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Assessment of the Environmental Profile of PLA, PET and PS Clamshell Containers using LCA Methodology

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ASSESSMENT OF THE ENVIRONMENTAL PROFILE OF PLA, PET, AND PS CLAMSHELL CONTAINERS USING LCA METHODOLOGY

By

Santosh Madival

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ABSTRACT

Assessment of the Environmental Profile of PLA, PET and PS Clamshell Containers using LCA Methodology

By

Santosh Madival

Biobased polymers have noticeably grown in the past years as an environmental and economical alternative to hydrocarbon based ones. For food packaging applications biobased polymers have been found to have comparable mechanical and physical properties to that of the petroleum based polymers. However, studies from environmental impact standpoint from cradle to cradle, which compare their environmental performance, are limited. In this work, the environmental profile from cradle to gate, grave and cradle of poly(lactic acid), PLA, a corn based material, poly(ethylene terephthalate) ,PET, and poly(styrene), PS, as clamshell containers for the packaging of strawberries was compared by using available Life Cycle Assessment (LCA) methodology. The cradle to cradle analysis found PET to be the highest contributor for global warming, ozone layer depletion, aquatic eutrophication, energy consumption and land occupation, PLA for aquatic acidification, respiratory organics and respiratory inorganics and PS for aquatic ecotoxicity. PLA had the lowest energy consumption due to the utilization of renewable energy during its resin production. The transportation system and the distances between the resin producers, container manufacturers, the strawberry exporter and the retail market play a major contributing role to the total burdens emitted by the packages. The data gathered and presented in this work provide a basis to identify and translate the environmental impact of these polymers based on the current inventory data.

Dedication

TO GOD, MY FAMILY AND MY COUNTRY.

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Chapter 1: Introduction

The inherent beneficial properties that uniquely separate plastics from other packaging materials are their light weight, barrier properties and ease in processing and converting into different forms and structures. These advantages make plastics the material of choice for various applications. Over 20 billion pounds of plastic resin is consumed annually in the United States (2004) [1]. The packaging industry in Europe uses plastics for packaging, about 50% of their products [2]. This huge demand for plastics directly affects the natural resources ore, since the traditional polymers are non renewable hydrocarbon based polymers. The projected scarcity of fossil resources intensifies the need of a reliable and a promising alternative for plastics in the future specifically for the packaging industry. Moreover, with the growing awareness for a clean and better environment, bio-based products are now finding applications in fuels, chemicals, construction, and an array of other products, packaging is no exception to that. Studies have shown that bio polymers have comparable functional properties to that of hydrocarbon based ones in terms of food packaging applications. In addition, they have shown lesser environmental impacts as compared to the traditional petroleum based polymers [3].

Out of the many available evaluation techniques, used to evaluate these polymers Life Cycle Assessment (LCA) is a tool, used to assess the environment viability of a product, which considers the burdens generated by it during the various stages of its life cycle. Various comparative LCA studies have been conducted in the packaging industry involving materials, processes, packaging systems, involving economic aspects and waste management criterions [4]. With the advent of biopolymers and LCA as an evolving tool, a direct comparison between petroleum based polymers and biodegradable ones has been possible. These comparisons have oriented to a more realistic and close approach towards the environment feasibility of biodegradable polymers. Although there are limitations within the LCA tool related to the boundary definition and interpretation of the study being conducted, it introduces and guides the audience to scientific and technology based facts which help them to understand the environment footprint of the system being studied [4]. The objective of this thesis is to evaluate the environmental performance of poly(lactic acid), PLA, poly(ethylene terephathalate), PET and poly(styrene), PS, clamshell containers for the packaging of strawberries using LCA methodology. Chapter 2 reviews the literatures regarding LCA studies for primary, secondary and tertiary packaging and those involving PLA. The methodology followed for the evaluation of the containers from cradle to grave and cradle to cradle is described in Chapter 3. Chapter 4 relates to a comparative LCA study between PET, PS and PLA clamshell containers used for packaging of strawberries. The study is from cradle to cradle for nine different impact categories. It portrays the importance of transportation systems in the life cycle of the three products, and the impacts contributed by it. Also this chapter quantifies the burdens generated through the different end of life options thereby striking a comparison with the actual waste management culture. Chapter 5 specifically deals with transportation scenario during the distribution of strawberry filled containers from the exporter to the market. It emphasizes the importance of distances and transportation system in the distribution chain of the life cycle of the three containers. Finally, Chapter 6 summarizes the study findings with a guideline for future work in this research area suggesting further improvements and changes.

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Chapter 2: Literature review

2.1 Introduction

The basic function of packaging is to protect and preserve natural or artificially manufactured or processed foods from spoilage simultaneously giving the package a shelf appeal with its aesthetics. The packaging domain primarily consists of raw material manufacturers, the converters and the users which include the distribution network from the wholesalers and retailers to the consumers [1]. In the entire system, the role of packaging is an integral one which cannot be disregarded or undermined, but at the same time one cannot neglect to observe the environmental burdens that a package emits during its journey from its production to the waste stream. In the year 2004, Australia generated 3.3 million tons and in 2005 Europe produced an annual packaging waste of 56.3 million tons [2]. In the year 2006, USA generated about 251 million tons of annual packaging waste [3]. The awareness of similar observations over the years has given rise to the concept of sustainable packaging [4]. Sustainability in packaging consists of three basic elemental functions- the social, the economic and the environment. Packaging enters the society by being an integral part of the supply chain which not only protects and preserves the product but also informs and guides a regulated consumer behavior. Packaging design controls the entire packaging system, which also includes transportation, the handling and the storage system [5]. The number of packaging components used in a package, the type of materials involved, the process ability, its end of life scenario and the overall energy and resource utility are the factors which directly affect the economy and the environmental aspects of the packaging system.

Among the number of environmental impact evaluation techniques available, Life Cycle Assessment (LCA) is regarded as an important tool which is used to determine a balance between the natural resources and the human activity through a comparative study and thus focusing exclusively on the ideologies of sustainable development [5]. LCA has been able to prove that materials which were once considered recyclable and 'environment friendly', in fact put more burdens on the environment when the issues related to it such as energy, materials , process inputs, transportation and the recycling options were taken into consideration [6].Therefore, LCA has emerged as a tool, which has generated a new trend of looking at products from the resources point of view not only in their optimization but also re-use and recycle to obtain the maximum output [4]. Unlike other conventional techniques, LCA gives a clearer and a better picture of a product's effect on the environment since it deals typically with the entire life cycle of the system under study [5]. Appendix A presents a glossary of the LCA terminology.

The traditional LCA has given birth to a whole new application of LCA called Life Cycle Product Design (LCPD). The framework of LCPD is based on designing a product taking an account various criteria such as product's technical performance, the legislative regulations, the safety, health and environment limit requirements, its distribution in the market, and finally the consumers and their requirements [6]. However, this modification is still developing with some work already done in the past. LCA has been successfully applied to a varied number of sectors including chemicals, construction, energy, automobile, electronics, textiles, packaging and an array of products [6]. The following paper will primarily focus on the review of LCA studies in the packaging industry emphasizing specifically on primary, secondary and tertiary packaging and studies involving biopolymers.

2.2 Packaging categories

Basically, packages consist of three different functional categories

- Primary Packaging
- Secondary Packaging
- Tertiary Packaging

Primary Packaging: Primary packaging is the first wrap, which is in direct contact with the product.

Secondary Packaging: Secondary package is the containment of a primary package.

Tertiary Packaging: Tertiary packaging, also known as the distribution package, contains several units of secondary packages [1].

The packaging industry is basically categorized as the suppliers and the users. The suppliers further are divided into converters, which convert the raw material into the desired package geometry, service providers which include testing, marketing, consultancy, graphic designers and lastly the machinery manufacturers. The user industry comprises consumer packaging, which include food, beverage, pharmaceuticals, hardware, personal care, toys, cosmetics, industrial packaging, which include bulk food, chemicals, electronic devices, and finally institutional packaging, which include food, non food, military supplies and medical devices [6]. The above mentioned categories deal directly or indirectly with the functional categories of packaging in the form of primary, secondary and tertiary packaging

2.3 LCA IN PACKAGING

LCA has been historically applied to these mentioned packaging categories for different applications. Studies evidently, can be found to assess the environmental performance of different packaging materials like paper, glass, plastics, steel, aluminum, and wood and for different forms like plastic containers, metal cans, glass bottles, flexibles, paper and board boxes, composites, pallets and a plethora of geometric structures. Most of the studies found in packaging are comparative studies which determined the environment viability of an option among its contemporaries for a common application. The contemporaries' not necessary being of the same material but could be of different materials and forms which execute a common function. According to Martino (2005), the evolution of LCA in packaging emerged out of a study which came up in the late 1960's and the early 1970's by Harry Teasley of Coca-Cola. The study was done on beverage containers and was conducted by Midwest Research Institute. In the year 1981, Gaines and in 1985 Lundholm and Sundstrom continued the trend of studies for the Resource and Environmental profile Analyses (REPA) which were used for decision and policy making [6, 8]. These studies typically were based on raw material demands, energy inputs and waste generation flows, which later on revolutionized and evolved as an important tool of LCA methodology dealing on sophisticated analysis through environment analysis [8].

2.3.1 LCA in primary packaging

LCA studies in primary packaging are very varied depending specifically on the goal of the study. Keoleian et al (2004) carried out a study for a yoghurt delivery system.

It compared the packaging system that used polypropylene (PP) cups of 2, 4, 6, 8 and 32 oz capacity for packaging and delivering yoghurt. The study found that the energy consumption for manufacturing 32 oz containers were the lowest while that of 8 oz containers was the highest for a functional unit of 1000 lbs of yoghurt. Furthermore, the energy consumption during the container manufacturing was a little more than half of the total life cycle energy, while one-third was used during yoghurt distribution stage. It concluded that the amount of solid waste generated was inversely proportional to the weight of the containers. Evidently as the 32 oz container was the best option among the other containers, a further improvement of reduction of energy consumption and solid waste by one fifth of the total was also calculated if the manufacturing of the 32oz container would be carried out by thermoforming instead of injection molding [9 The emission values associated with the life cycle of each of the container are as given in Table 1.The air emission and water emission values are found to be lowest for the 32 oz containers, while the water consumption during its manufacturing just seems to highest.

Table 1: Life cycle burden values for 2,4,6,8 and 32 oz containers, adapter from Keoleain et al (2004) [9].

Impact category	**Units**	**2 oz**	**4 oz**	**6 oz**	**8 oz**	**32 oz**
Air emission except CO_2	gms.	3280	3420	3440	3000	2610
Water emissions	gms.	1410	1270	1200	1050	899
Water use	lts.	1150	3550	3080	2560	3590
Global warming potential	Kg. CO_2	226	256	240	209	195
Ozone depletion potential	mg. CFC-11	8.83	6.60	5.05	4.13	3.05

Zabaniotou et al (2003) carried out a comparative LCA study to determine the performance of eggcups for packaging of eggs made from polystyrene (PS) and recycled paper. They found that throughout the life cycle PS eggcups contributed mainly to global warming, acidification, winter smog and summer smog impact categories, while recycled paper cups had high values for heavy metals and winter smog. A further comparison showed that PS had more energy consumption than recycled paper and emitted more air emissions and liquid waste, while the latter had higher emissions for some organic and dissolved inorganic chemicals and generated comparatively higher solid wastes than PS. Overall, the study concluded recycled paper eggcups to be more environment friendly than PS eggcups [10]. A similar study for paper cups was carried out by Garrido et al (2007). He compared single-use PP cups with the reusable ones. The cups were of different dimensions with the functional unit of 1000 lt of beverage distribution. For the reusable cups he considered different scenarios in which the cups were used for 2, 9, 10, and 14 cycles before they were disposed. This study was from cradle to grave including transportation. On the basis of different assumptions for transportation and waste management options for ten different impact categories, they found that the reusable cups with a cycle of 10 had the least contribution to the overall environmental impact. The main contributing factor for the single use cups came from the production of PP resins and the fabrication processes for the cups. They also found that as the number of reuse cycles increased the waste generation and the overall environmental effect decreased, but the impact category values for the ozone layer depletion, heavy metals and carcinogens increased due the emissions coming from the washing and cleaning processes involved during the reuse operations. Also there was a subsequent increase in the electricity consumption associated with the washing and reuse activities [11]. Improvements in the beverage sector in Norway using LCA methodology was carried by Hanssen et al (2007). They studied the Norwegian scenario for two different criterions. Impacts based on per litre consumption of beverage and per total volume beverage sale per capita for the year 2000. For the two impact categories, global warming and energy consumption, they found that the packaging system was the most efficient and a low contributor stage in the beverage life cycle in Norway. This was related to the fact that 95% of the packaging used was on a returnable basis which were reused and recycled. However the beverages which used cartons as the packaging material had scope for improvement since the recyling rates for these materials were comparatively lower than others. Overall, the production of raw materials used for beverage production was most responsible for the total burden and packaging was just one tenth of the total impact [12].

Petcore, the European trade association for promoting the growth and development of polyethylene terephthalate (PET) containers, carried out a study to determine the performance of a refillable glass bottle and one way PET bottle under kerbside collection situation and for deposits. Since the soft drinks and mineral water market was dominated by the 1.5 lt PET bottle and 0.7 lt glass bottle, the study compared these two packaging materials with a functional unit of 1000 lt units of each for eight impact categories. Both under the kerbside collection and deposits PET bottle had comparatively high impact values for terrestrial eutrophication, summer smog, summer smog (NO_X –corr.), and use of nature while it showed benefit over glass for global warming, fossil resources and aquatic eutrophication. For acidification, PET had a benefit over glass for deposits.

The study concluded that one way PET bottles had equal advantages than that of glass bottle and also that PET would be more environmentally viable if used under kerbside collection than rather under the deposit system. [13]. Lehmann et al carried out a comparative LCA on beverage bottles made of High Density Polyethylene (HDPE) and PET in Sweden. This study was from cradle to cradle and considered eight impact categories. It found that even though PET had higher impact values for categories like carcinogens, radiation, ecotoxicity, land use and minerals HDPE had overall a higher environmental impact than PET. They also concluded that even though PET had higher impact values for some categories, it was environmentally preferred for the bottle applications since it was reusable [14]. A different LCA study for the packaging of paints was carried out by Bushby (1994) for RPC Containers Ltd, Leics England. He compared a 5 lt capacity polypropylene (PP) container to that of tinplate can of same capacity. Despite the assumption that the tinplate can contained 25% recycled material, PP container was found to have lesser environmental impacts and its total energy consumption throughout its life cycle was 60% to that of the tinplate can [15]. A similar non food application of LCA study conducted by Bovea et al (2006) was for the packaging system of ceramic tiles. They studied the primary packaging in terms of corrugated box and tertiary packaging in terms of pallets for six impact categories. They found the raw material acquisition stage, for corrugated box, to have the highest impact that the other stages followed by the packaging process and the distribution operation. Since the pallets were reusable they had a comparatively lesser environmental impact. They further calculated that a reduction in the thickness of the corrugated box from 3 to 1.5 mm would require 11.5% lesser amount of raw material. A further decrease in the amount of adhesive applied by applying through dots rather than a line was also found to have 64% lesser adhesive consumption and about 23% reduction in the energy consumption. Both the modifications had an affect on the total weight of packaging and raw material utility, thereby directly affecting the packaging and transportation system of the ceramic tiles [16]. Singh et al (2006) applied LCA methodology to reusable plastic containers (RPC) and corrugated paper trays (CPP) for the application of packaging of fresh produce. The study was from cradle to grave including transportation and covered the North American market as the geographical scope. They studied the system for 10 different fruits and vegetables packed in containers of different sizes and shapes. The plastic containers which were a traditional package in the many of the European countries consumed 39% less energy than the paper ones. Not only did it generate 95% less solid waste since they were non reusable unlike the plastic containers, but also it had a lesser impact on the climate change by contributing 29% less to greenhouse gas emission [17]. An overview of the results is shown in table 3.

Table 2: Comparative average impact category values for returnable plastic containers (RPC) and corrugated paper trays (CPP) (2006) [17].

Fresh product	**Greenhouse gas emission (kg CO_2) *PC / *****CPT***	**Energy consumption (million BTU) *PC / *****CPT***	**Solid waste generated (tons) *PC / *****CPT***
Apples	62.7 / *67.1*	853 / *1073*	1.35 / *25.3*
Bell peppers	81.3 / *113.0*	1121 / *1818*	1.99 / *43.2*
Carrots	37.8 / *61.1*	531 / *981*	1.04 / *23.4*
Grapes	78.3 / *120.0*	1080 / *1920*	2.15 / *45.5*
Lettuce	65.9 / *92.8*	905 / *1485*	1.53 / *35.1*

Table 2: (Continued)

Oranges	46.6 / *76.9*	650 / *1241*	1.23 / *30.2*
Peaches	49.0 / *80.1*	671 / *1284*	1.25 / *30.5*
Onions	38.2 / *67.0*	533 / *1075*	1.09 / *25.7*
Tomatoes	57.5 / *77.0*	797 / *1241*	1.57 / *30.1*
Strawberries	145.0 / *155.0*	1975 / *2455*	4.03 / *55.6*

* Plastic containers
**Corrugated paper trays

2.3.2 LCA in secondary packaging

Keoleian et al (2004) apart from comparing different sizes of Polypropylene cups for yoghurt packaging focused on the environmental load generated by secondary packaging like corrugated boxes and tertiary packaging like wooden pallets. The life cycle for the boxes and pallets was studied from cradle to grave which excluded the conversion (conversion of corrugated board into boxes and wood into pallets) stage. This also included the transportation stage from the yogurt filler to the distributor. The secondary packaging life cycle with the distribution could be referred to as the distribution phase. They found that the secondary packaging production accounted for 55% of the total energy during the distribution phase and 15% of the total LCA study. Out of remaining 45%, the total energy consumed by secondary packaging during transportation was 3% while the rest was mainly due to yoghurt and primary packaging. Out of the various factors responsible for the energy consumption, the weight of the product and packages was one of the prime factors. Table 2 gives a brief idea of the comparative weights for the secondary and tertiary packaging components included in the study [9].

Table 3: Secondary and tertiary packaging component weights adapted from Zabanitou et al (2003) [9].

Product unit oz	Packaging component	Units / package	Weight (g)	Components per functional unit	Component weight per functional unit (g)	Packaging weight per functional unit (g)
2	Corrugated Box	96	243	83.33	20.250	21484
	Wooden pallet	119808	18144	0.07	1212	
	LLDPE Stretch wrap	119808	331	0.07	22	
4	Corrugated Box	24	158	166.67	26.333	41729
	Wooden pallet	4800	18144	0.83	15120	
	LLDPE Stretch wrap	4800	331	0.83	276	
6	Corrugated Box	12	132	222.25	29337	44002
	Wooden pallet	3360	18144	0.79	14402	
	LLDPE Stretch wrap	3360	331	0.79	263	
8	Corrugated Box	12	137	166.67	22833	41162
	Wooden pallet	2016	18144	0.99	18000	
	LLDPE Stretch wrap	2016	331	0.99	328	
32	Corrugated Box	6	188	83.33	15667	27510
	Wooden pallet	780	18144	0.64	11631	
	LLDPE Stretch wrap	780	331	0.64	212	

Anon (1998) conducted a study where the performance of corrugated board was compared to plastic crates and the entire system was evaluated for distribution packaging. He concluded that the new board system, a double corrugated board with impregnated fluting, was 30% better than the old system, a single corrugated board, in terms of LCA impacts [18]. A different type of study in case of corrugated board was done where in a LCA software program was described which determined the environmental effects of the board during different stages of its production [19].

2.3.3 LCA in tertiary packaging

Studies on LCA studies of tertiary packaging are very few. Lee et al (2004) compared the conventional wooden pallets to that of thermoformed HDPE pallets. The study was conducted from cradle to grave with a functional unit of one pallet. The impact assessment method chosen was EPS 2000 Default Method which expresses the impacts in a single impact unit called the Environmental load unit (ELU).They concluded that the impact generated by the wooden pallets was three times higher than that of the HDPE ones [20]. A similar study was found which compared the performance of pallets made from wood, steel, virgin HDPE, and two recycled HDPE pallets of different recycled material composition. The study found that the wooden pallet and the virgin HDPE pallet had similar burdens and both had about 53% and 74% respective higher impacts than the recycled HDPE pallets ones. Table 3 shows the different criteria considered for the pallet comparison [21].

Table 4: Comparison of the types of pallets adapted from Cardo et al (2004) [21].

Pallet Type	Composition of pallet (%)	Weight of pallet (Kg)	No of trips/ cycles	Nominal Load capacity	Required no of pallets
Wooden Pallet	Wood -98.3 Steel -1.7	23	17	1	294
Virgin Pallet	Virgin HDPE - 100	18	50	1	100
Recycled HDPE	Recycled pallets -90 Recycled HDPE-9.6 Phenol- 0.4	18	50	1	100
Plastic RECYPALLET	Recycled pallets -50 Recycled HDPE – 27.49 *GFRP-15 Additives- 7.51	24	50	1.5	67

*Glass fiber reinforced PET

Brookes et al (2005) conducted an LCA study comparing foams made from starch and polyethylene. The scope of the study was from cradle to grave excluding the common consumption and transportation stages for eight impact categories and a functional unit of amount of foam required for packaging 50,000 laptops. They found that the Polyethylene (PE) foam production system predominantly had higher impact values than the starch foam production system in all the categories. They further concluded that PE foams required eighteen times the energy required by starch foams [22]. Coltro et al (2000) conducted a study on the energy modeling for Brazil for the production of different packaging systems consisting of primary, secondary and tertiary packaging materials. He found that the electric energy use represented only 10-15% of the total energy consumed by the packaging industries considered and also that the energy production in Brazil was a clean process [23]. A popular and traditional method of packaging and transporting fresh produce such as fruits and vegetables is through wooden crates. Lelievre (1999) studied the packaging system for the transportation system for fruits and vegetables using wooden crates. The study was from the production of crates to the end of life disposal with different end of life alternative scenarios. She emphasized transportation during distribution stage to be the most contributing factor towards the air emissions. The transportation stage also accounted for 90% of the total energy consumed during its life cycle journey. She found several advantages with reusing the crates rather than dumping or recovering them. Incineration also had some reduction in the global warming and energy consumption values but concluded reuse to be the best alternative among the end of life options [24].

2.3.4 LCA for comparison of packaging systems and processes

Andersson et al (1998) did a study on the different stages of life cycle of tomato ketchup manufacturing and different subsystems for these processes were studied, one of which was packaging. The following table shows the summary of the systems studied for the tomato ketchup production [25].

Table 5: The subsystem included in the production of tomato ketchup adapted from Andersson et al (1998) [25].

Subsystems	Processes included in the system	Investigated cases
Agriculture	Tomato and sugar beet cultivation	-
Food processing	Production of tomato paste, raw sugar, sugar solution, vinegar, spice, emulsion salt and ketchup.	-
Packaging	Production and transportation processes related to packaging of tomato paste and ketchup.	Disposal – Landfill, incineration, recycling and energy recovery.
Transportation	All transportation except for packaging subsystem	-
Shopping House hold	Transportation of ketchup from retailer to end. user	Storage time 1)One month 2) One year.

Table 6: The packaging subsystem for the tomato paste and the ketchup Andersson et al (1998) [25].

	Tomato paste packaging system	Ketchup packaging system
Case 1	Steel barrels, plastic materials and wood pallets - landfill	Plastic materials - landfill. Corrugated cardboard : 80% - recycling 20% - landfill Wood pallets : reused 100 trips- landfill
Case 2	Steel barrel- 70% recycling 30% landfill. PP- 80% incineration 20%- landfill Wood pallets – incineration	LDPE – incineration PP- 80% incineration 20% landfill. Corrugated cardboard 80% recycling and 20 % - incineration. Wood pallets reused 100 trips- incinerations.

The conclusion of the study was that most of the impact categories had packaging and food processing systems as the main sources. For one year storage period the primary energy usage for household subsystem would be considered equal to the packaging and food processing subsystems. Agriculture subsystem was the main source of eutrophication. For toxicity, the agriculture, the food processing and packaging subsystems were found to be highest [25]. Thrane et al (2006) studied the environmental effect for the life cycle of Danish fish products. They found that the fishing stage was the most contributing factor for the eight different impact categories that they considered. However, for some types of fish products like pickles which used glass and aluminium as the packaging material the processing stage was a significant consideration for the impacts especially the energy consumption [26].

Similar study was carried out by Saouter et al (2001) on LCA of detergents and had a similar conclusion that packaging was responsible for a higher impact on the environment throughout the system of the life cycle of the detergent [27]. Amelia et al (1995) evaluated specifically the recycling efficiency for aluminum, steel, paper, glass and high density polyethylene, Poly vinyl chloride (PVC) and for PET bottles. She found that, if life cycle evaluation considers the combination of external costs with the private costs, then it would be helpful in determining the actual relative cost of the different recycling schemes which eventually would help in the development of sustainable waste management. End of life disposal is an integral part of a product's life cycle. With different options such as landfilling, incineration, composting, reusing and recycling an entire new genre of processes can be identified associated with these different scenarios [28]. Perugini et al (2005) carried an LCA study to examine the recycling of PET and PE liquid containers for five different scenarios. Out of the five mechanical recycling was a realistic scenario which represented the Italian scenario, for which the study was primarily carried out. Two scenarios were hypothetical ones which were landfilling and incineration. The remaining two were considered as future possible alternatives which were mechanical recyling with low temperature pyrolysis and hydrocracking of the polyolefin fraction. The system boundaries were from collection of the waste through different processes involved to polymer reprocessing which also included transportation at various stages. They found that the landfill and incineration had the most impacts for all the six impact categories while the mechanical recycling having the most benefits for greenhouse gas emission, organic air emission, water consumption and waste consumption and the mechanical recyling with hydro cracking, being the most beneficial for crude oil consumption and energy consumption [29].

2.3.5 LCA studies involving biopolymers

The evolution of bio based polymers and their successful applications in packaging in various forms have created a heavy demand for them in the market which has qualified them to be compared with the conventional hydrocarbon based polymers. Bio based polymers like the Polyhydroxyalkanoates (PHA) and Polylactic acid (PLA) have been successful in finding applications in the form of films and containers for packaging. The comparison of these renewable resource bio based polymers and the non renewable resource petroleum based polymers have led to a few LCA studies which provide evidence of the environment viability of these polymers [7]. Kim et al (2005) conducted a study on the green house effect on the production of biomass and bio based products which estimated the global warming impact on the production of corn, soybeans and switchgrass, and he found that the cumulative energy requirement for producing and transporting corn was 1.99- 2.66 MJ/kg, for soybeans it was 1.98-2.04 MJ/Kg,1.24 and 0.97-1.34 MJ/Kg for switchgrass .He also found that the global warming impact for corn was highest followed by soybeans and switchgrass [30]. Dornburg et al (2003) studied the energy savings and greenhouse gas emission between biobased polymers and that of bio based energy on the agricultural land use. They concluded that in case of biobased polymers if land use is used as a basis of comparison for the study then the results of the study changes significantly [31]. On a hectare basis with residue utilization bio based polymers like the fiber composites and PLA were better in terms of energy savings and Greeen house gas (GHG) emission reduction than bioenergy production from energy crops except for PHA which was found to be worse while on comparison on a per hectare basis with residue utilization even PHA was better for bioenergy production. Vink et al (2003) determined the gross energy contribution for production of PLA from corn. This study also compared production of PLA from corn and biomass with the petroleum based polymers and it focused on the potential improvement in reducing the emissions using the biomass scenario The study was helpful in determining that PLA production systems generally outperform the traditional petroleum based polymers in terms of green house gas emissions and energy use [32]. Vink et al (2007) provided the life cycle inventory data for PLA production. The study consisted of inventory emission values for factory to gate situation for PLA production during the year 2006. They also provided the data which is expected to be emitted after the implementation of their new improved technology. The details of the new technology were not disclosed for proprietary reasons. However, they claimed that the new technology would require lesser amounts of dextrose, lime, sulphuric acid, steam, and natural gas and also produce comparatively lesser amounts of co-products [33]. Kim et al (2005) estimated the environmental performance of PHA production based on corn grain and corn grain and corn stover They found that production of PHA with corn stover was more environmentally viable than production with corn [34].A different study conducted by James et al (2005) compared shopping bags made out of degradable material and the other alternatives such as petroleum based polymeric bags, paper based bags and calico bags. The study was from cradle to grave, excluding the consumption stage of the bags and considered five different impact categories. They found that the biodegradable bags had similar burdens than the HDPE bags for green house and eutrophication and lower impact for abiotic resource depletion. Kraft paper being the highest contributor for all the impact categories and PLA being the second highest contributor for greenhouse and eutrophication [35]

2.3.6 Comparative LCA studies on PLA

Hakala et al (1997) evaluated diapers made from PLA and combination of PP and PE. The study had come with an outcome that there was no much difference in the impacts between the conventional diapers and the biodegradable ones [36]. A comparative study by Bohlmann et al (2004) on thermoformed containers made from PLA and PP for packaging of yoghurt was done. This study was from cradle to grave and took the end of life for both the system as landfill. The study found that PLA was more energy efficient than PP as far as thermoformed containers were concerned [37].

Detzal et al (2006) compared PLA clamshell containers with those made from PET, PP and PS. The study was done exclusively for the German market and the environment assessment was based on eight impact categories which were Fossil fuel consumption, global warming, acidification, terrestrial eutrophication, aquatic eutrophication, summer smog, and human toxicity. The scope of this study covered the production of the polymers, production of clamshells, the recycling and disposal of the used packages. Transportation of the resins to the converters and transportation to the recycling and disposal sites were also included. They concluded that PLA had advantages than the hydrocarbon based polymers for fossil resource consumption, global warming, and summer smog, while it had disadvantages for acidification, terrestrial eutrophication and human toxicity when compared to PS and PP and for terrestrial and aquatic eutrophication when compared to PET. For aquatic eutrophication it showed advantages with PP and disadvantages with PS and PET [38]. A similar study was carried out by Franklin Associates, KS (2006) for Athena Institute, Canada whereby different plastic products made from hydrocarbon and bio-based resins was compared. The following table illustrates a brief overview of the study findings [39]

Table 7: Impact assessment results for different plastic products [39].

Products compared	Materials used	Functional unit	Energy requirement	Solid waste generation	Greenhouse gas emissions
16 oz cold drink cups	PLA, **HIPS,PP and PET	10,000 cups	PET >PLA>PP. *PLA = HIPS	PLA and PET > PP and HIPS	PET >PLA>PP. *PLA = HIPS
16 oz two piece deli containers.	PLA, ***GPPS and PET	10,000 containers	PET >PLA. PLA>GPPS	PLA and PET	PET>PLA *PLA = GPPS
Envelope windows film	PLA and GPPS	1,000,000 sq. in. of 1.15 mil	*PLA=GPPS	PLA>GPPS	*PLA = GPPS
Foam meat trays	PLA and GPPS	10,000 trays	*PLA=GPPS	*PLA=GPPS	*PLA=GPPS
12oz water bottles	PLA and PET	10,000 water bottles	*PET=PLA	*PET=PLA	PET > PLA

* Not significantly different.
** High Impact Polystyrene.
***General purpose polystyrene

Very few, cradle to cradle, LCA studies comparing clamshell containers made of PLA and those of traditional hydrocarbon based polymers were found [38,39]. Existing studies did consider transportation, but not all of the transportation stages were included in the scope of their study. Also the distribution network was kept out of their system boundaries. Transportation operations contribute largely to the total impacts generated during the life cycle of the polymers. This thesis presents a cradle to cradle LCA study for thermoformed clamshell container made of PLA, PET and PS used for packaging of strawberries which also quantifies emissions generated due to the transportation operations, at all the stages including distribution. A separate study analyzing the effect of distance and type of transport vehicle on the emission is also presented in this thesis.

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Chapter 3: Methodology

A set of international standards from the International Standard Organization (ISO) and American Society for Testing and Materials (ASTM) International are used as guidelines for the systematic approach and conduct of this study. The different standards used to achieve different motives are explained as follows:

- ASTM 7075-04 – Standard practice for evaluating and reporting environmental performance of bio based products [1].
- *ISO 14040 – LCA principles and framework.* This standard outlines the general principles and requirements for conducting and reporting an LCA study. This standard was used to familiarize with the basic framework of an LCA study and the terms mentioned along with. The scope of this standard specified that it did not describe the life cycle assessment technique in detail but just defined the following sections a) goal of the study, b) life cycle inventory analysis, c) life cycle assessment, d) life cycle interpretation, e) reporting, and f) critical review. The general framework to be followed in the study is as follows [2].

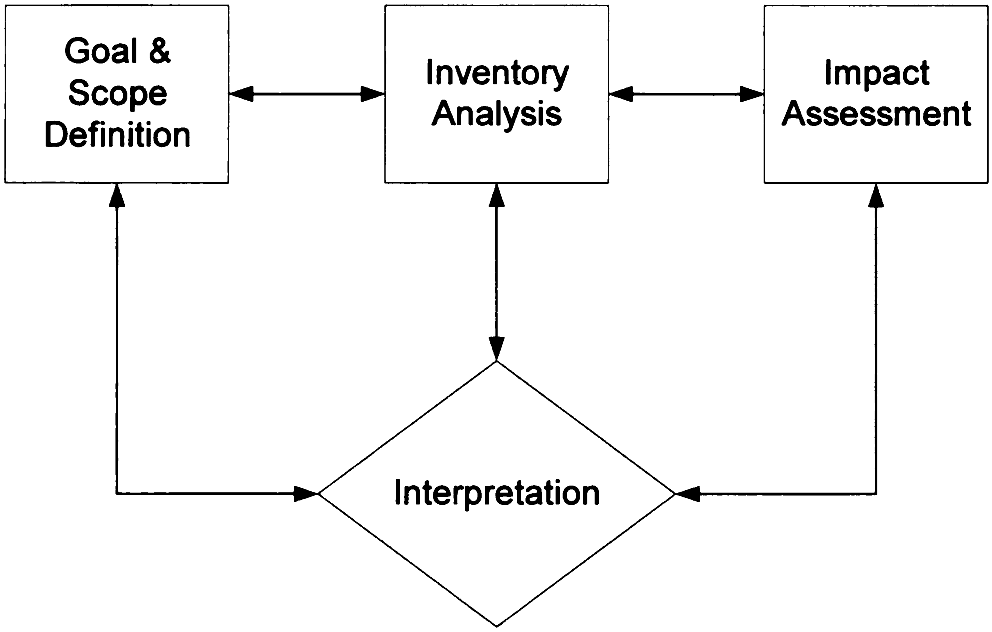

Figure 1: General framework / phases of an LCA study [2].

- *ISO 14041 – Environmental management – Life cycle assessment –Goal and scope definition* and *Inventory Analysis* – This standard described specifically the goal and inventory analysis of the study. With the help of this standard the goal and scope of the study, the functional unit and the system boundaries of the study were formed. Also the data categories, data quality, preparation of data collection and its validation were carried out [3].
- *ISO 14042 – Environmental management – Life cycle assessment – Life cycle impact assessment* - This standard dealt with the intricacies of the life cycle impact assessment procedure. This standard was used for the selection of impact categories, category indicators, and characterization models. The standard supports the assignment of the LCI results, calculation of category indicator results i.e (characterization), grouping, weighting, and data quality analysis. The classification and characterization factors were calculated within the software.[4].

- *ISO 14043 – Environmental management – Life cycle assessment – Life cycle interpretation-* This standard discussed the issues related to life cycle interpretation procedure. It was helpful in structuring the information of the inventory phase and determining the significant issues with the inventory data, impact categories. It evaluated the appropriateness of the results by doing completeness check and sensitivity check. Conclusion and interpretation of the results on the basis of inventory analysis was done with this standard [5].
- *ISO 14044* – ISO 14044 (2006) Environmental Management – Life Cycle Assessment –

  requirements and guidelines 2006. This standard discussed the guidelines for defining the goal and scope of the study, inventory analysis, impact assessment and interpretation. It also provided guidelines for reporting of LCA results, and conditions for use of optional [6].
- *ISO 14049 – Environmental management – Life cycle assessment – Examples of application of ISO 14041 to goal and scope definition and inventory analysis-* This standard was used to study the given examples of developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries, examples of allocations procedures [7].
- SimaPro™ Software version 7.1.6. from Pre® consultants (The Netherlands) was used as the primary source for the life cycle inventory (LCI). This software is supported with databases for the LCI for over 2500 processes and is recommended for obtaining inventory data for processes involved in the packaging industry. Most of the data was obtained from the Ecoinvent database version 1.2. Also other databases such as Buwal 250 were used to obtain specific

process data. Out of the various impact assessment methods available with the software, Impact 2002+ method was chosen, which is a combination of IMPACT 2002 Eco-Indicator 99, CML, and IPCC methods and the one which gave us the results with the desired format and units [8].

The different stages leading to impact assessment is shown in the following figure.

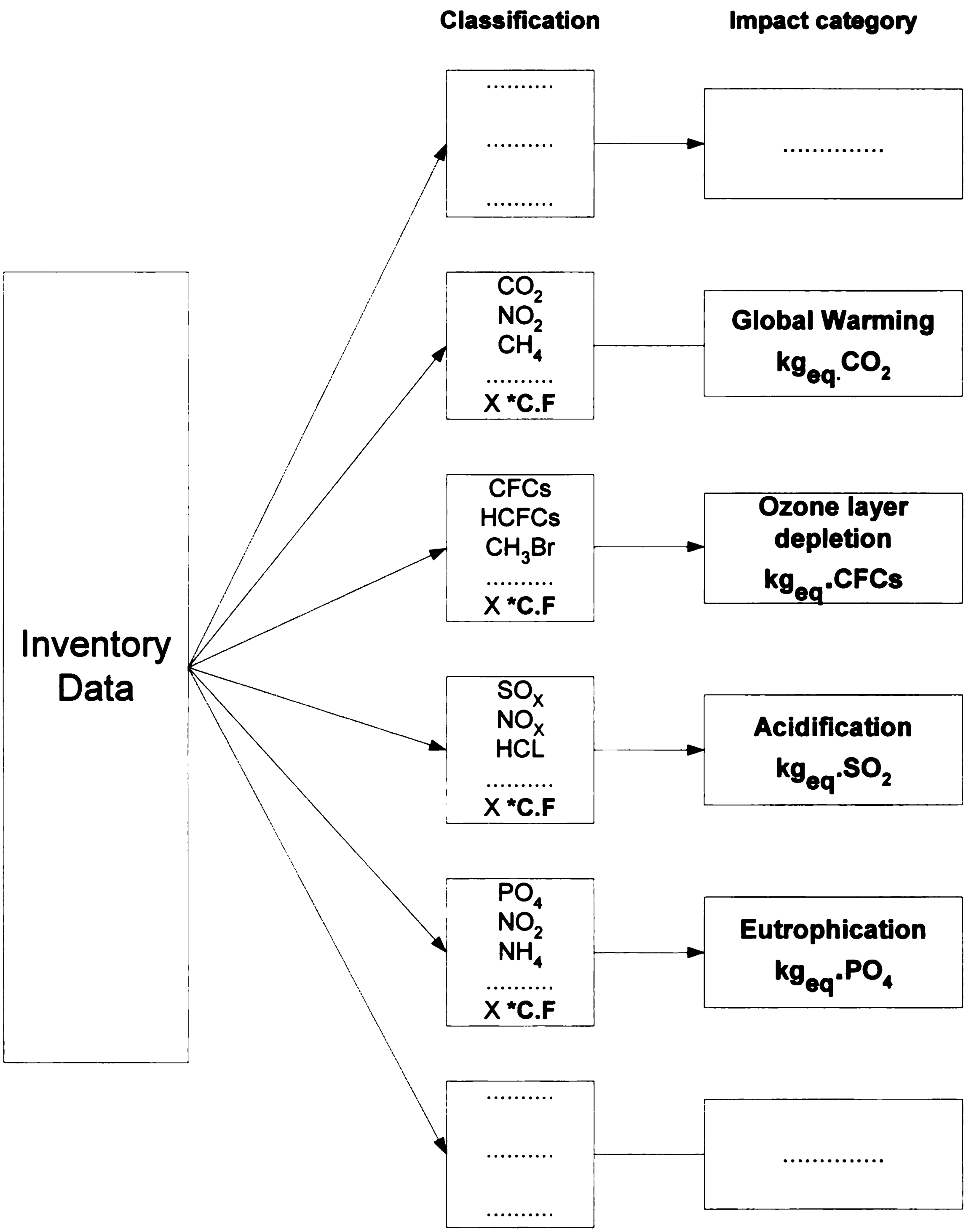

Figure 2: Calculation format for impact assessment. * - *Characterization factor*

With the help of the above methods, a LCI was generated for the three polymers. The impact assessment method yielded the final results. The final chapter contains the conclusion and future work suggestions.

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CHAPTER 4

Madival. S, Auras. R, Singh.S.P, Narayan. R, *Assessment of the Environmental Profile of PLA, PET and PS Clamshell Containers using LCA Methodology*, Biomacromolecules, submitted.

Chapter 4: Assessment of the Environmental Profile of PLA, PET and PS Clamshell Containers using LCA Methodology.

4.1 Abstract

LCAs of bio-based products historically have shown favorable results in terms of environmental impacts and energy use when compared to petroleum based products. This paper reports a cradle to cradle Life Cycle Assessment (LCA) of polylactide (PLA) in comparison with polyethylene terephthalate (PET) and polystyrene (PS) thermoformed clamshell containers, used for packaging of strawberries with emphasis on different end of life scenarios. It considers all the inputs such as fertilizers, pesticides, herbicides and seed corn required for the growing and harvesting of corn used for manufacturing PLA. Global warming, aquatic acidification, aquatic eutrophication, aquatic ecotoxicity, ozone depletion, non renewable energy and respiratory organics, land occupation and respiratory inorganics are the selected impact categories. The geographical scope of the study reflects data from Europe, North America and the Middle East. PET showed the highest overall values for all the impact categories. The transportation stage of PLA, PET and PS was responsible for the greatest impact on the environment. When these values were compared with the impacts produced by the transportation of the product, they were below 25% of the total emissions. This implied that the transportation stage in the LCA is an important contributor to the environmental impact.

4.2 Introduction

Life Cycle Assessment is an environment tool. It relates a material's performance as an environmentally viable option compared to its functional alternatives. Within an industry, LCA can be used for product development and improvement, strategizing plans, making public policies, developing new marketing norms, and a number of different applications [1]. LCA considers products not just as "products" but as product systems and beyond, which includes its various stages throughout its life journey. A cradle to gate LCA study starts with the extraction of raw material and ends when the finished product leaves the factory gate. These kinds of studies are typical for polymer resin manufacturing companies. A cradle to grave LCA study comprises the extraction of the raw materials, used for manufacturing of products, through the disposal of the product which ends up in landfill, or goes for incineration or recycling. A cradle to cradle study starts from the raw material extraction through disposal and extends from the disposal onwards considering the energy recovered through incineration or the raw material replacement obtained through recycling of the products being studied [1].

LCA has widespread applications in automobiles, construction, electronics, chemicals, textiles, packaging and an array of other sectors [2]. In the packaging industry several studies have been done for comparison of packages used for different applications, food packaging being just one of them. The basic function of food packaging is to protect and preserve natural or artificially manufactured or processed foods from spoilage, simultaneously giving the package shelf appeal with its aesthetics. The packaging domain consists of raw material manufacturers, the converters, and the users or consumers. It also includes the distribution network from the wholesalers to retailers and from retailers to the consumers. In the entire system, the role of packaging is an integral one which cannot be disregarded or undermined, but at the same time one cannot neglect to observe the environmental burdens that a package emits during its journey from its production to the waste stream [3].

Sustainability in packaging consists of its three basic elemental functions- social equity, ecological footprint and economic value [4]. In the last few decades, the ecological footprint component of sustainable packaging systems has been attempted to be quantified by LCA studies. LCA in packaging has emerged out of a study on beverage which came up in the late 1960's and the early 1970's by Harry Teasley of Coca-Cola [5]. LCA studies can assess the environmental performance of different packaging materials like paper, glass, plastics, steel, aluminum, and wood and for different forms like plastic containers, metal cans, glass bottles, flexible packaging, paper and board boxes, composites, pallets and an array of geometric structures. Most of the studies found in packaging are comparative studies determining the environment viability of a package among its alternatives for a common application. The package which executes a common function is not necessary of the same material and forms.

With the growing awareness for a clean and better environment, biobased packaging is now becoming a trend to replace the traditional petroleum based packaging materials. Biopolymers, in particular, have created an entire new market for themselves for packaging of food products. They score over the traditional polymers with the fact that they are considered as environmentally favorable materials since they are biodegradable and derived from renewable resources [6]. LCAs of bio-based products and biopolymers historically have shown reduced impacts and favorable results in terms of environmental burden and energy use when compared to hydrocarbon based polymers [4].

Polylactide (PLA), one of the biobased polymers derived from corn-based starch, has recently been drawing attention of the food packaging industry. PLA has progressively created a market for packaging of fresh cut produce like salads, replacing the conventional petroleum based polymers like polyethylene terephthalate (PET) and polystyrene (PS). Studies have been done which have found PLA having comparable mechanical and physical properties to that of PET and PS [6]. However, LCA studies comparing biobased containers to hydrocarbon-based containers for packaging of fresh produce are scarce. Therefore, the objective of the present study is to compare the environmental impact of containers made from PLA, a biobased polymer, and traditional hydrocarbon-based PET and PS polymers, used for packaging of strawberries.

4.3 Goal, scope and functional unit of the study

The goal of this study was to compare the environmental impact of PLA, PET, and PS thermoformed clamshell containers used for the packaging of strawberries.

The scope of the study was from the extraction of the raw material for the three polymers followed by the processes for their resin production, through the container formation followed by their end of life disposal, and it considers global warming, acidification, ozone depletion, aquatic eutrophication, non-renewable energy, land occupation, respiratory organics, respiratory inorganics and aquatic ecotoxicity as impact categories.

The functional unit was chosen as 1000 containers of capacity 1 lb each.

4.4 Methods

A set of international standards from the International Standard Organization (ISO) and ASTM International were used as guidelines for the systematic approach and conduct of the study. The framework of this study was defined according to ISO 14040 guidelines [7]. The goal and scope definition of the problem and the inventory analysis were framed and conducted according to ISO 14041 recommendations [8]. The life cycle assessment and interpretation were conducted according to ISO 14042,14043 and 14044 respectively [9, 10, 11], and ISO 14049 was used for examples of developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries, and examples of allocations procedures [11]. ASTM 7075 was consulted to comply with U.S. standards [12]. SimaPro™ software from Pre® consultants (The Netherlands) [13] was used as the primary source for the life cycle inventory (LCI). The software contains LCA data for over 2500 processes typically used in the packaging industry [14].

4.5 System boundaries

The life cycle flow for the hydrocarbon based polymers, PET and PS, starts with the extraction of crude oil and cracking of the extracted oil which was common for both polymers. For PET, from cracking onwards, conversion of associated gases into ethylene, naphtha to benzene and ethylene oxide, ethylene oxide to ethylene glycol and eventually PET resin formed the resin production part [13]. For PS, after cracking, oil is transformed into ethylene which is then reacted with benzene to convert to ethyl benzene followed by styrene and finally polymerized to polystyrene resin [14]. For PLA, which is a biobased polymer derived from corn based starch, the life cycle begins with corn growing and harvesting. The harvested corn is sent to a corn wet mill where corn starch is separated and converted to dextrose. The dextrose obtained is converted to lactic acid which through the lactide production is polymerized to polylactide (Figure 1) [15].

The resins of the three polymers then go to a converter/container manufacturer. The resin is extruded into sheets. These sheets undergo a thermoforming operation and are converted into containers. The containers are then transported to Driscolls Strawbery Associates, California, USA, a leading fresh strawberry producer and exporter, who harvests and fills strawberries into these containers. The filled containers are distributed to the market where they go to the consumer. The containers after consumption then reach the end of life stage where they either end up in a landfill or a recycling center or are incinerated. The energy recovered from the incineration is credited to the energy consumption for the polymer manufacture. Figure 1 shows the life cycle inventory flow chart for the three polymers.

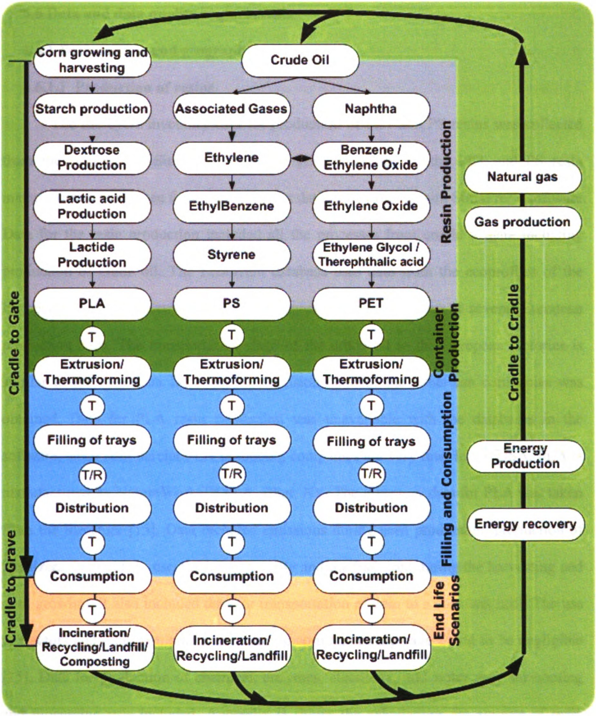

Figure 3. Life Cycle Inventory flow chart for PLA, PET and PS thermoformed containers.
(T – Transport, T/R – Transport with Refrigeration)

4.6 Data and data quality requirements

4.6.1 Data sources and geography

4.6.1.1 Production of resins

The life cycle inventory data for production of PET and PS resins was collected from the commercial SimaPro™ software [14]. The data for the PET and PS resin manufacturing was taken from the Ecoinvent database available with SimaPro™ software. Data for the resin production included all the processes from cradle to gate including production of crude oil. The Ecoinvent database uses data from the ecoprofiles of the European Plastics Industry (APME) and represents manufacturing at several European production sites. The transportation stage of the crude oil to the European factories is similar to the American factories. No emission data for the American companies was obtained. Data for PLA resin production was unavailable with the databases in the software, since commercial PLA producing companies are very few. In the USA, PLA is manufactured by NatureWorks™ PLA, Blair, NE. The inventory data for PLA was taken from the literature [15]. Data included emissions during corn production, production of fertilizers, herbicides, insecticides, electricity and the fuel used during the harvesting and corn growing. It also included data for transportation of corn to a corn wet mill. The use of tractors and other equipment used during corn harvesting were found to be negligible [15]. Data for production of chemical, enzymes, electricity, and water used for cooling and processing was included. Appendix B shows the calculations for amount of resin used to meet the functional unit.

4.6.1.2 Production of containers

No specific data for the extrusion and thermoforming of the three resins was available. Inventory data for both operations were taken from the Ecoinvent database and included emissions for the extrusion and thermoforming of a general plastic film. The data was a representative of different European companies. However, the energy consumption during the thermoforming process was calculated separately using the specific heat, temperature difference and heat of fusion values [16]. The energy used for thermoforming of 1 kg of PET, PS and PLA sheet was calculated to be 0.31 MJ, 0.30 MJ and 0.21 MJ, respectively. The calculations were material specific and not machine specific. Sample containers of dimensions 19 cm x 16.5 cm x 7 cm, for PS and PLA were used for the study. The weights of these containers were 24.96 g and 30.54 g respectively. Since no PET container of the same dimensions was available, the weight of the PET container was calculated on the basis of its specific gravity (□= 1370 kg/m^3), and assuming a sheet thickness of 457 mm (18 mils) [6]. PS and PLA thickness were the same. Appendix B shows the calculations for the energy consumption during the thermoforming stage.

4.6.1.3 Consumption stage

The filling operation, comprising filling of trays with strawberries, storage, and the distribution of filled containers to the market through wholesalers and retailers was assumed to result in similar burdens and for all three containers was excluded from the study.

4.6.1.4 Distances and Transportation

Distances from the resin supplier to the converter were not available for PS and PET due to company confidential information; therefore, they were assumed to be as follows. PET resin was assumed to be provided by Eastman Chemical Corporation, Columbia, SC, (29202), and PS resin was assumed to be provided by INEOS Corporation, Joliet, IL (60434) (formerly BASF corp.) to Sambraillo Packaging, Watsonville, CA (95077). These distances were found to be 4251 kms and 3509 kms respectively [17]. NatureWorks LLC, Blair, NE (68008) is the sole PLA resin supplier in the United States. The distance between Natureworks LLC and Pinnacle Plastic Container, Oxnard, CA (93033) (the PLA container supplier) was found to be 2592 kms. Distances between converter and strawberry exporter were calculated with reference to Driscoll Strawberry Associates, (DSA) Watsonville, CA (95077) and their local suppliers. DSA procures PET and PS containers from Sambraillo Packaging, Watsonville, CA. The distance between them is 1.92 kms [17]. Distance between DSA and Pinnacle Plastic Container was calculated to be 470 kms. Transportation was assumed to be carried out using a 16 t capacity truck for which the data was obtained from the Ecoinvent database. After the containers were filled by DSA, it was assumed that all the containers were shipped to four retailers distribution centers in equal proportions located in Tacoma, WA (1363 kms); Loveland, CO (2071 kms); Hooksett, NH (5166 kms); and Lakeland, FL (4504 kms). These distribution centers were included to calculate the effect of the distribution channel. The data included operation of vehicles, production, maintenance, and represented generic European data while disposal of vehicles reflected Swiss data. The data for road construction, maintenance and disposal was taken from the Swiss conditions. Since no data for the use of freezers was available in the Ecoinvent database, data from the LCA food DK database, which is one of the different databases available with SimaPro™ software were used. This database had data for processes in the food product chain.

Appendix B gives the calculations for the distances and transportation load.

4.6.1.5 End of life stages

The study considered different end of life scenarios in terms of landfill, incineration and recycling. The scenarios were as follows:

- Scenario I - (40R/30I/30L) - 40% Recycling / 30% Incineration / 30% Landfill.
- Scenario II – (100L) - 100% Landfill
- Scenario III – (100R)-100% Recycling
- Scenario IV – (50I/50L)50% Incineration / 50% Landfill
- Current – 23.5 % Incineration / 76.5 % Landfill

Scenarios I to IV are hypothetical scenarios which generate information for different disposal options while the current scenario was based on current trends of waste treatment for the three types of the containers. The U.S average rate for municipal waste stream of polymers was 23.5% incineration and 76% landfill [18]. Therefore, for the three containers, as per the average municipal rate, 23.5% was treated for incineration and 76.5% for land filling. Since commercially available centers for the composting and recycling of PLA are not available, they were also treated as the other polymers. All the five scenarios assumed that no container is being retained by the consumer whatsoever and that all the 1000 containers for the three polymers undergo the waste treatment. For PET & PS, the landfill, incineration and recycling data was taken from waste type category which comprised emissions specifically for 100% PET and 100% PS, respectively. The category included waste specific air and water emissions. Since no separate data for PLA was available, waste specific emission data for 100% mixed plastics category was considered. For the three polymers data for landfill and incineration was taken from the Ecoinvent database while for recycling the data was compiled by Pre® consultants, Netherlands.

4.6.2 Allocation procedure

Allocation is necessary for processes which yield more than one product output. It is a procedure whereby burdens are allocated to the products on the basis of different factors. Allocation may be done on the basis of mass, their molar flow or even the economic value of the products [8]. For this study the only process which was accountable for allocation is the production of PLA, PET and PS resins. Since data for PET and PS were taken from secondary sources which comprised of inventory emissions for system process. These processes had allocation rules defined in the database module. No separate allocation rule was considered. Data for PLA was taken from literature and hence no allocation rule was defined for it. It is of prime importance to mention here that in this study the amount of carbon di oxide released due to the inherent carbon present in the PET and PS resin is not considered. The CO_2 emission reported in case of the hydrocarbon polymers are those liberated during the resin production process. In case of PLA the literature data considered the CO_2 uptake by the corn feedstock during the photosyntheis process.

4.7 Impact Assessment

Different LCA impact assessment methods were available with the SimaPro™ Software. Eco Indicator method available with the eco invent database is one of the advanced methods of impact assessment. The Impact 2002+ method was chosen, which is a combination of IMPACT 2002 Eco-Indicator 99, CML, and IPCC methods. The impact categories discussed in the method are global warming, acidification, ozone layer depletion, aquatic eutrophication, respiratory organics, respiratory inorganics land occupation, non renewable energy and aquatic ecotoxicity. The calculations were carried out with SimaPro™ software. The Impact 2002+ method carries out the impact assessment by basically converting the LCI results into midpoint categories which are the impact categories and then converts the impact categories into damage categories (endpoint) by means of midpoint reference units[1].

4.8 Results and Discussion

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[1] The respective midpoint reference units are the following: kg_{eq} CO_2 into air (written "kg CO_2") for global warming, kg_{eq} SO2 into air (written "kg SO2") for Aquatic acidification, kg_{eq} CFC-11 into air (written "kg CFC-11") for Ozone layer depletion, kg_{eq} PO4--- into a P-limited water (written "kg PO3 P-lim") for Aquatic eutrophication, kg_{eq} ethylene into air (written "kg ethylene") for Respiratory organics, kgeq PM2.5 into air (written "kg PM2.5") for Respiratory inorganics, MJ primary non-renewable (written "MJ primary") for Non-renewable energy, , kg_{eq} triethylene glycol into water (written "kg TEG water") for Aquatic ecotoxicity, m2eq organic arable land (written "m2org.arable") for Land occupation The ozone layer depletion and respiratory organics fall under the human health damage category. The aquatic ecotoxicity, acidification and aquatic eutrophication falls under the ecosystem quality damage category. Global warming comes under the climate change damage category and the non renewable energy comes under the resources damage category. A detailed description of the damage categories can be found elsewhere [21].

Figure 2 shows the normalized values for the main emissions produced by thousand PLA, PET and PS container. The values are normalized by the normal emission produced by one European citizen.

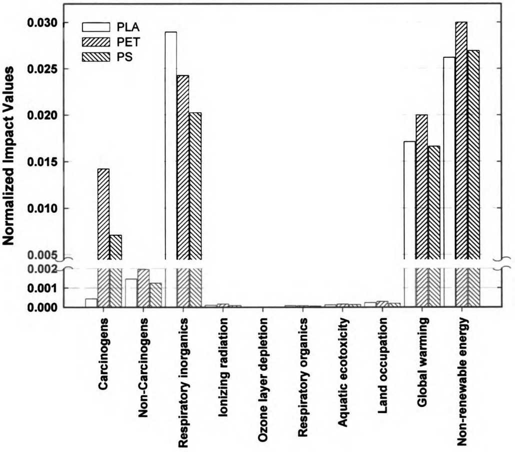

Figure 4. Normalized impact value comparing one PLA, PS and PET container. Method of comparison IMPACT2002+ V2.02. Values are normalized according to the emission produced annually by a European citizen.

PET had the highest values for all the impact categories, except for aquatic acidification, respiratory organics and respiratory inorganics, which were expected due to the higher weight of the containers and the longest transportation distance of the resins.

For PLA, the main impact categories were aquatic acidification, respiratory organics, and respiratory inorganics. The results of the cradle to grave analysis for 1000 containers of PLA, PET and PS with empty containers and with food are shown in Table 1. PET shows the higher values for most of the categories, and PLA shows higher values than PS for all the categories except aquatic ecotoxicity.

Table 8: Impact category values for 1000 containers of PLA, PET and PS filled with strawberries.

Impact Category	Stage	PLA	PET	PS
Global warming, kg CO_2.eq.	Resin production	60	72	70
	Extrusion	15	16	12
	Thermoforming	22	24	18
	Electricity production	3	4	3
	Transportation (R)	28.7	50.2	31.7
	Transportation (C)	41.8	39.3	30.1
	Sub-Total	**171**	**198**	**165**
	Transportation (S)	564	565	565
	Total	**735**	**763**	**730**
Aquatic acidification, kgSO_2.eq.	Resin production	1.17	0.36	0.47
	Extrusion	0.06	0.07	0.05
	Thermoforming	0.11	0.12	0.09
	Electricity production	0.01	0.02	0.02
	Transportation (R)	0.19	0.34	0.22
	Transportation (C)	0.28	0.27	0.20
	Sub-Total	**1.82**	**1.14**	**1.04**
	Transportation (S)	3.84	3.83	3.83
	Total	**5.66**	**4.97**	**4.87**
Ozone layer depletion, kg CFC-11.eq	Resin production	2.88E-06	4.10E-06	2.77-9
	Extrusion	8.21E-07	8.77E-07	6.17E-07
	Thermoforming	1.17E-06	1.25E-06	9.56E-07
	Electricity production	1.09E-07	9.56E-08	7.34E-08
	Transportation (R)	3.91E-06	6.84E-06	4.32E-06
	Transportation (C)	5.70E-06	5.36E-06	4.18E-06
	Sub-Total	**1.45E-05**	**1.79E-05**	**1.01E-05**
	Transportation (S)	7.70E-05	7.69E-05	7.70E-05
	Total	**9.15E-05**	**9.48E-05**	**8.71E-05**

Table 8 Continued

Aquatic eutrophication, kg PO_4.eq.	Resin production	5.56E-03		6.83E-02	1.97E-04
	Extrusion	3.00E-04		3.78E-04	2.89E-04
	Thermoforming	1.10E-03		1.20E-03	9.18E-04
	Electricity production	0.00013		4.95E-05	3.79E-05
	Transportation (R)	0.00370		0.00645	0.00407
	Transportation (C)	0.00537		0.00505	0.00387
	Sub-Total	**0.01603**		**0.07530**	**0.00940**
	Transportation (S)	0.0726		0.0727	0.0725
	Total	**0.0886**		**0.1480**	**0.0819**
Respiratory organics, kg. Ethylene .eq	Resin production	1.30E-01		6.52E-02	5.60E-02
	Extrusion	3.18E-03		3.40E-03	2.60E-03
	Thermoforming	8.26E-03		8.83E-03	6.75E-03
	Electricity production	3.56E-03		1.97E-04	1.61E-04
	Transportation (R)	0.0537		0.0940	0.0594
	Transportation (C)	0.0783		0.0736	0.0564
	Sub-Total	**0.277**		**0.2340**	**0.1810**
	Transportation (S)	1.053		1.056	1.059
	Total	**1.33**		**1.29**	**1.24**
Aquatic ecotoxity, water kg TEG eq (TEG: (Triethylene glycol)	Resin production	2650		3888	9240
	Extrusion	857		916	700
	Thermoforming	1400		1500	1150
	Electricity production	93		126	96
	Transportation (R)	11400		20000	12600
	Transportation (C)	16600		15600	12000
	Sub-Total	**33000**		**41600**	**35700**
	Transportation (S)	224000		224400	224300
	Total	**257000**		**266000**	**260000**
		R	NR	NR	NR
Energy, MJ surplus.eq.	Resin production	991/32.4*	1019/33.4*	2412/74.0*	2400/96.1*
	Extrusion		283	303	231
	Thermoforming		476	508	389
	Electricity production		41	54	42
	Transportation (R)		477	837	528
	Transportation (C)		697	655	501
	Sub-Total	**991**	**2993**	**4560**	**4090**
	Transportation (S)		9416	9440	9410
	Total		**13400**	**14000**	**13500**
Land occupation m2org.arable .eq	Resin production	0.04		0.37	0.001
	Extrusion	0.62		0.66	0.50
	Thermoforming	1.33		1.42	1.08
	Electricity production	0.0009		0.0015	0.0011
	Transportation (R)	0.38		0.66	0.42
	Transportation (C)	0.55		0.51	0.39
	Sub-Total	**2.92**		**3.62**	**2.4**
	Transportation (S)	7.4		7.38	7.4
	Total	**10.3**		**11**	**9.8**

Table 8 Continued

Respiratory inorganics, kg PM2.5 .eq	Resin production	2.650	0.0508	0.0683
	Extrusion	0.01	0.01	0.008
	Thermoforming	0.018	0.019	0.015
	Electricity production	0.0024	0.0038	0.0029
	Transportation (R)	0.052	0.091	0.057
	Transportation (C)	0.08	0.07	0.05
	Sub-Total	**0.294**	**0.246**	**0.206**
	Transportation (S)	1.016	1.015	1.014
	Total	**1.31**	**1.26**	**1.22**

* Energy consumption for 1 kg of resin. R= Renewable; NR= Non renewable
Transportation (R) – Transportation of resin from resin supplier to container manufacturer.
Transportation (C) – Transportation of containers from strawberry filler to distributors / market.
Transportation (S) – Transportation of 1000lbs of strawberries (only food and no containers). Variation of between the PLA, PET and PS values are due to rounding error in the software.

4.8.1 Sensitivity analysis

A sensitivity analysis was carried out to analyze the effect of each step during the cradle to grave life journey of the containers [10]. Table 1 gives the process contribution values for each polymer towards the total emission. These values depict as to which stage in the life cycle contributes the maximum to the impact categories and indirectly reflects the extent of variation in the results which may occur due to any uncertainty in the data of that particular stage.

Global warming (Carbon dioxide emission): Table 1 provides the process contribution for global warming impact for the hydrocarbon and biobased containers through the cradle to grave life journey. The resin production stage contributed the highest CO_2 for PLA, PET and PS containers after the transportation scenario. However PET contains 62.5% of carbon and PS contains 92% carbon in their resin which is not accounted in the emissions. The CO_2 value present in their inventory are the emissions generated during the manufacturing operations. The literature data for PLA reports total emission of 3.84

kg of CO_2 eq. per kg of PLA resin, out ot which 1.82 is the CO_2 uptake by the corn feedstock. Thus the data considers the carbon content of PLA resin According to the functional unit of this study 24.96 kg of PS resin, 30.54 kg of PLA resin and 32.64 kg of PET resin were required to manufacture 1000 containers each, but since 8.2% of recycled PET is used in the manufacturing of sheets, there is some reduction in the consumption of virgin material [18]. The CO_2 emission values during the extrusion and thermoforming stages for PS are the lowest followed by PLA and PET. Transportation distance was longest between the PET resin supplier and the converter (4251 kms) which was responsible for the high values of CO_2 for PET transportation stage. Overall for PLA & PET the resin production stage contributed 36% (62 kg. equivalent and 72 kg. equivalent respectively) of the subtotal 171 and 172 kg CO_2 emission and for PS the resin production stage contributed 43% (70 kg. equivalent) of the subtotal 165 kg CO_2 emission. However, these CO_2 emissions represented less than 26% of the total emission produce by the packaging system when considering the transportation of the product.

Aquatic acidification: The resin production stage for PLA contributed 1.15 kg of SO_2 which was about 63% of the total SO_2 emission during its life journey. The most contributing stage for SO_2 emission for PET was during the transportation with 0.61 kg. The resin production stage for PET and PS produced 0.36 kg and 0.47 kg, respectively, which was about 31% and 45% respectively of their total SO_2 emission.

Ozone layer depletion potential (ODP): ODP value for PLA during the transportation stage was 9.6E-06 kg of CFC-11, which was about 66% of the total ODP. For PET and

PS, the highest ODP value was also found during transportation which was 1.22E-05 and 8.42E-06 kg of CFC-11, respectively.

Aquatic eutrophication: PLA resin production contributed around 0.00556 kg of PO_4 equivalents about 36% of the total potential. PET resin production contributed 0.068kg PO_4 equivalents about 84% and PS resin production stage contributed 0.00019 kg PO_4 equivalents about 2% of the total while its transportation stage contributed around 84% of the total emission. The lower PS value for aquatic eutrophication for the resin stage as compared to PET are mainly due to the lower chemical oxygen demand value accounted for PS resin production. The characterization value for this waterborne emission in terms of PO_4 ions is 0.0717 for PET and 0.000209 for PS. The rest of the emissions which are air borne and soil emissions characterized to PO_4 ions for aquatic eutrophication for the PS resin stage are almost negligible.

Respiratory organics: PLA transportation contributed about 48% of the total ethylene equivalents, while PET and PS transportation contributed about 72% and 64% respectively.

Respiratory inorganics: PLA transportation contributed about 43% of the total ethylene equivalents, while PET and PS transportation contributed about 66% and 54% respectively.

Aquatic ecotoxicity: For PLA, PET and PS the major contribution for this category came from the transportation stage which contributed around 85%, 86% and 68% of the total burdens respectively.

Energy (Electricity consumption): Table 1 gives the electricity as renewable and non renewable energy consumption during the different stages of the container manufacturing. The energy consumption for 1 kg of PLA resin was 65.8 MJ out of which 32.4 MJ was from non renewable resources mainly obtained from biomass [15]. One kg of resin production for PET and PS required 74 and 96.1 MJ of energy. In this case should be also considered that PET and PS resin producers can also procure or buy renewable energy credit to reduce the non-renewable energy consumption. The energy required to produce resins for manufacturing 1000 containers were 2010 MJ for PLA, 2412 MJ for PET and 2400 MJ for PS. The energy used during the extrusion operation was 283 MJ for PLA, 303 MJ for PET and 231 MJ for PS which is mainly related to the amount of resin extruded to produce sheets. The energy consumption during the thermoforming operation was calculated based on the specific heat of each polymer, the temperature difference and heat of fusion of the polymers. The energy values for this operation was found to be lowest for PLA which was 0.21 MJ/ kg and 0.31 MJ/kg for PET and PS. The energy required for thermoforming 1000 containers for PLA, PET and PS were 476 MJ, 508 MJ and 389 MJ, respectively. The transportation stage energy consumption was 1170 MJ, 1490 MJ and 1030 MJ for PLA, PET and PS, respectively. For PLA, PET and PS the highest energy consumption was during the resin production stage.

Land occupation: Land use for PLA accounts for 36.42% of its total land consumption while for PET and PS land use values are 31.31% and 36.11% of its total consumption. However when it comes to land occupation for industrial activities and traffic area for road and rail embankment and network PLA accounts for 63.6%, PET for 68.6% and PS for 63.9% of the total land occupied.

4.8.2 End of life scenarios

Five different end of life scenarios were considered in terms of landfill, incineration and recycling of the containers. In the case of PLA, landfill was considered as one of the end of life option, which does not make sense since biopolymers are meant for end of life stage such as composting and not landfill. At this point, composting was not considered as an end life scenario since no emission data were available. The first four scenarios are hypothetical and the last one is the current scenario of disposal in the U.S.

Carbon dioxide emission: Figure 3 shows the carbon dioxide emission for the five different ends of life scenarios. The values for CO_2 emissions for PET were highest for all the scenarios. CO_2 values for PS were lower than PET for the five scenarios showing the primordial roll that polymer down-gauging and light-weighting plays on reduction of CO_2 emissions. This finally can be correlated to the fact that for 32.64 kg of PET and 24.96 kg of PS was used for manufacturing 1000 containers each.

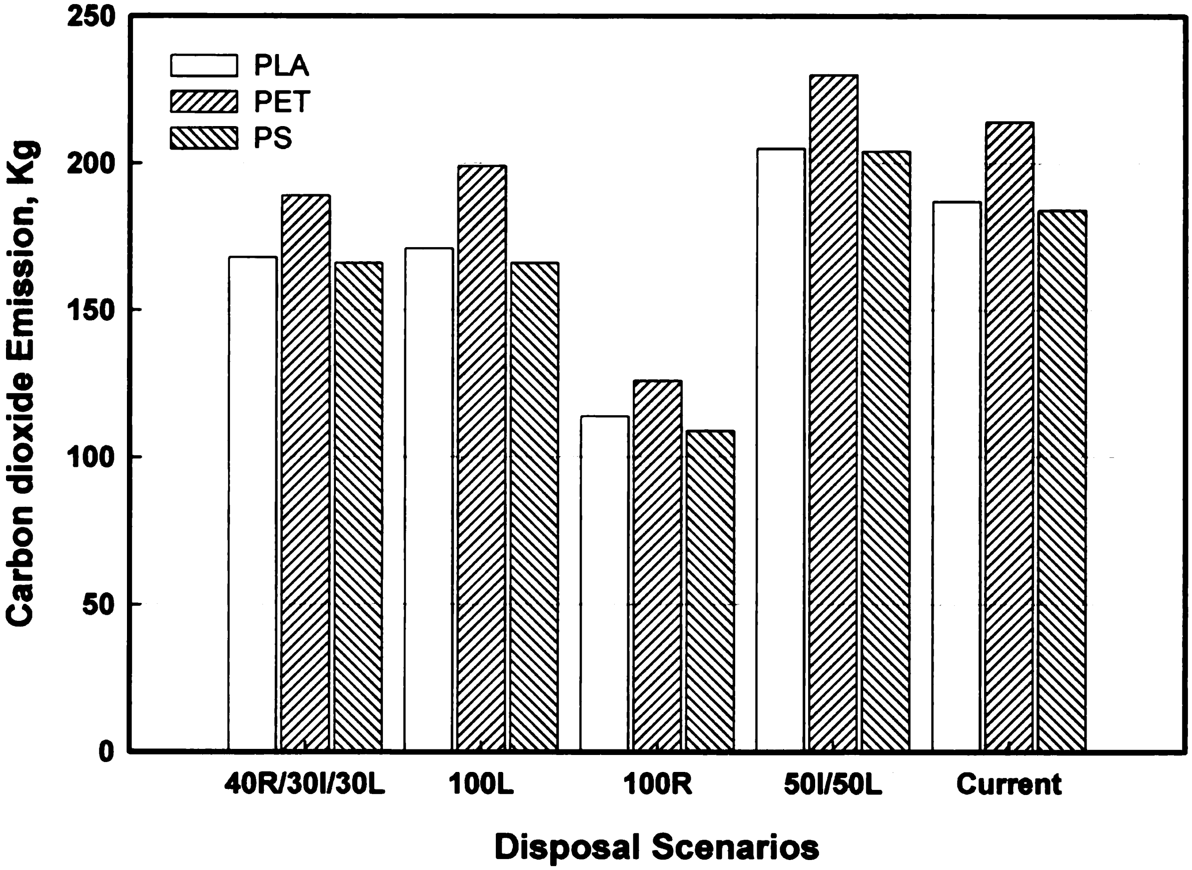

Figure 5. Carbon di oxide emission for cradle to cradle analysis of 1000 containers of PLA, PET and PS.

The CO_2 emission values for PS were almost similar for scenario I and II indicating that 40% recycling, 30% incineration and 30% landfill of PS have almost the same CO_2 emissions as 100% of landfill. Scenario III has the lower CO_2 emission; however, 100% recycling of the containers is not a realistic number to achieve. This scenario was introduced to indicate an extreme condition. Finally, scenario IV and the current present the highest CO_2 emissions for PLA, PET and PS, respectively. However, in this case we can observe that an increase in landfill content reduces the amount of CO_2 emission for the three polymers due to the capture of the CO_2 emission.

Energy consumption: Figure 4 shows the energy consumption for the cradle to cradle analysis for 1000 PLA, PET and PS containers. For PLA, PET and PS, scenarios II, IV and the current scenario have similar energy consumption values indicating that increasing the incineration percent from 0 % to 50% does not recover energy significantly. If we compared the energy consumption for PLA for all the scenarios, we can observe that the current scenario for PLA (i.e., 23.5% incineration and 76.5% landfill) does not produce an appreciable advantage when we considered energy consumption with respect to other alternatives such as PS and PET containers. Therefore, for PLA containers to reduce its energy consumption, recycling should be established.

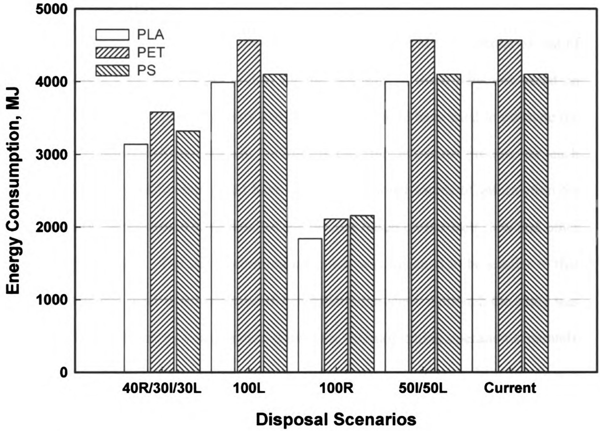

Figure 6. Energy consumption for cradle to cradle analysis 1000 containers of PLA, PET and PS

4.9 Limitations and assumptions

4.9.1 Resin production

No specific data for the emissions and energy consumption for PLA were available in the databases with the SimaPro™ software. Literature data was taken for PLA and hence the calculation of energy consumption during its resin production was not possible with the software, and it was additionally added to the calculations. PET and PS resin production data mostly reflected the European situation; in addition, this study did not include emission due to the local transportations.

4.9.2 Conversion processes

The extrusion process for the three polymers was assumed to be similar to that of a general plastic film. More specific data for the extrusion of these polymers based on temperature difference, specific gravity and specific heat could have used to estimate the actual energy consumed and burdens emitted during the extrusion process for each polymer. Machine specific data could have been an additional source of information for the comparison, which could have detailed the process based on the melt flow and other processing parameters. The thermoforming operation was assumed to be similar to that of a general plastic sheet which included the calendaring process. Although the study was able to calculate the energy consumption during the thermoforming operation separately for the three polymers, a similar but specific data on the emissions could have given a clear picture for a better comparison for this operation. The calculations for the actual amount of resin required to make 1000 containers was based on available PS and PLA sample containers, which were equal in volume and capacity. No sample was available for PET. The calculations for PET were done based on the assumption of a container equal in volume and capacity to that of PS and PLA. The calculations were carried out based of the specific gravity of PET and the thickness of the sheet. The total amount of sheet wasted as scrap during the converting process was assumed to be 3.61% for PET, 3.15% for PS and 3.19% for PLA [20].

4.9.3 Transportation and distances

No specific data was available for the burdens for refrigerated trucks. The emissions were calculated separately for the truck, which was assumed to be a 16t capacity truck, and freezer of 2631 capacity and the data reflected Swiss conditions. Since NatureWorks recommends to ship PLA resins below its glass transition temperature (~55°C), no separate data for refrigerated transportation for PLA resin to converter and from converter to the filler was considered. This could have lead to higher emissions for PLA during the transportation stage. Eastman Chemical Corporation, Columbia, SC, was assumed as PET resin supplier and INEOS Corporation, Joliet, IL (60434) (formed BASF corp.) was assumed as PS resin supplier to Sambraillo Packaging, Watsonville,CA (PET and PS container supplier). For PLA containers, Pinnacle Plastic Container was assumed as their supplier since they were locally situated with respect to Driscolls. The distance between NatureWorks LLC, Blair NE (PLA resin supplier) and Pinnacle Plastic Container, Oxnard, CA was calculated and included in the analysis. Distances were also calculated with respect to the Driscoll Strawberry Associates Inc., California, the strawberry exporter and the PET and PS container supplier. The distances from the exporter to the retailers were considered according to four retailer distribution centers located in Tacoma, WA; Loveland, CO; Hooksett, NH; and Lakeland, Fl. The distances from the retailer centers to the market, market to the consumers, from consumer to the landfill, incineration and recycling centers were considered to be common or negligible and hence were excluded from the study.

4.9.4 End of life scenario

No data for land filling, incineration or recycling was available for PLA and hence the emission for the disposal scenario for mixed plastics was considered for PLA. Out of the total 1000 containers, all of them were assumed to reach the ends of life scenarios and no container was assumed to be retained by the consumer for whatsoever purposes. PLA containers can be 100% recyclable and/or compostable. Since there is a lack of commercially available recycling and composting centers for PLA, inventory data specific to these processes could be expected to change the impact values for PLA. Further study is being carried out in this direction by some of the authors.

5. Final remarks

The current works evaluate the environmental impact produced by PLA, PET and PS containers for distribution of fresh produce. PET contributed the highest towards almost all the impact categories. This could be mainly attributed to the higher weight of the containers. The transportation stage of PLA, PS and PET was the major contributor for the global warming, ozone layer depletion, and aquatic ecotoxity burdens emitted by it through its life journey. This study found and demonstrated that the transportation stage is a major contributor for most of the impact categories during the life cycle of the three clamshell containers. Since the strawberry exporter and the container supplier were situated in California, the locally possible PET resin manufacturing site was available in Columbia, SC. Similarly, for PS the locally situated resin production site was found to be at Joliet, IL. There may be PET and PS resin companies having manufacturing sites much closer to California than the ones assumed by this study. In that case, the results would change depending on the distances between the resin supplier and the converter. The only supplier for PLA resin in the United States of America is NatureWorks LLC, NE. In a case where the distances between the PET and PS resin suppliers and the converter is lesser compared to that of PLA resin then the data obtained in this study would invariably show different results. Thus, procurement of resin and supplies closest to the manufacture and end life scenario would have a greater impact in the majority of the cases. Moreover, if the PET and PS producers are willing to procure renewable energy credits, the environmental footprint of PET and PS clamshell container will also change. In addition, when considering the emissions produced by the transportation of the product, the total emissions of the containers are lower than 26%. Finally, if the ecological footprint of a package must be minimized, production and procurement of the majority of the available materials should be obtained locally. However, if we look at the total sustainability of the packaging system, further consideration to the social equity and economic value generated by the system approach should be assessed and balanced, accordingly. To the authors' best knowledge research work is needed in this direction.

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Chapter 5. Effect of Distance and Transportation on the environmental impact of PLA, PET and PS containers.

5.1 Introduction

According to Chapter 4, transportation is one of the important stages of the environmental impact of PLA, PET and PS clamshell containers. This system as a whole depends on different factors such as the mode of transport (land, air, rail or road), the type and make of the transport vehicle, the transport conditions (road conditions), the load and the distance traveled. Each of these factors displays a different set of inventory data and hence the results vary extensively depending upon a certain set of conditions [1]. Earlier studies have found that the emission generated and the energy consumed during the transportation process can be quite dominating on the overall results of the study and the environmental impacts, so they cannot be undermined. Also, few studies have suggested that an improvement in the transport system would greatly improve the environmental burden values [2]. Comparative LCA's have also adopted the policy of eliminating the transportation system out of the system boundary on the grounds of being a "common stage" in the life cycle and thereby assuming to exhibit similar burdens [3]. Although it is a better alternative, in comparative LCA's, to simplify the study and determine the environmental viability of a particular product but more often than not the essence of deriving the actual impact value becomes obscure. The following study aimed at analyzing the importance of transportation and distances during the distribution of strawberry filled PLA, PET and PS clamshell containers.

5.2 Goal and scope

The goal of the study was to analyze the effect of distance and transportation during the distribution stage of strawberry filled PLA, PET and PS clamshell containers. Data was taken from Europe and North America. The impact categories considered were same as those described in the previous chapter. The functional unit was also chosen as 1000 containers of capacity 1 lb each.

5.3 System boundaries

The empty PLA, PET and PS containers were filled with strawberries at Driscolls Strawberry Associates, California and transported to four different Walmart distribution centers located at Tacoma, (WA), Loveland (CO), Lakeland (FL) and Hooksett (NH).The filling operation and the post distribution stages was kept out of the system boundary. The distances from the exporter to the four distribution locations were about 1522 kms (Tacoma, WA), 2230 kms (Loveland, CO), 4664 kms (Lakeland, FL) and 5327 kms (Hooksett, NH) by road and about 1100 kms (Tacoma, WA), 1700 kms (Loveland, CO), 4400 kms (Lakeland, FL) and 4500 kms (Hooksett, NH) by rail [4, 5].

5.4 Assumptions

The truck used for transportation was a 16 and 28 ton capacity truck and a rail diesel locomotive was used as the railway mode of transportation. Driscolls Strawberry Associates, California, USA, was assumed to be the strawberry exporter. The filled containers were distributed among four different Walmart distribution centers located at

Tacoma, (WA, 98499), Loveland (CO, 80538), Lakeland (FL, 34602) and Hooksett (NH, 63077).

Methods

The framework of this study was defined according to ISO 14040 guidelines [6]. The goal and scope definition of the problem and the inventory analysis were framed and conducted according to ISO 14041 recommendations [7]. The life cycle assessment and interpretation were conducted according to ISO 14042,14043 and 14044 [8, 9, 10], and ISO 14049 was used for examples of developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries, and examples of allocations procedures [11]. ASTM D 7075 was consulted to comply with U.S. standards. SimaPro™ software version 7.1.6 from Pre® consultants (The Netherlands) with the Ecoinvent database version 1.2 was used as the primary source for the life cycle inventory (LCI) [12, 13]. The transportation stage of the life cycle system used to conduct the study in Chapter 4 was utilized to generate the inventory data. Impact 2002+ was chosen as the method for impact assessment.

Results and discussion

This chapter analyzed the variation of environmental impact values caused due to transportation and distances. To achieve this, two separate transportation system were studied. In the first scenario, 1000 strawberry filled PLA, PET and PS clamshell containers were distributed equally and transported through a 16 and 28 ton capacity truck from Driscolls Strawberry Associates to four different Walmart distribution centers throughout the US in Washington, Colorado, Florida and New Hampshire. For the same situation the second scenario used a rail diesel locomotive. It is of outmost importance to mention here, that the main objective of this chapter is not comparing the burdens among the containers, but to translate the effect of changes in distances and transportation system on emissions caused due to the activities. Table 1, 2 and 3 provide the burden values for the nine different impact categories for 16, 28 ton capacity truck and rail diesel locomotive respectively.

Table 9: Impact category values due to transportation of strawberry filled containers from exporter to market by a 16 ton capacity truck.

Impact Category	Stage	PLA	PET	PS
Global warming, kg CO_2.eq	Washington	59.60	59.90	59.00
	Colorado	90.60	91.00	89.60
	Florida	197.00	198.00	195.00
	New Hampshire	226.00	227.00	224.00
Aquatic acidification, kg SO_2.eq	Washington	0.40	0.41	0.40
	Colorado	0.62	0.62	0.61
	Florida	1.34	1.34	1.32
	New Hampshire	1.53	1.54	1.52
Ozone layer depletion, kg CFC-11.eq	Washington	8.12E-06	8.16E-06	8.03E-06
	Colorado	1.23E-05	1.24E-05	1.22E-05
	Florida	2.69E-05	2.70E-05	2.66E-05
	New Hampshire	3.08E-05	3.09E-05	3.05E-05
Aquatic eutrophication, kg PO_4	Washington	0.0077	0.0077	0.0076
	Colorado	0.0116	0.0117	0.0115
	Florida	0.0253	0.0254	0.0250
	New Hampshire	0.0290	0.0291	0.0287
Respiratory organics, kg Ethylene.eq	Washington	0.112	0.112	0.110
	Colorado	0.170	0.170	0.168
	Florida	0.369	0.370	0.365
	New Hampshire	0.423	0.425	0.418
Aquatic ecotoxity, water kg TEG.eq (TEG: (Triethylene glycol)	Washington	23700	23800	23400
	Colorado	36000	36100	35600
	Florida	78300	78600	77400
	New Hampshire	89800	90200	88800

Table 9 Continued

Energy, MJ surplus.eq	Washington	993	997	982
	Colorado	1510	1520	1490
	Florida	3280	3300	3250
	New Hampshire	3760	3780	3720
Land occupation m2org.arable.eq	Washington	0.781	0.784	0.772
	Colorado	1.190	1.190	1.170
	Florida	2.580	2.590	2.550
	New Hampshire	2.960	2.970	2.930
Respiratory inorganics, kg PM2.5.eq	Washington	0.107	0.108	0.106
	Colorado	0.163	0.164	0.161
	Florida	0.355	0.356	0.351
	New Hampshire	0.407	0.409	0.403

Table 10: Impact category values due to transportation of strawberry filled containers from exporter to market by a 28 ton capacity truck.

Impact Category	Stage	PLA	PET	PS
Global warming, kg CO_2.eq	Washington	36.1	36.2	35.7
	Colorado	54.8	55.1	54.2
	Florida	119	120	118
	New Hampshire	137	137	135
Aquatic acidification, kg SO_2.eq	Washington	0.256	0.257	0.253
	Colorado	0.389	0.391	0.385
	Florida	0.847	0.850	0.837
	New Hampshire	0.971	0.975	0.961
Ozone layer depletion, kg CFC-11.eq	Washington	6E-06	6.03E-06	5.93E-06
	Colorado	9.12E-06	9.16E-06	9.02E-06
	Florida	1.98E-05	1.99E-05	1.96E-05
	New Hampshire	2.28-05	2.28E-05	2.55E-05
Aquatic eutrophication, kg PO_4.eq	Washington	0.00351	0.00352	000347
	Colorado	0.00533	0.00535	0.00527
	Florida	0.0116	0.0116	0.0115
	New Hampshire	0.0133	0.0134	0.0132
Respiratory organics, kg Ethylene.eq	Washington	0.0400	0.0402	0.0396
	Colorado	0.0608	0.061	00601
	Florida	0.132	0.133	0.131
	New Hampshire	0.152	0.152	0.150
Aquatic ecotoxity, water kg TEG.eq (TEG: (Triethylene glycol)	Washington	13000	13100	12900
	Colorado	19800	19800	19500
	Florida	43000	43100	42500
	New Hampshire	49300	49500	48700

Table 10 Continued

Energy, MJ surplus.eq	Washington	610	613	604
	Colorado	928	931	917
	Florida	2020	2030	2000
	New Hampshire	2310	2320	2290
Land occupation m2org.arable.eq	Washington	0.287	0.289	0.284
	Colorado	0.437	0.438	0.432
	Florida	0.950	0.954	0.939
	New Hampshire	1.09	1.09	1.08
Respiratory inorganics, kg PM2.5.eq	Washington	0.0571	0.0573	0.0565
	Colorado	0.0868	0.0871	0.0858
	Florida	0.189	0.189	0.187
	New Hampshire	0.216	0.217	0.214

Table 11: Impact category values due to transportation of strawberry filled containers from exporter to market by a Rail diesel locomotive.

Impact Category	Stage	PLA	PET	PS
Global warming, kg CO_2	Washington	2.57	2.58	2.54
	Colorado	3.93	3.98	3.92
	Florida	10.30	10.30	10.10
	New Hampshire	10.50	10.30	10.50
Aquatic acidification, kg SO_2	Washington	0.0252	0.0253	0.0249
	Colorado	0.0386	0.0391	0.0385
	Florida	0.1010	0.1010	0.0997
	New Hampshire	0.1030	0.1010	0.1040
Ozone layer depletion, kg CFC-11	Washington	1.38E-09	1.38E-09	1.36E-09
	Colorado	2.10E-09	2.13E-09	2.10E-09
	Florida	5.50E-09	5.52E-09	5.44E-09
	New Hampshire	5.63E-09	5.52E-09	5.65E-09
Aquatic eutrophication, kg PO_4	Washington	0.000002	0.000002	0.000002
	Colorado	0.000003	0.000003	0.000003
	Florida	0.000009	0.000009	0.000009
	New Hampshire	0.000009	0.000009	0.000009
Respiratory organics, kg Ethylene	Washington	0.0090	0.0090	0.0089
	Colorado	0.0137	0.0139	0.0137
	Florida	0.0359	0.0361	0.0355
	New Hampshire	0.0368	0.0361	0.0369
Aquatic ecotoxity, water kg TEG (TEG: (Triethylene glycol)	Washington	0.575	0.578	0.569
	Colorado	0.880	0.893	0.879
	Florida	2.300	2.310	2.280
	New Hampshire	2.350	2.310	2.360

Table 11 Continued

Energy, MJ surplus	Washington	35	35	34
	Colorado	53	54	53
	Florida	139	139	137
	New Hampshire	142	139	143
Land occupation m2org.arable	Washington	0.0000	0.0000	0.0000
	Colorado	0.0000	0.0000	0.0000
	Florida	0.0000	0.0000	0.0000
	New Hampshire	0.0000	0.0000	0.0000
Respiratory inorganics, kg PM2.5	Washington	0.0079	0.0080	0.0079
	Colorado	0.0122	0.0123	0.0121
	Florida	0.0318	0.0319	0.0314

Table 9, 10 and 11 show that, with the increase in the distance, there was a subsequent increase in the impact values for all the categories. When the distances were equal, the impact values were fairly the same for the polymers. For global warming, the CO_2 values increased from about 59 kgs to about 226 kgs, with increase in the distance from Washington to New Hampshire while using a 16 ton capacity truck and about 36.1 kgs to 137 kgs with a 28 ton capacity truck. For the rail diesel locomotive, the global warming values increased from 2.57 to 10.50 kgs. With about three times increase in the distance from Washington to New Hampshire, there was about four times increase in the impact values. A similar trend was observed for all the impact categories in the three cases. A reduction in the overall burden values was observed with the usage of a higher capacity truck. This could be correlated to the consumption of fuel and energy by the trucks used during the transportation. A 16 ton capacity truck consumes 0.09l of diesel and a 28 ton capacity truck uses 0.04l of diesel for a transportation load of 1 ton.km. Furthermore, the energy consumption for a 16 ton capacity truck was 3.4MJ and 1.5MJ for 28 ton capacity truck for the same transportation load. This suggested that a higher capacity truck had lower emissions and is more energy efficient than a lower capacity truck. For railways, the impact values were even lower than 10 times that of a 28 ton capacity truck. Also a direct relationship between the distance and impact values was observed for both the transport system. Table 12 displays the minimum distance values responsible for emitting 1 kg. equivalent of burdens for global warming, aquatic acidification and aquatic ecotoxicity. For energy consumption, the values show the minimum distance that lead to a consumption of 1 MJ of non renewable energy. These values are average distance values calculated for PLA, PET and PS containers. (See Appendix B for distances and transportation load values)

Table 12: Minimum distance responsible for emitting 1 kg. equivalent burdens while using an empty 16 and 28 ton capacity truck and rail diesel locomotive.

Impact category	Minimum distance responsible for emission by a 16 ton capacity truck	Minimum distance responsible for emission by a 28 ton capacity truck	Rail diesel locomotive
Global warming (per kg CO_2.eq)	23 kms	38 kms	428 kms
Aquatic acidification (per kg SO_2.eq)	3300 kms	5200 kms	43650 kms
Aquatic ecotoxicity (per kg TEG.eq)	0.06 kms	0.1 kms	1913 kms
Non renewable energy (per MJ surplus.eq)	1.4 kms	2.2 kms	31.4 kms

A 16 ton capacity truck emits one kg of CO_2.eq after it travels a distance of 23 kms, while a 28 ton capacity truck travels 38 kms to emit similar burdens. This indicates that for same distances, a 16 ton capacity truck would have more emissions than a 28 ton capacity truck. For railways, this minimum distance was 428 kms, indicating lower emissions than the trucks. A similar trend was observed for other impact categories. Table 13 gives the global warming emission values for a transportation load of 1 ton.km.

Table 13: Global warming values per ton.km transportation load for 16, 28 ton capacity truck and rail diesel locomotive.

Transport mode	Global warming emission values per ton.km transportation load.
16 ton capacity truck	0.35 kg CO_2.eq / ton.km
18 ton capacity truck	0.21 kg CO_2.eq / ton.km
Rail diesel locomotive	0.015 kg CO_2.eq / ton.km

The above table suggested that railways were the most viable transport medium from the emission standpoint with global warming emission value of 0.015 kg CO_2.eq per transportation load of 1 ton.km while a 16 and 28 ton capacity truck emitted 0.35 kg and 0.21 kg CO_2. eq for the same load. A different scenario that could have altered the results was if the containers were exported out of the United States through a ship or an airplane. The transportation system played a major role in a life cycle assessment study and this stage forms an important factor in the determination of the environment viability of a product life journey. It was quite evident that a local market, with respect to the exporter, using railways as the mode of transportation would have the lowest emissions irrespective of the packaging material used for the application.

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Chapter 6: Conclusions

Life Cycle Assessment (LCA) is a tool which relates a material performance to its sustainability as an environmentally viable option when compared to its functional contemporaries. Although there are voids in the quantitative and qualitative interpretations, the ultimate implication of an LCA is not to derive a result but to provide with a perspective which would aid in an imperative planning process. This thesis has analyzed and presented separately, the emissions liberated during the different stages of the life cycle journey of PLA, PET and PS clamshell containers for packaging of strawberries.

For the nine different impact categories considered, PET had highest impact values for global warming, ozone layer depletion, aquatic eutrophication, aquatic ecotoxicity, energy, and land occupation. PLA had overall higher values for aquatic acidification, respiratory organics, and respiratory inorganics and comparative high values than PS for global warming, ozone layer depletion, aquatic eutrophication, and land occupation. As compared to PLA, PS had higher values for aquatic ecotoxicity and energy. The resin production stage for PLA had the least contribution for global warming, aquatic ecotoxicity, and energy consumption whereas it contributed the highest for aquatic acidification, respiratory organics and respiratory inorganics. The amount of resin required to meet the functional unit of the study was 32.64 kgs for PET, 30.54 kgs for PLA and 24.96 kgs for PS. The emissions during the extrusion and thermoforming stage for the three polymers followed the same trend as the functional unit with PET having the highest contribution followed by PLA and PS. Of all the stages, the transportation of the strawberry filled containers from the exporter to the market contributed to about 76% of the total impact. Out of the remaining 24%, the other stages having impacts in the order from highest to lowest were resin production, transportation of resins from manufacturer to converter and transportation of container to the filler, thermoforming operation, extrusion of resin into sheets, and electricity production. Distances and the transportation system were the two controlling factors for the burdens emitted during this stage. The emission values increased with a subsequent increase in the distance between the exporter and the market. Also, a 28 ton capacity truck had lesser impact than a 16 ton capacity truck while transporting the containers from the exporter to market.

The study has found that transportation is the main contributor to impacts caused by the three package systems on the environment. Reduction in the distances between the resin manufacturer, the converter, the exporter and the market and proper selection of the mode of transport could have a positive effect on the ecological value of the containers.

For future work, the thesis suggests work and research in the different areas which would aid in determining the environmental viable option among the three containers. The data for the resin production for PET and PS reflected European data while for PLA it was US specific. Hence, for PET and PS, US specific data is needed. The extrusion and thermoforming operations for converting the resins into sheets and then manufacturing the containers would result in different emission and energy consumption depending on the polymer matrix. Specific data with regards to machinery and the processing parameters during conversion is also an important criterion to be considered. For transportation the distances and the type of transport vehicle are the areas to be looked upon. Another scenario that could have altered the results was if the containers were exported out of United States through a ship or an airplane. For PET and PS, specific data for landfill, incineration and recycling is necessary and for PLA, specific data on emissions and commercialization of composting, as the end of life fate, for the biodegradable polymer would be something that could be looked upon in the future.

Appendix A

Life Cycle Assessment glossary

Life Cycle Assessment (LCA) – A systematic and scientific approach which evaluates the environmental viability of a product, process or an activity. It considers the entire life cycle from the raw material to the final disposal of a particular product.

Goal of the study – The goal of the study is stated to define the intentional application of the LCA study.

Scope of the study – The scope of the study defines the extent to which the study is performed. It marks the staring and the ending point of the study. The scope also outlines the geographical coverage of the study and the impact categories considered for the evaluation.

Functional Unit – This is the unit of comparison on the basis of which the comparison between products or its functions are carried out.

System – Stepwise progression of operations or processes which forms an entire life cycle of a particular product.

Life Cycle Inventory – List of quantified amounts of the chemical emissions (affecting air, water and soil) liberated during raw material consumption, energy utilized and waste generated during a process or an activity of different stages of a system.

Impact categories – Categorization of the environmental impacts/effects caused by the emissions caused by the different processes of a system.

Impact indicator – Representative potential unit of an impact category which is prime responsible for the effect caused by that impact category.

Classification – Assignment of the results of life cycle inventory into specific impact categories.

Characterization – Characterization of the magnitude of the classified emissions of an impact category with specific factors so to obtain a single value of an impact indicator.

Impact Assessment – Systematic assessment of the effects caused due to the impact categories.

Normalization – Conversion of the results of Impact assessment values of different indicators into common unitless values so as to have a comparison between the effects caused by different impact categories.

Sensitivity analysis – A process which analyzes the variations of the data which ultimately affects the final results.

APPENDIX B

Calculations for obtaining total amount of resin required to manufacture 1000 clamshell containers of PLA, PET and PS

Weights of the clamshell containers used for the study

Weight of empty PLA container + lid = 29.6 gms
Weight of empty PET container + lid = 31.5 gms
Weight of empty PS container + lid = 24.2 gms

Quantity of the total amount of resin required to manufacture the containers to meet the functional unit

Amount of resin required for manufacturing 1000 PLA containers = 29.6 kgs + 3.19% scrap = 30.54 kgs.
Amount of resin required for manufacturing 1000 PET containers = 31.5 kgs + 3.61% scrap = 32.64 kgs.
Amount of resin required for manufacturing 1000 PS containers = 29.6 kgs + 3.15% scrap = 24.96s kgs.

Calculations for energy requirement for the thermoforming operation

Formula: Length * width* thickness* density* (specific heat * temperature difference + heat of fusion)

Length = 1200 inch /min (assumption)
Width = 40 inch (1 m) (assumption)
Thickness = 0.018 in. (assumption)

For PLA
1200 inch/min *40 inch * 0.018 in *0.045lb/ cu.inch* (0.39 btu/lb F * (230 – 70 F) + 11.63 Btu/lb.
= 2878.29 Btu / min
= 3.036 MJ

As per the above dimensions the total volume of the polymers is 17.25 kgs of PLA 18.91 kgs of PET and 14.49 kgs of PLA.

For PET
1200 inch/min *40 inch * 0.018 in *0.05lb/ cu.inch* (0.44 btu/lb F * (325 – 70 F) + 14.63 Btu/lb
= 5479.06 Btu / min
= 5.78 MJ

For PS
1200 inch/min *40 inch * 0.018 in *0.038lb/ cu.inch* (0.54 btu/lb F * (360 – 70 F) + 0
= 5141.49 Btu / min
= 5.42MJ

Therefore Energy requirement for thermoforming of 1 kg of each polymer = 0.18 MJ (PLA), 0.31 MJ (PET) and 0.37 MJ (PS)

<u>Distances and calculations involved in calculating transportation load from resin suppliers to converters and converters to strawberry exporter</u>

<u>For PLA:</u>
Distances between ***Natureworks LLC,650, Industrial road, P.O box 564 Blair, NE 68008*** and ***Pinnacle Plastic containers,1151, Pacific ave, Oxnard, CA*** - 93033 = 2592 kms

Transportation load from ***Natureworks LLC,650, Industrial road, P.O box 564 Blair, NE 68008*** and ***Pinnacle Plastic containers,1151, Pacific ave, Oxnard, CA*** – 2592 * 30.54 = 79159.68 kg.km.

Distances between ***Pinnacle Plastic containers,1151, Pacific ave, Oxnard, CA,95077*** and ***Driscolls Strawberry Associates,P.O box 50045,Watson ville,CA 95077*** = 470kms

Transportation load from ***Pinnacle Plastic containers,1151, Pacific ave, Oxnard, CA,95077*** and ***Driscolls Strawberry Associates, P.O box 50045,Watson ville, CA 95077*** = 470*29.6 = 13912 kg. kms.

<u>For PET:</u>
Distances between ***Eastman Chemical Corporation,Columbia,SC,29202*** and ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** = 4251 kms

Transportation load from ***Eastman Chemical Corporation,Columbia,SC,29202*** and ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** = 4251*32.64 = 138752.7 kg.km

Distance between ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** and ***Driscolls Strawberry Associates,P.O box 50045,Watson ville,CA 95077*** = 1.92 kms

Transportation load from ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** and ***Driscolls Strawberry Associates,P.O box 50045,Watson ville,CA 95077*** = 1.92*31.5 = 60.48 kg.km

<u>For PS:</u>
Distances between ***INEOS corporation Joliet,IL – 60434*** *and* ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** = 3509 kms

Transportation load from ***INEOS corporation Joliet,IL – 60434*** and ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** =3509*24.96 = 87584.64 kg.km

Distances between ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** and ***Driscolls Strawberry Associates,P.O box 50045,Watson ville,CA 95077*** = 1.92 kms

Transportation load from ***Sambraillo Pkg, 800,Walker street, Watsonville,CA,95077*** and ***Driscolls Strawberry Associates,P.O box 50045,Watson ville,CA 95077*** = 24.2 * 1.92 = 46.46 kg kms.

Distances and calculations involved in calculating transportation load from strawberry exporter to assumed Walmart distribution centers (empty containers)

For PLA:

7.4 kgs * 1522 kms = 11262.8 Kg kms.- Tacoma,WA
7.4 kgs * 2230.78 kms = 16507.77 Kg kms.- Loveland, CO
7.4 kgs * 5326.59 kms = 39416.77 Kg kms.- Hooksett, NH
7.4 kgs * 4664.61 kms = 34518.11 Kg kms.- Lakeland, FL

Total for 29.6 kgs, total distance = **101705.45 kg.kms**

For PET:

7.9 kgs * 1522 kms = 12023.8 Kg kms.- Tacoma,WA
7.9 kgs * 2230.78 kms = 17623.16 Kg kms.- Loveland, CO
7.9 kgs * 5326.59 kms = 42080.06 Kg kms.- Hooksett, NH
7.9 kgs * 4664.61 kms = 36850.42 Kg kms.- Lakeland, FL

Total for 31.5 kgs, total distance = **108577.44 kg.kms**

For PS:

6.05 kgs * 1522 kms = 9208.1 Kg kms.- Tacoma,WA
6.05 kgs * 2230.78 kms = 13496.22 Kg kms.- Loveland, CO
6.05 kgs * 5326.59 kms = 32225.87 Kg kms.- Hooksett, NH
6.05 kgs * 4664.61 kms = 28220.89 Kg kms.- Lakeland, FL

Total for 24.2 kgs, total distance = **83151.08 kg.kms**

Distances and calculations involved in calculating transportation load from strawberry exporter to assumed Walmart distribution centers (containers with food)

For PLA

(7.4 + 113.5) * 1362.82 = 164765 kg km. – Tacoma.WA
(7.4 + 113.5) * 2070.78 = 250357.3 kg km. – Loveland, CO
(7.4 + 113.5) * 5166.59 = 624640.7 kg km. – NH
(7.4 + 113.5) * 4504.61 = 544607.3 kg km. - FL

The total distance for PLA becomes **1657010.3 kg km.**

For PET

(7.9 + 113.5) * 1362.82 = 165446.3 kg km. – Tacoma.WA
(7.9 + 113.5) * 2070.78 = 251392.7 kg km. – Loveland, CO
(7.9 + 113.5) * 5166.59 = 627224 kg km. – NH
(7.9 + 113.5) * 4504.61 = 546858.44 kg km.- FL.

The total distance for PET becomes **1663561.4 kg km**

For PS

(6.05 + 113.5) * 1362.82 = 162925.13 kg km. – Tacoma.WA
(6.05 + 113.5) * 2070.78 = 247561.8 kg km. – Loveland, CO
(6.05 + 113.5) * 5166.59 = 617665.8 kg km. – NH
(6.05 + 113.5) * 4504.61 = 538526.1 kg km. - FL

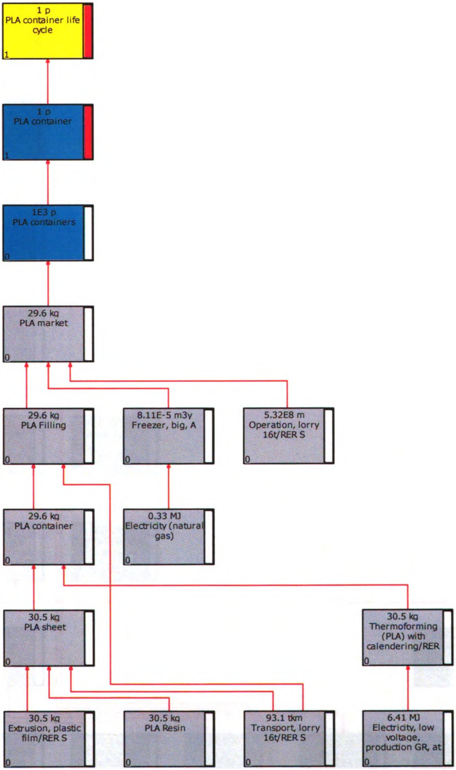
The total distance for PS becomes **1639319 kg km.**

APPENDIX C: A typical inventory emission data sheet.

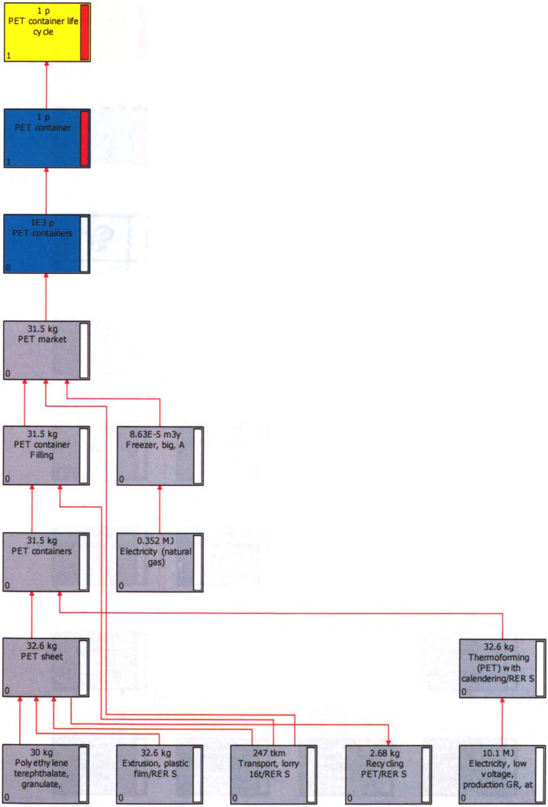
No	Substance	Compartmei /	Sub-compartment	Unit	PLA container life cycle
1	Energy, gross calorific value, in biomass	Raw	biotic	MJ	5.5
2	Peat, in ground	Raw	biotic	mg	307
3	Wood, hard, standing	Raw	biotic	cm3	135
4	Wood, soft, standing	Raw	biotic	cm3	384
5	Wood, unspecified, standing/m3	Raw	biotic	mm3	14.3
6	Carbon dioxide, in air	Raw	in air	g	483
7	Energy, kinetic, flow, in wind	Raw	in air	MJ	3
8	Energy, solar	Raw	in air	kJ	95.9
9	Aluminium, 24% in bauxite, 11% in crude ore, in ground	Raw	in ground	g	150
10	Anhydrite, in ground	Raw	in ground	mg	2.04
11	Barite, 15% in crude ore, in ground	Raw	in ground	g	335
12	Basalt, in ground	Raw	in ground	g	16.2
13	Borax, in ground	Raw	in ground	mg	8.34
14	Calcite, in ground	Raw	in ground	kg	4.34
15	Chromium, 25.5 in chromite, 11.6% in crude ore, in ground	Raw	in ground	g	6.97
16	Chrysotile, in ground	Raw	in ground	mg	2.11
17	Cinnabar, in ground	Raw	in ground	µg	177
18	Clay, bentonite, in ground	Raw	in ground	g	74.8
19	Clay, unspecified, in ground	Raw	in ground	kg	1.39
20	Coal, brown, in ground	Raw	in ground	kg	4.09
21	Coal, hard, unspecified, in ground	Raw	in ground	kg	3.96
22	Cobalt, in ground	Raw	in ground	mg	1.71
23	Colemanite, in ground	Raw	in ground	mg	26.1
24	Copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	Raw	in ground	g	1.29
25	Copper, 1.18% in sulfide, Cu 0.39% and Mo 8.2E-3% in crude ore, in ground	Raw	in ground	g	7.15
26	Copper, 1.42% in sulfide, Cu 0.81% and Mo 8.2E-3% in crude ore, in ground	Raw	in ground	g	1.89
27	Copper, 2.19% in sulfide, Cu 1.83% and Mo 8.2E-3% in crude ore, in ground	Raw	in ground	g	9.41
28	Diatomite, in ground	Raw	in ground	µg	163
29	Dolomite, in ground	Raw	in ground	g	7.22
30	Feldspar, in ground	Raw	in ground	µg	5.21
31	Fluorine, 4.5% in apatite, 1% in crude ore, in ground	Raw	in ground	mg	221
32	Fluorine, 4.5% in apatite, 3% in crude ore, in ground	Raw	in ground	mg	104

Comparing 1 p 'PLA container life cycle'; Method: IMPACT 2002+ V2.02 / IMPACT 2002+

APPENDIX D: PLA Life cycle tree



APPENDIX E: PET Life cycle tree



APPENDIX F: PS Life cycle tree