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Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology

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ABSTRACT

Life cycle assessments of bio-based polymer resin and products historically have shown favorable results in terms of environmental impacts and energy use compared to petroleum-based products. However, calculation of these impacts always depends on the system and boundary conditions considered during the study. This paper reports a cradle-to-cradle Life Cycle Assessment (LCA) of poly(lactic acid) (PLA) in comparison with poly(ethylene terephthalate) (PET) and poly(styrene) (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. For PET and PS, the extraction of crude oil and the entire cracking processes from crude oil through styrene and ethylene glycol and terephathalic acid are considered. Global warming, aquatic acidification, aquatic eutrophication, aquatic ecotoxicity, ozone depletion, non-renewable energy and respiratory organics, land occupation and respiratory inorganics were the selected midpoint 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, mainly due to the higher weight of the containers. The main impacts to the environment were the resin production and the transportation stage of the resins and containers. This implies that the transportation stage of the package is an important contributor to the environmental impact of the packaging systems, and that it cannot be diminished.

1. Introduction

LCA is an environmental tool that compares a material's performance as an environmentally viable option 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 [1–3]. LCA considers products not just as "products" but as product systems and beyond, which includes the various stages throughout their 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 ranges from the extraction of the raw materials used for manufacturing of products through the disposal of the product in landfill, incineration or recycling. A cradle-to-cradle study starts from the raw material extraction through disposal and extends from the disposal onward, 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 [2–4]. In the packaging industry several studies have been done for comparison of packages used for different applications, food packaging being 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 through aesthetics. The packaging domain comprises raw material manufacturers, the converters, and the users or consumers. It also includes the distribution network from wholesalers to retailers and from retailers to 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

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creates during its journey from production to waste stream. The awareness of this observation over the years has given rise to the concept of sustainable packaging systems [5].

Sustainability in packaging has three elemental components: social equity, ecological footprint and economic value [6]. In the last few decades LCA studies have attempted to quantify the ecological footprint of sustainable packaging systems [7–10]. Such studies can assess the environmental performance of different packaging materials such as paper [11], glass [12], plastics [13,14], steel [15], aluminum [16], and wood [17] and for different forms such as plastic containers [7,18], metal cans [19], glass bottles [12], flexible packaging [5], paper and board boxes [7], composites [17], pallets and an array of geometric structures [19]. Most studies compare the environmental viability of various packages suitable for a common application.

Because of the public's growing awareness of the need for a clean environment, the trend is for bio-based packaging to replace the traditional petroleum-based packaging materials. Biopolymers in particular have created an entirely new market for the packaging of food products [4]. They are more desirable than traditional polymers because they are considered environmentally favorable materials, they could be biodegradable, and they are derived from renewable resources [20,21]. LCAs of bio-based products and biopolymers have shown reduced impacts and favorable results in terms of such environmental burdens as greenhouse gas emissions and energy use when compared to hydrocarbon-based polymers [22–24].

Poly(lactic acid) (PLA), one of the bio-based polymers derived from corn-based starch, has recently been drawing the attention of the food packaging industry. PLA has progressively created a market for the packaging of fresh cut produce like salads, replacing the conventional petroleum-based polymers like poly-(ethylene terephthalate) (PET) and poly(styrene) (PS) [20,21]. Some studies have found that PLA has comparable mechanical and physical properties to that of PET and PS [20,21]. Earlier studies comparing PLA, PET and PS resins showed that first generation PLA polymers had fossil energy requirements similar to that of their petroleum counterparts [14]. However, current LCA studies report that PLA requirements for resin fossil energy are almost ten times lower than petroleum-based polymer resins, after calculating in the purchase of wind power credits and the energy produced from biomass in the plant [25].

LCA studies comparing actual bio-based and hydrocarbon-based packaging containers are scarce. The Athena institute produced a life cycle inventory study comparing the environmental impact of PLA packages and their petroleum counterparts to produce cold drink cups, deli containers, envelope window films, meat trays and water bottles [23]. Results showed no clear environmental win in choosing one material over another but identified trade-offs. Although this study considered the production of the raw materials, transportation of the resins, fabrication of the products from their resins, and disposal of the products including landfill and combustion of mixed municipal solid waste (MSW), it did not account for different transportation scenarios, nor did it report the full environmental impact of the whole packaging/product system. This information is needed if sustainable packaging systems are to be implemented.

The IFEU Institute (Institute for Energy and Environmental Research) produced a similar report about PLA clamshell containers used for food packaging applications, comparing them with PET, PP (polypropylene) and oriented-PS clamshells. They also found trade-offs between the polymer resins when all the environmental indicators were considered, but PLA specifically showed lower fossil resource consumption, global warming and summer smog values [24]. Although the IFEU LCA does include part of the transportation scenario of the resins, it does not evaluate this for the American market. Therefore, a complete picture of the packaging system implementation is missing because transportation could produce a net environmental footprint in the product package systems [26].

2. Goal, scope and boundaries

2.1. 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 ranged from the extraction of the raw material for the three polymers and the processes of their resin production, through container formation, followed by their end-of-life disposal. The scope includes consideration of 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 0.4536 kg (1 lb) each for the packaging of strawberries.

2.2. Methods

A set of international standards from the International Organization for Standardization (ISO) and ASTM International was used as guidelines for the systematic approach and conduct of the study. The framework of this study was defined according to ISO 14040 guidelines [27]. The goal and scope definition of the problem and the inventory analysis were framed and conducted according to ISO 14040 recommendations [27]. The LCA and interpretation were conducted according to ISO 14044 respectively [28], and ISO 14049 was used for developing function, distinguishing function of comparative systems, establishing inputs and outputs of unit processes and system boundaries [29]. ASTM 7075 was consulted to comply with U.S. standards [30]. SimaPro™ software from PRe® consultants (The Netherlands) [31] was used as the primary source for the life cycle inventory (LCI). The software contains LCI data for over 2500 processes typically used in the packaging industry. The time span of the data ranges from 1999 to 2006.

2.3. System boundaries

Fig. 1 shows the life cycle inventory flow chart for PLA, PET and PS product/package systems. The life cycle flow for the hydrocarbon-based polymers – PET and PS – starts with the extraction of crude oil and the cracking of the extracted oil. These steps are common for both polymers. For PET, after the extraction of crude oil, resin production included, comes the conversion of associated gases into ethylene, naphtha to benzene and ethylene oxide, ethylene oxide to ethylene glycol, and eventually to PET [32]. 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 [32]. For PLA, the life cycle begins with corn growing and harvesting. The harvested corn is sent to a corn-wet mill where cornstarch is separated and converted to dextrose. The dextrose obtained is converted to lactic acid which, through lactide production, is polymerized to PLA [25].

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 PS and PET containers are then transported from Sambrailo Packaging, Watsonville, California to Driscoll

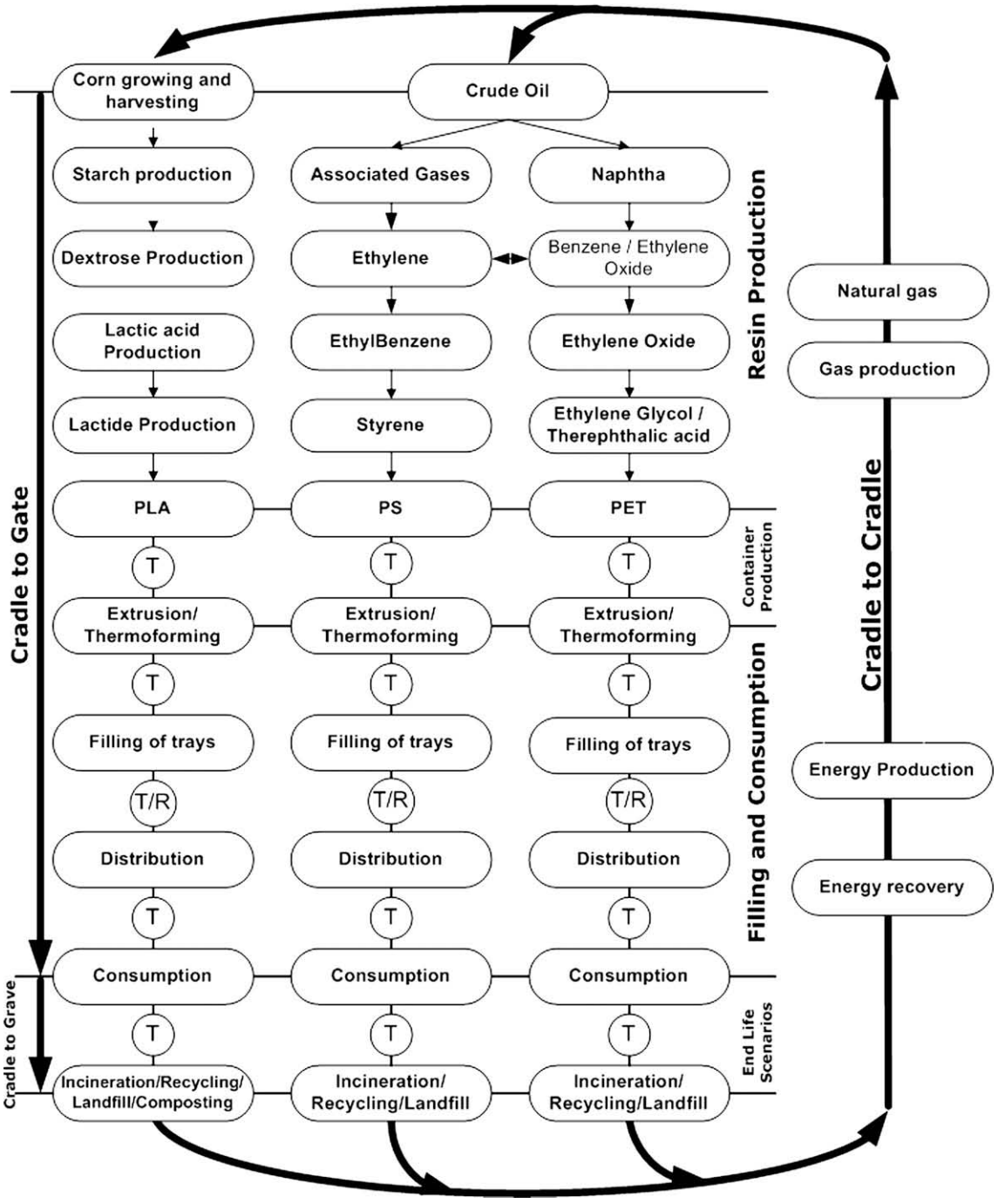

Fig. 1. Life cycle inventory flow chart for PLA, PET and PS thermoformed containers from cradle to gate, cradle-to-grave, and cradle-to-cradle.(T – transport, T/R – transport with refrigeration).

Strawberry Associates (DSA), also in Watsonville. The PLA containers are transported to DSA from Pinnacle Plastic Container, Oxnard, California. We used DSA, a leading fresh strawberry producer and exporter who harvests and fills strawberries into these containers, for modeling purposes. The filled containers are distributed to the market, where they are bought by consumers. After strawberry consumption the containers reach the end-of-life stage where they end up in a landfill or a recycling center or are incinerated. The energy recovered from the incineration is credited to the energy consumption used for the polymer manufacture. Fig. 1 shows the life cycle inventory flow chart for the three polymers.

3. Data and data quality requirements (sources and geography)

3.1. Production of resins

The LCI data for production of PET and PS resins was collected from the commercial SimaPro™ software [32]. The data for the PET and PS resin manufacturing was taken from the Ecoinvent database that is available with SimaPro™ software. Data for the resin production included all the processes from cradle to gate including extraction and production of crude oil to resin manufacture. The Ecoinvent database uses data from the ecoprofiles of the Association

of Plastics (PlasticsEurope) 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 from the databases in the software, since commercial PLA production companies are few. In the USA, PLA is manufactured by NatureWorks™ PLA, Blair, Nebraska. The inventory data for PLA was taken from the literature [25]. 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 regarding emissions [25]. Data for production of chemicals, enzymes, electricity and water used for cooling and processing was included. Renewable Energy Certificates (RECs) are purchased by NatureWorks to offset PLA resin externally produced electricity and to offset the production and delivery of operating supplies [25].

3.2. Production of containers

No specific data for the extrusion and thermoforming of the three resins was available. Inventory data for both operations was taken from the Ecoinvent database and included emissions for the extrusion and thermoforming of a general plastic film. The data was 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 according to Equation (1) shown below [32],

$$\text{Heat Requirement} = L \times W \times T \times \rho \times (cp \times \Delta T \times \Delta H_f) \quad (1)$$

where L, W and T are the length, width and thickness of the polymer sheet; ρ is the density of PLA, PET and PS, cp is the specific heat of the polymer, ΔT is the temperature difference between the polymer sheet and the thermoforming setting temperature; and ΔH_f is the heat of fusion of PLA, PET or PS. The length, width and thickness of the roll to produce the functional unit of 1000 containers were 30 m min^{-1}, 1 m, and 4.5672×10^{-4} m (18 mil), respectively. Table 1 shows the material specific values for each term of Equation (1) [32,33].

The energy used for the thermoforming of 1 kg of PLA, PET and PS sheets was calculated to be 0.21, 0.31, and 0.30 MJ, respectively. The calculations were material specific and not machine-specific. Sample containers of dimensions 19 × 16.5 × 7 cm for PS and PLA were used for the study. The weights of these containers were 24.2 and 29.6 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 ($\rho = 1370$ kg m^{-3}) and assuming a sheet thickness of 4.5672×10^{-4} m (18 mil) [20]. PS and PLA thickness were the same. It was assumed that the same mold was used for all the containers [20]. Before extrusion, PET and PLA resins are generally dried at 140 °C for 4 h and at 60 °C for 4 h, respectively. Due to the lack of reliable data about this process and much different type of equipments used for the drying process, this step was not included in the LCI. If this data is included should produce a minor increase of the emissions of PLA and PET since the emission values in each category should be lower than the extrusion process, which account for less than 8% of the total emissions of the containers.

Table 1
Density, specific heat, temperature difference, and heat of fusion of PLA, PET and PS resins, respectively; and energy required to thermoform 1 kg of PLA, PET and PS resins as calculated by Eq. (1).

Polymer	ρ, kg m^{-3}	cp, J kg^{-1} K^{-1}	ΔT, K		ΔH_f, kJ kg^{-1}	Heat required, MJ
			T_{tf}, K	T_{sheet}, K		
PLA	1246	503	383	294	27.03	0.21
PET	1370	568	435	294	34.00	0.31
PS	1052	697	455	204	0.00	0.30

T_{tf}: thermoforming setting temperature; T_{sheet}: polymer sheet temperature.

3.3. Consumption stage

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

3.4. Distances and transportation

Distances from the resin supplier by truck and train to the converter were not available for PS and PET due to confidential company information. They were assumed to be as follows and are shown in Fig. 2. PET resin was assumed to be provided by Eastman Chemical Corporation, Columbia, South Carolina (29202), and PS resin was assumed to be provided by INEOS Corporation, Joliet, Illinois (60434) (formerly BASF Corp.) to Sambrailo Packaging, Watsonville, California (95077). These distances were found to be 4251 and 3509 km by truck, respectively, and 4491 and 3513 km by train, respectively, using MapQuest [34]. NatureWorks LLC, Blair, Nebraska (68008) is the sole PLA resin supplier in the United States. The distance between NatureWorks LLC and Pinnacle Plastic Container, Oxnard, California (93033) (the PLA container supplier) was found to be 2592 km by truck and 3136 km by train. Distances between converter and strawberry exporter were calculated with reference to DSA, Watsonville, California (95077) and their local suppliers. DSA procures PET and PS containers from Sambrailo Packaging, also in Watsonville. The distance between them is 1.92 km by truck, and the same distance was assumed by train [34]. Distance between DSA and Pinnacle Plastic Container was calculated to be 470 km by truck and 500 km by train.

Transportation was assumed to be carried out by train and by using 16- and 28-ton capacity trucks. The data for them was obtained from the Ecoinvent database. After the containers were filled by DSA, it was assumed that all the containers were shipped in equal proportion to four retail distribution centers located in: Tacoma, Washington (truck = 1363 km; train = 1100 km); Loveland, Colorado (truck = 2071 km; train = 1700 km); Hooksett, New Hampshire (truck = 5166 km, train = 4500 km); and Lakeland, Florida (truck = 4504 km; 4400 km). These distribution centers were included to calculate the effect of the distribution channel. Further gate-to-gate analysis of the effect that different modes of transportation (16 and 28 tons capacity trucks and rail diesel locomotives) have on the environmental footprint was also performed. Railroad distances were manually calculated from public maps provided by the National Atlas system [38]. The data included operation of vehicles, production, and maintenance, and represented generic European data. Disposal of vehicles, road construction, maintenance and disposal was reflected by Swiss data. Since no data for the use of freezers was available in the Ecoinvent database, data from the LCA food DK database, which is another database available with SimaPro™ software, was used. This database contained data for processes in the food product chain.

3.5. 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

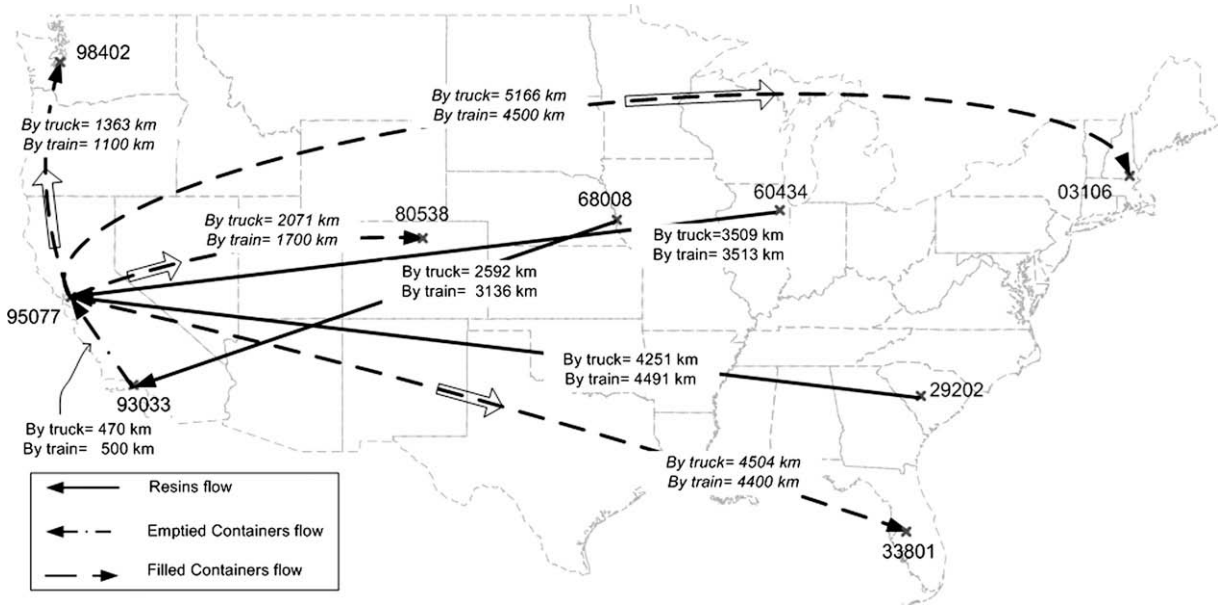

Fig. 2. Distances from the PLA, PET and PS resin producers NE, SC, and IL respectively to the resin convertors in CA and the Strawberry distributor in CA (solid lines). Distances from the Strawberry exporter (CA) to four-warehouse located in WA, CO, NH and FL (dashed lines).

- 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–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 containers. The average U.S. rate for municipal waste stream of polymers was 23.5% incineration and 76% landfill in 2005 [35]. Therefore, for the three containers, as per the average municipal rate, in this scenario 23.5% was treated for incineration and 76.5% for landfilling. Since commercially available centers for the composting and recycling of PLA are not available, they were also treated as the other polymers. It was considered that PLA, PET and PS do not degrade in landfill, which is a reasonable assumption because researchers have shown that no degradation of organic compounds in landfill is produced due to the presence of an anaerobic environment [22,36]. All five scenarios assumed that no container is being retained by the consumer whatsoever and that all 1000 containers for the three polymers undergo the waste treatment. For PET and PS, the landfill, incineration and recycling data were taken from waste type categories in the SimaPro™ software, 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 used. 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, The Netherlands.

3.6. Allocation procedure

The allocation procedure, necessary for processes that yield more than one product output, allocates burdens to the products on the basis of different factors. Allocation may be done on the basis of their mass, molar flow, or even the economic value of the products [27]. For this study the only process that was accountable for allocation was the production of PLA, PET and PS resins because the data for PET and PS was taken from secondary sources whose system process caused inventory emissions. These processes had allocation rules defined in the database module, therefore no separate allocation rule was considered. Data for PLA was taken from the literature, and hence no allocation rule was defined for its process.

4. Impact assessment

Different LCA impact assessment methods are available with the SimaPro™ software. The Eco-Indicator method available with the Ecoinvent 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 [37]. The impact categories considered 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 IMPACT 2002+ method carries out the impact assessment by basically converting the LCI results into midpoint categories, which are the impact categories, and then converting the impact categories into damage categories (the endpoint) by means of midpoint reference units.[1]

[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, and 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 fall 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 [37].

5. Results and discussion

PLA is currently considered one of the most widely used biodegradable plastic alternatives to traditional petroleum-based plastics. It is used to package short shelf life products not exposed to high humidity and temperature conditions in packaging such as blister, clamshell, trays and bottles. Vink et al. [25] have shown that PLA resin produces a lower environmental footprint than its petroleum-based counterparts such as PET, PS and PP. However, environmental footprint studies that assess the package-product systems are scarce. Therefore, this study focuses on the assessment of the whole use, production and disposal scenarios of packages made with PLA, and two other petroleum-based resins, PET and PS. Specifically, the study looks at the impact of distance and transportation methodologies of the polymeric resins and the containers. Fig. 3 shows the normalized values for the main emissions produced by 1000 PLA, PET and PS containers from cradle-to-grave. The end-of-life stage of the containers is not included. The values are normalized by the normal emission produced by one European citizen.[2]

The highest normalized impact values for the three types of containers were respiratory inorganics, global warming, and non- and renewable energy. PET had the highest values for all the impact categories, except for respiratory inorganics, aquatic acidification (data not shown), and respiratory organics. These data were expected due to the higher weight of the PET containers and the longest transportation distance of the resin. For PLA, the main impact values were respiratory inorganics and organics, and aquatic acidification (data not shown).

Table 2 shows the cradle-to-grave contribution towards the total emission made by the process for each polymer. These values depict 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 [28]. Transportation was calculated for a 16-ton capacity truck.

5.1. Global warming (carbon dioxide emission)

Table 2 lists the process contribution to global warming impact for the hydrocarbon and bio-based containers through the cradle-to-grave life journey. The resin production stage contributed the highest CO_2 for PET, PS and PLA containers after the transportation scenario. The literature data for PLA resin reports total emission of 3.84 kg of CO_2 eq. per kg of PLA resin, out of which 1.82 is the CO_2 uptake by the corn feedstock. 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 [35]. 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 km), which was responsible for the high values of CO_2 for the PET transportation stage. Overall for PLA and PET, the resin production stage contributed around 35% (60 kg equivalent CO_2 and 65 kg equivalent CO_2, respectively) of the sub-total 171 and 198 kg CO_2 emission, and for PS the resin production stage contributed 43% (70 kg equivalent) of the sub-total 165 kg CO_2 emission. However, these CO_2 emissions represented less than 26% of the total emission produced by the packaging system when considering the transportation of the strawberries.

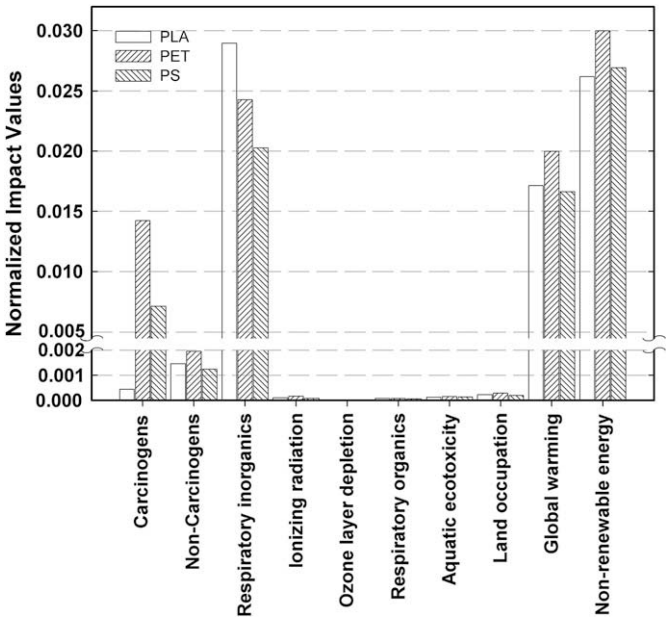

Fig. 3. Normalized impact value comparing 1000 PLA, PS and PET containers from cradle to gate. Method of comparison IMPACT 2002+ V2.02. Values are normalized according to the emission produced annually by a European citizen. Each total emission value in Table 2 was divided by the reference (normal emission produced by one European citizen) as established by IMPACT 2002+ V2.02.

5.2. Aquatic acidification

The resin production stage for PLA contributed 1.17 kg of SO_2 that was around 63% of the total SO_2 emission during its life journey. The stage that contributed the most to 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. The transportation of the product produces almost double the amount of aquatic acidification than does the production of the PLA containers, and more than ten times the amount allocated to the transportation of the resin and containers.

5.3. Ozone layer depletion potential (ODP)

The ODP value for PLA during the transportation stage of the resin and containers was 9.6E-06 kg of CFC-11, which was about 66% of the sub-total ODP. For PET and PS, the highest ODP value was also found during the transportation of the resins and containers, which was 1.22E-05 and 8.42E-06 kg of CFC-11, respectively. However, these values were at least 80% lower than the ODP values allocated to the transportation of strawberries.

5.4. Aquatic eutrophication

PLA resin production contributed around 5.56E-03 kg of PO_4 equivalents, which was around 36% of the total potential. PET resin production contributed 0.068 kg PO_4 equivalents, about 84%. The PS resin production stage contributed 1.9E-04 kg PO_4 equivalents, about 2% of the sub-total, while its transportation stage contributed around 84% of the sub-total emission. The lower PS value for aquatic eutrophication for the resin stage as compared to PET is mainly due to the lower chemical oxygen demand value accounted

[2] Normalization values help to gain a better understanding of the true impact of the packaging system. Each total emission value in Table 2 was divided by the reference (normal emission produced by one European citizen) as established by IMPACT 2002+. All the final impact indicators of Fig. 3 have the same unit, which makes it easier to compare them.

Table 2
Impact assessment values for 1000 PLA, PET and PS containers. The values are for cradle-to-grave analysis carried for nine impact categories according to IMPACT 2002+ V2.02.

Impact category	Stage	PLA		PET	PS
Global warming, kg CO_2	Resin production	60		65	70
	Extrusion	15		16	12
	Thermoforming	22		24	18
	Electricity production	3		4	3
	Transportation (R)[a]	28.7		50.2	31.7
	Transportation (C)[b]	41.8		39.3	30.1
	Sub-Total	**171**		**198**	**165**
	Transportation (S)[c]	564		565	565
	Total	**735**		**763**	**730**
Aquatic acidification, kg SO_2	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	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**
Aquatic eutrophication, kg PO_4	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	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**
Respiratory inorganics, kg PM2.5	Resin production	0.135		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**
Aquatic ecotoxity, water, kg TEG (TEG: (triethylene glycol)	Resin production	2650		3888	9240
	Extrusion	857		916	700
	Thermoforming	1400		1500	1150
	Electricity production	93		126	96
	Transportation (R)	11,400		20,000	12,600
	Transportation (C)	16,600		15,600	12,000
	Sub-Total	**33,000**		**41,600**	**35,700**
	Transportation (S)	224,000		224,400	224,300
	Total	**257,000**		**266,000**	**260,000**
		R	NR	NR	NR
Energy, MJ surplus	Resin production	991/32.4[d]	1019/33.4[d]	2412/74.0[d]	2400/96.1[d]
	Extrusion	283		303	231
	Thermoforming	476		508	389
	Electricity production	41		54	42
	Transportation (R)	477		837	528

(*continued on next page*)

Table 2 (*continued*)

Impact category	Stage	PLA		PET	PS
	Transportation (C)	697		655	501
	Sub-Total	**991**	**2993**	**4560**	**4090**
	Transportation (S)	9416		9440	9410
	Total	**13,400**		**14,000**	**13,500**
Land occupation, m2org.arable	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**

[a] Transportation (R) – transportation of resin from resin supplier to container manufacturer by a 16 ton truck.
[b] Transportation (C) – transportation of containers from strawberry filler to distributors/market by a 16 ton truck.
[c] Transportation (S) – transportation of 1000 lbs of strawberries (only food and no containers) by a 16 ton truck. Variation of between the PLA, PET and PS values are due to rounding error in the software.
[d] Energy consumption for 1 kg of resin. R = renewable; NR = non-renewable.

for by PS resin production. The characterization value for this waterborne emission in terms of PO_4 ions is 0.0717 for PET and 2.09E-04 for PS. The rest of the emissions, which are airborne, and soil emissions characterized by PO_4 ions for aquatic eutrophication for the PS resin stage, are almost negligible.

5.5. Respiratory organics

The transportation of PLA resin and containers contributed about 48% of the sub-total ethylene equivalents, while the transportation of PET and PS resins and containers contributed about 72% and 64% of the sub-total ethylene equivalents, respectively.

5.6. Respiratory inorganics

The transportation of PLA contributed about 43% of the sub-total PM2.5, while the transportation of PET and PS contributed about 66% and 54% of the sub-total respiratory inorganic emissions, respectively.

5.7. Aquatic ecotoxicity

For PLA, PET and PS the major contribution to this category came from the transportation stage of the resin and containers, which contributed around 85%, 86% and 68% of the sub-total burdens, respectively.

5.8. Energy (electricity consumption)

Table 1 shows renewable (R) and non-renewable (NR) electricity energy consumption during the different stages of container manufacturing for PLA, and NR for PET and PS. The energy consumption for 1 kg of PLA resin was 65.8 MJ out of which 32.4 MJ was from non-renewable resources [25]. 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 the sheets, as calculated by Equation (1). 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 were found to be lowest for PLA. The energy required for thermoforming 1000 containers for PLA, PET and PS were 476, 508, and 389 MJ, respectively. The transportation stage energy consumption was 1170, 1490 and 1030 MJ for PLA, PET and PS, respectively. For PLA, PET and PS the highest energy consumption was during the resin production stage, although these values were less than 30% the amount of energy used to distribute the strawberries.

5.9. Land occupation

Higher land occupation values for thermoforming and extrusion are attributed because the extrusion and thermoforming plastic films component of the Ecoinvent database account for the industrial, traffic as rail network, and dump site areas occupied or allocated to run these operations.

6. Effect of mode of transportation

Further analysis was conducted by assuming that two separate modes of transportation – truck and railroad – were used (see Fig. 2). Table 2 shows the impact assessment for transporting PLA, PET and PS resins from the production plants to Watsonville, California by a 16-ton truck. Fig. 4a) and b) compare the global warming in kg eq CO_2 to that of non-renewable energy in MJ of transporting the amount of PLA, PET and PS resins necessary to produce 1000 containers of each from the production plants to Watsonville by 16- and 28-ton trucks and railroad diesel locomotive. By transporting the resins by 28-ton truck, the global warming impact and non-renewable energy are reduced by around 40%. By transporting by train, the global warming impact and non-renewable energy are reduced by around 96% compared to a 16-ton truck. All the other transport emissions shown in Table 2 follow the same trend when the transportation is changed from 16- to 28-ton truck and/or railroad diesel locomotive. These results suggest that railways are the transport medium that produces the lower environmental impact for transporting PLA, PET and PS resins. Different supply chain scenarios such as distribution of the resins by a mixed distribution system (truck and train) to minimize the environmental footprint of the packaging and product system should deliver different outcomes.

Because some retailers are concerned about the cradle-to-grave and cradle-to-cradle environmental impact of their products, they are looking at different modes of transportation by which to ship their product through the supply chain. The environmental impact of transporting PLA, PET and PS containers by 16- or 28-ton trucks or a diesel locomotive between DSA to different distribution centers in four states was evaluated. One thousand strawberry-filled PLA

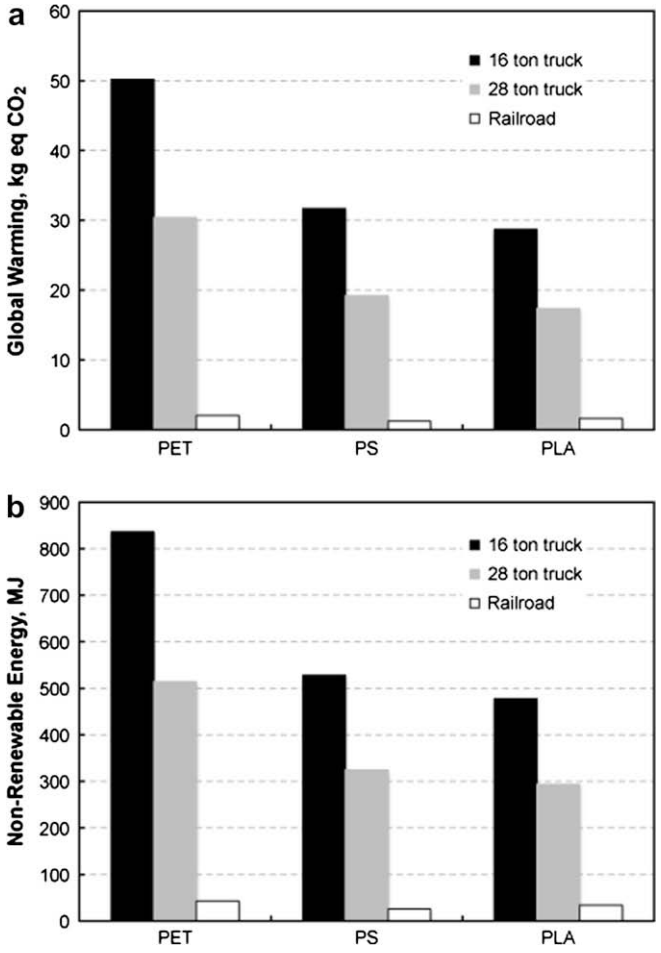

Fig. 4. a) Global warming emission in kg eq CO_2 for 1000 of each type of resins (PLA, PET, PS) distributed by a 16- or 28-ton truck or diesel locomotive; b) non-renewable energy in MJ for 1000 of each type of resins (PLA, PET, PS) distributed by a 16- or 28-ton truck or diesel locomotive.

clamshell containers were distributed equally and transported via 16- and 28-ton capacity trucks and a rail diesel locomotive from DSA to four distribution centers in Washington, Colorado, Florida and New Hampshire (see Fig. 2). The main objective of this distribution scenario was not comparing the burdens among the containers, but to translate the effect of changes in distance and transportation system on emissions caused by the activities.

The scenarios were analyzed from gate-to-gate (i.e., from the DSA to the retailer). Fig. 5 shows the global warming impact and non-renewable energy for 250 PLA containers distributed to Washington, Colorado, Florida and New Hampshire by 16- and 28-ton trucks and rail diesel locomotive. Table 3 provides the minimum distance responsible for emitting 1 kg equivalent burdens for global warming, aquatic acidification, aquatic ecotoxicity and non-renewable energy for these transportation modes. Table 3 shows that, among all the indicators, a 16-ton capacity truck emits 1 kg of CO_2 eq after it travels a distance of 23 km, while a 28-ton capacity truck travels 38 km to emit similar burdens. This indicates that for the same distances, a 16-ton capacity truck would have more emissions than a 28-ton capacity truck. For railways, this minimum distance was 428 km, indicating lower global warming emissions than the trucks.

A similar trend was observed for other impact categories, again suggesting that transportation by rail diesel locomotive of strawberries from exporter to retailers produces a lower environmental impact. Different mixed supply chain scenarios such as distribution of the resins by different transportation systems or a change in the site of the production plant, or a mixed distribution system comprising trucks and rail will deliver different results. However, this exercise indicates that the distances between main producers of a product package system should not be neglected, and that evaluation of these alternatives should be conducted if sustainable packaging systems are to be designed.

7. End-of-life scenarios

Five different end-of-life scenarios were considered in terms of landfill, incineration and recycling of containers. At this point, composting was not considered as an end-of-life scenario because no emission data was available. The first four scenarios are hypothetical; the last one is the current scenario of disposal in the U.S.

7.1. Carbon dioxide emission

In the five end-of-life scenarios about carbon dioxide emission, the values for CO_2 emissions for PET were the highest (see Fig. 6). CO_2 values for PS were lower than PET, showing the role that polymer down-gauging and light-weighting play on reduction of CO_2 emissions. PS container weight was 21% lighter than PET. The reduction of CO_2 emissions can be correlated to the fact that 32.64 kg of PET and 24.96 kg of PS were used for manufacturing 1000 containers of each.

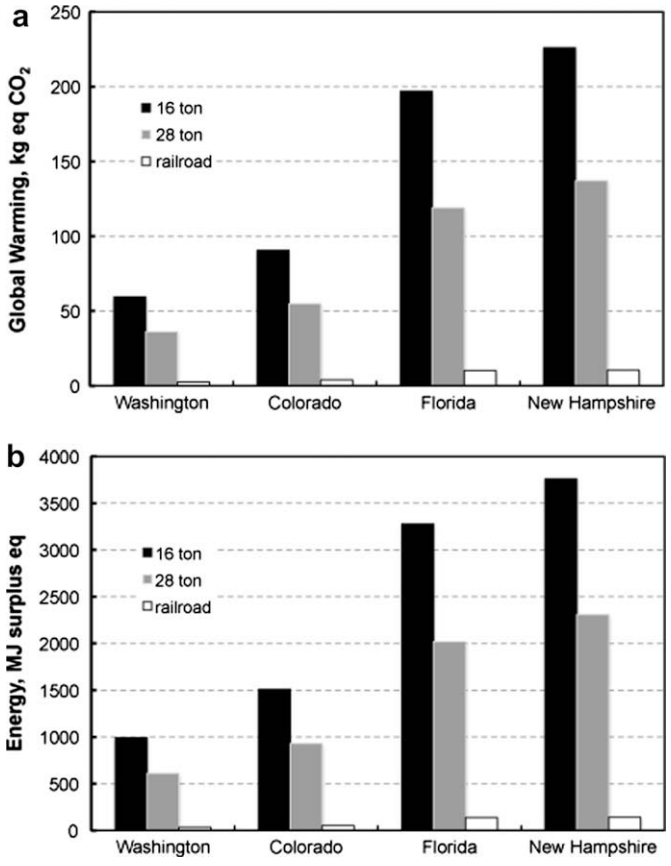

Fig. 5. a) Global warming emission in kg eq CO_2 for 250 of each type of containers (PLA, PET, PS) distributed by a 16- or 28-ton truck or railroad to WA, CO, FL and NH; b) non-renewable energy in MJ for 250 of each type of containers (PLA, PET, PS) distributed by a 16- or 28-ton truck or railroad WA, CO, FL and NH.

Table 3
Minimum distance responsible for emitting 1 kg equivalent burdens of global warming, aquatic acidification, aquatic ecotoxicity and non-renewable energy for 1000 PLA containers using a 16- and 28-ton capacity truck and rail diesel locomotive.

Minimum distance in kilometers responsible for emission of 1 kg equivalent burdens by			
Impact category	16-Ton capacity truck	28-Ton capacity truck	Rail diesel locomotive
Global warming (per kg CO_2 eq)	23	38	428
Aquatic acidification (per kg SO_2 eq)	3300	5200	43,650
Aquatic ecotoxicity (per kg TEG eq)	0.06	0.1	1913
Non-renewable energy (per MJ surplus eq)	1.4	2.2	31.4

The CO_2 emission values for PLA, PET and PS were almost similar for scenarios I and II, indicating that 40% recycling, 30% incineration and 30% landfill of these containers have almost the same CO_2 emissions as 100% of landfill. One-hundred percent recycling of containers has the lower CO_2 emission; however, this is not a realistic number to achieve. This scenario was introduced to indicate an ideal condition. Scenario IV (50I/50L) and the current scenario V (23.5I/76.5L) show 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 CO_2 emission.

7.2. Energy consumption

Fig. 7 shows the energy consumption for the cradle-to-grave analysis for 1000 PLA, PET and PS containers. For PLA, PET and PS, scenarios II (100L), IV (50I/50L) and the current scenario (23.5I/76.5L) have similar energy consumption values, indicating that increasing the incineration percent from 0 to 50 does not recover energy significantly in the overall system. If we compare 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 consider energy consumption with respect to other alternatives such as PS and PET containers. Therefore, to reduce the energy consumption for PLA containers, recycling should be established.

8. Limitations and assumptions

8.1. Resin production

The databases that came with the SimaPro™ software did not contain specific data for emissions and energy consumption for PLA. Data was taken from the literature for PLA, and the calculation of energy consumption during its resin production was added to the other calculations. PET and PS resin production data mostly reflected the European situation; in addition, this study did not include emissions from local transportation.

8.2. Conversion processes

Although more specific data for the extrusion of these polymers based on temperature difference, specific gravity and specific heat could have been used to estimate the actual energy consumed and burdens emitted during the extrusion process for each polymer, we assumed that the extrusion process for the three polymers was similar to that of a general plastic film. 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.

We also assumed that the thermoforming operation, which includes the calendaring process, was similar to the thermoforming operation of a general plastic sheet. Although the study was able to calculate the energy consumption during the thermoforming operation separately for the three polymers, similar but specific data on the emissions could have given a clear picture for a better comparison of 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 based on the assumption of a container equal in volume and capacity to that of PS and PLA and produced in the same mold. The calculations were carried out based on 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 [24].

8.3. Transportation and distances

No specific data was available for the burdens for refrigerated trucks. The emissions were calculated separately for the truck,

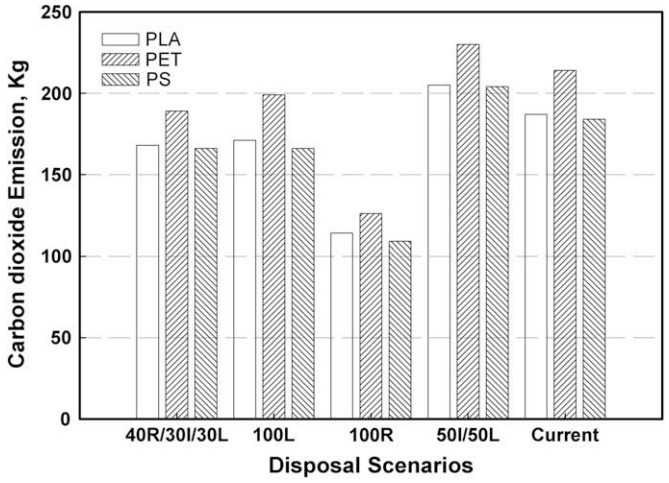

Fig. 6. Carbon dioxide emission for cradle-to-grave analysis of 1000 containers of PLA, PET and PS (R = recycling; L = landfilling; I = incineration).

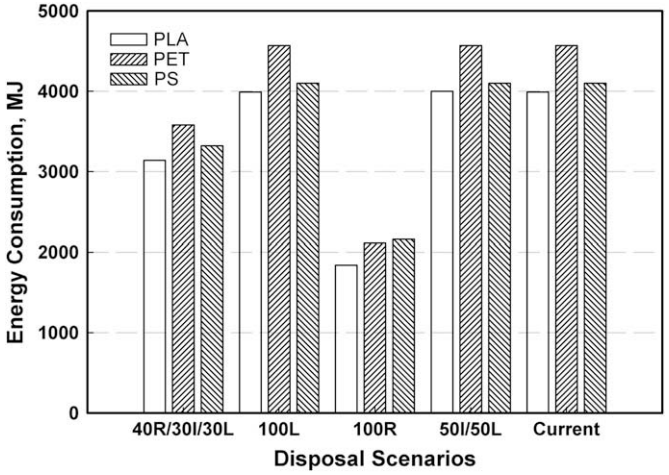

Fig. 7. Energy consumption for cradle-to-grave analysis 1000 containers of PLA, PET and PS (R = recycling; L = landfilling; I = incineration).

which was assumed to be a 16-ton capacity truck, and freezer of 0.263 m^3 capacity and the data reflected Swiss conditions. Eastman Chemical Corporation, Columbia, South Carolina, was assumed to be the PET resin supplier and INEOS Corporation, Joliet, Illinois (which was previously part of BASF Corporation) was assumed to be the PS resin supplier, both shipping to the PET and PS container supplier Sambrailo Packaging, in Watsonville, California. For PLA containers, Pinnacle Plastic Container was assumed to be their supplier, since they are locally situated with respect to Driscolls. The distance between NatureWorks LLC, in Blair, Nebraska (a PLA resin supplier) and Pinnacle Plastic Container, in Oxnard, California, was calculated and included in the analysis. Distances were also calculated between Driscoll Strawberry Associates, Inc., the strawberry exporter in California, and the PET and PS container supplier. The distance from the exporter to the four retail distribution centers in Tacoma, Washington, Loveland, Colorado, Hooksett, New Hampshire and Lakeland, Florida was calculated. The distance from the retail distribution centers to the market, market to consumers, and consumer to landfill, incineration and recycling centers was considered to be common or negligible and hence were excluded from the study. All truck distance was calculated using MapQuest [34], and all railroad distance was estimated using the National Atlas system [38]. These distances were taken as estimation, however, due to the huge differences between the emission values obtained from the different transportation systems, they can be considered reasonable assumptions.

8.4. End-of-life scenario

No data for landfilling, incineration or recycling was available for PLA, hence the emission for the disposal scenario for mixed plastics was considered for PLA. The mixed plastics data contained inventoried waste emissions for 100% mixed various plastics. Out of the total 1000 containers, all of them were assumed to reach the end-of-life scenarios and no container was assumed to be retained by the consumer for any purpose. 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.

9. Final remarks

This work evaluated the environmental impact of PLA, PET and PS containers used for distribution of fresh produce. PET contributed the highest in almost all the impact categories. This could be largely attributed to the higher weight of the containers. The transportation stage of PLA, PS and PET was the major contributor for global warming, ozone layer depletion and aquatic ecotoxity burdens through its life journey. This study found that the transportation stage of the resins and containers is a major contributor to most of the impact categories during the life cycle of the three clamshell containers. This finding cannot be neglected.

Although the strawberry exporter and the container supplier are situated in California, the PET resin manufacturing site is in Columbia, South Carolina. Similarly for PS, the resin production site was found to be at Joliet, Illinois. 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 U.S. is NatureWorks LLC, Nebraska. In a case where the distance between the PET and PS resin suppliers and the converter is shorter than that of the PLA resin supplier, the data obtained in this study would invariably show different results. Thus, procurement of resin and supplies closest to the manufacturer and variation of the end-of-life scenario would have a greater impact in the majority of the cases. Thus, the distance and type of transportation system used to distribute the packaging systems cause the design of the system to have a substantial environmental impact.

Moreover, if the PET and PS producers are willing to procure renewable energy credits, the environmental footprint of PET and PS clamshell containers will also change. When considering the emissions produced by the transportation of the product, the total emissions of the resin plus containers were under 26%. If the ecological footprint of a package system 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, the total footprint of the package and the product should be considered. Finally, consideration of the social equity and economic value generated by the system approach should be assessed and balanced accordingly. To the authors' best knowledge, research is needed in this area.

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