plant/RER U	Polyethylene terephthalate, granulate, amorphous, at plant/RER U	Kraft paper, bleached, at plant/RER U (NE. mix)
Ozone depletion	kg CFC-11 eq	1.12E-06	1.53E-07	2.45E-10	4.34E-09	5.12E-09	4.54E-08
GWP	kg CO2 eq	17.73266	8.908641	0.682859	0.090097	0.088694	0.351519
Smog	kg O3 eq	0.778537	0.31989	0.030731	0.003566	0.003342	0.031105
Acidification	mol H+ eq	3.946273	1.464943	0.134097	0.013666	0.015385	0.119542
Eutrophication	kg N eq	6.75E-02	0.003562	0.000188	0.000181	0.000179	0.001151
Carcinogenics	CTUh	6.43E-07	2.82E-07	2.83E-08	2.08E-09	3.80E-09	9.90E-09
Non carcinogenics	CTUh	1.28E-06	7.75E-08	6.84E-09	3.70E-09	4.46E-09	3.25E-08
Respiratory effects	kg PM10 eq	0.015471	0.005424	0.000499	5.25E-05	6.48E-05	0.000517
Ecotoxicity	CTUe	25.08131	11.09701	1.190738	0.064803	0.12206	0.249517

Impact category	Unit	Aluminum, primary, at plant/RER U	Printing color, offset, 47.5% solvent, at plant/RER U (NE. electricity mix)	Solid unbleached board, SUB, at plant/RER U (Vermont electricity mix)	Extrusion, plastic film/RER U (VT. electricity mix)	Thermoforming, with calendering/RER U (VT. electricity mix)	Calendering, rigid sheets/RER U (VT. electricity mix)
Ozone depletion	kg CFC-11 eq	6.34E-08	2.38E-08	2.67E-07	8.82E-08	1.14E-07	4.87E-09
Global warming	kg CO2 eq	0.822431	0.058737	2.40856	1.212382	1.659992	0.051903
Smog	kg O3 eq	0.031586	0.003215	0.250593	0.026685	0.050207	0.001458
Acidification	mol H+ eq	0.185643	0.018239	1.156308	0.377776	0.564049	0.017773
Eutrophication	kg N eq	0.002651	0.000277	0.007298	0.000754	0.001288	2.97E-05
Carcinogenics	CTUh	2.16E-07	1.30E-09	3.72E-08	1.72E-08	2.82E-08	5.63E-10
Non carcinogenics	CTUh	1.47E-07	8.69E-09	7.54E-07	9.60E-08	1.30E-07	4.42E-09
Respiratory effects	kg PM10 eq	0.00149	6.90E-05	0.00536	0.001304	0.001974	6.13E-05
Ecotoxicity	CTUe	2.418775	0.075282	3.281315	1.413777	1.901957	0.043227

Impact category	Unit	Sheet rolling, aluminum/RER U (NE. electricity mix)	Production of carton board boxes, offset printing, at plant/CH U (VT. mix)	Transport, lorry 7.5-16t, EURO5/RER U	Transport, transoceanic freight ship/OCE U	Waste collection (Transport, lorry 7.5-16t, EURO5/RER U)	Landfill	Solid unbleached board, SUB, at plant/RER U (NE. electricity mix)
Ozone depletion	kg CFC-11 eq	3.64E-09	1.99E-07	2.95E-07	7.53E-09	1.11E-08	3.13E-09	-1.67E-07
Global warming	kg CO2 eq	0.035836	0.936971	1.481428	0.04448	0.055484	0.349057	-1.50641
Smog	kg O3 eq	0.000857	0.036257	0.118743	0.017435	0.004447	0.00515	-0.15673
Acidification	mol H+ eq	0.009286	0.25653	0.252482	6.19E-02	9.46E-03	0.012411	-0.7232
Eutrophication	kg N eq	4.49E-05	0.002222	7.47E-04	5.54E-05	2.80E-05	5.14E-02	-0.00456
Carcinogenics	CTUh	2.88E-09	1.72E-08	1.88E-09	7.58E-11	7.02E-11	1.67E-08	-2.33E-08
Non carcinogenics	CTUh	3.25E-09	1.05E-07	4.72E-08	8.80E-10	1.77E-09	3.26E-07	-4.71E-07
Respiratory effects	kg PM10 eq	4.09E-05	0.000936	0.000769	0.00018	2.88E-05	5.17E-05	-0.00335
Ecotoxicity	CTUe	0.043307	0.806544	0.332913	0.00432	0.012469	4.075571	-2.05227

Appendix B Characterization Results of Aluminum Pod

Title: Analyzing 1,000 p 'Aluminum Pod 14% recycling'
Method: TRACI 2 V4.00
Indicator: Characterization

Impact category	Unit	Aluminum, primary, at plant/RER U	Polyethylene, LDPE, granulate, at plant/RER U	Polyethylene terephthalate, granulate, amorphous, at plant/RER U	Solid bleached board, SBB, at plant/RER U	Sheet rolling, aluminum/RER U	Extrusion, plastic film/RER U	Calendering, rigid sheets/RER S
Ozone depletion	kg CFC-11 eq.	1.70E-06	6.69E-11	2.92E-09	4.65E-07	2.34E-09	3.64E-09	3.43E-09
Global warming	kg CO2 eq.	22.01073	0.186425	0.050682	4.438948	0.024916	0.054284	0.040378
Smog	kg O3 eq.	0.845349	0.00839	0.00191	0.467749	0.000843	0.001971	0.00179
Acidification	mol H+ eq.	4.968357	0.036609	0.008792	1.557339	0.004569	0.0106	0.008785
Eutrophication	kg N eq.	0.070947	5.13E-05	0.000102	0.023446	0.000113	0.000291	0.000228
Carcinogenics	CTUh	5.79E-06	7.74E-09	2.17E-09	1.89E-07	2.51E-09	2.97E-09	2.91E-09
Non carcinogenics	CTUh	3.92E-06	1.87E-09	2.55E-09	9.07E-07	3.10E-09	7.00E-09	6.49E-09
Respiratory effects	kg PM10 eq.	0.03988	0.000136	3.70E-05	0.009036	2.44E-05	4.66E-05	4.09E-05
Ecotoxicity	CTUe	64.7337	0.325079	0.069748	6.126686	0.033052	0.072754	0.052363

Cold impact extrusion, steel, 1 stroke/RER U	Anodizing, aluminum sheet/RER U	Production of carton board boxes, offset printing, at plant/CH U	Transport, lorry 7.5-16t, EURO5/RER U	Transport, transoceanic freight ship/OCE U	Waste Collection (Transport, lorry 7.5-16t, EURO5/RER U)	Waste scenario/US U (Incineration excluded)	Aluminum, primary, at plant/RER U	Solid bleached board, SBB, at plant/RER U (ON. electricity mix)
1.66E-07	1.48E-06	3.08E-07	1.72E-07	1.33E-07	1.18E-08	6.32E-09	-2.31E-07	-3.33E-07
1.46994	17.59151	1.165796	0.863704	0.787248	0.059183	0.054495	-2.99498	-2.23703
0.037711	0.665935	0.055149	0.06923	0.30858	0.004744	0.009272	-0.11503	-0.27116
0.181961	4.110336	0.236858	0.147203	1.095371	0.010087	0.049298	-0.67604	-0.88569
0.005048	0.099369	0.004287	0.000435	0.00098	2.98E-05	0.025816	-0.00965	-0.0105
7.69E-08	1.00E-06	3.27E-08	1.09E-09	1.34E-09	7.49E-11	5.63E-09	-7.88E-07	-8.02E-08
1.76E-07	2.70E-06	1.64E-07	2.75E-08	1.56E-08	1.89E-09	1.79E-07	-5.34E-07	-5.09E-07
0.000672	0.016785	0.000991	0.000449	0.003182	3.07E-05	0.000148	-0.00543	-0.00518
1.916641	17.47744	1.112585	0.194095	0.076468	0.0133	0.662084	-8.80826	-3.34542

Appendix C Characterization Results of Biodegradable Pod

Title:	Analyzing 1,000 p 'Biodegradable Pod 40% Composting'
Method:	TRACI 2 V4.00
Indicator:	Characterization

Impact category	Unit	Polylactide, granulate, at plant/GLO U (Compost)	Polyethylene, LDPE, granulate, at plant/RER U	Kraft paper, unbleached, at plant/RER U (ON. mix)	Solid unbleached board, SUB, at plant/RER U (ON. electricity mix)	Injection molding/RER U (ON. electricity mix)	Thermoforming, with calendering/RER U (ON. mix)
Ozone depletion	kg CFC-11 eq	7.42E-07	9.47E-10	3.34E-08	5.91E-07	1.81E-06	8.48E-08
Global warming	kg CO2 eq	6.289934	2.639272	0.145541	2.791637	1.469409	0.391045
Smog	kg O3 eq	0.217324	0.118775	0.02353	0.423532	0.056821	0.019198
Acidification	mol H+ eq	1.229102	0.51829	0.077802	1.405527	0.271512	0.097832
Eutrophication	kg N eq	0.048896	0.000726	0.000658	0.012206	0.000969	0.000445
Carcinogenics	CTUh	1.81E-07	1.10E-07	3.56E-09	5.55E-08	2.13E-08	1.05E-08
Non carcinogenics	CTUh	-1.78E-07	2.64E-08	6.69E-08	1.29E-06	1.27E-07	5.31E-08
Respiratory effects	kg PM10 eq	0.00336	0.001928	0.000426	0.007513	0.001076	0.00042
Ecotoxicity	CTUe	11.36143	4.602237	0.226216	4.8869	0.988073	0.650824

Calendering, rigid sheets/RER U (ON. electricity mix)	Extrusion, plastic film/RER U (ON. electricity mix)	Production of carton board boxes, offset printing, at plant/CH U (ON. electricity mix)	Transport, lorry 7.5-16t, EURO5/RER U	Waste Collection (Transport, lorry 7.5-16t, EURO5/RER U)	PurPod composting	Solid unbleached board, SUB, at plant/RER U (ON. electricity mix)
1.30E-09	1.30E-08	3.84E-07	1.37E-07	1.66E-08	6.31E-09	-3.69E-07
0.004426	0.058767	1.233298	0.686154	0.083226	0.290829	-1.74266
0.000211	0.001926	0.059195	0.054999	0.006671	0.00939	-0.26439
0.001066	0.011636	0.272656	0.116943	0.014184	0.037424	-0.87739
3.42E-06	4.90E-05	0.003726	0.000346	4.20E-05	0.046327	-0.00762
6.83E-11	1.24E-09	2.74E-08	8.68E-10	1.05E-10	7.55E-08	-3.47E-08
7.06E-10	7.99E-09	1.76E-07	2.19E-08	2.65E-09	5.73E-07	-8.07E-07
4.60E-06	5.04E-05	0.001106	0.000356	4.32E-05	0.000106	-0.00469
0.004829	0.099383	1.167415	0.154196	0.018703	5.371654	-3.05061

Appendix D Weighing Results of Three Coffee Pods

Title: Comparing 1,000 p 'Polystyrene Pod', 1,000 p 'Aluminum Pod' and 1,000 p 'Biodegradable Pod'
Method: ReCiPe Endpoint (E) V1.06 / World ReCiPe E/A
Indicator: Weighting

Impact category	Unit	Polystyrene Pod	Aluminum Pod	Biodegradable Pod
Total	Pt	4.549212	13.77414	4.434934
Climate change Human Health	Pt	0.929125	2.645079	0.795137
Ozone depletion	Pt	4.09E-05	0.000132	0.00011
Human toxicity	Pt	2.141543	8.760281	2.529279
Photochemical oxidant formation	Pt	4.00E-05	8.14E-05	3.67E-05
Particulate matter formation	Pt	0.094989	0.321374	0.078099
Ionising radiation	Pt	0.000769	0.004708	0.002121
Climate change Ecosystems	Pt	0.050916	0.145005	0.043574
Terrestrial acidification	Pt	0.000184	0.000504	0.000157
Freshwater eutrophication	Pt	9.93E-06	0.000174	3.07E-05
Terrestrial ecotoxicity	Pt	0.00027	0.000866	0.000638
Freshwater ecotoxicity	Pt	1.07E-05	2.47E-05	1.28E-05
Marine ecotoxicity	Pt	2.19E-05	0.00011	3.70E-05
Agricultural land occupation	Pt	0.026884	0.025705	0.048821
Urban land occupation	Pt	0.00076	0.000947	0.001439
Natural land transformation	Pt	0.017615	0.050258	0.028917
Metal depletion	Pt	3.40E-05	0.00015	2.83E-05
Fossil depletion	Pt	1.285998	1.818743	0.906496