Corn-based Polylactide vs. PET Bottles – Cradle-to-gate LCA and Implications

SLAVKA NIKOLIĆ[1], **FERENC KISS**[2], **VALENTINA MLADENOVIĆ**[3], **MAŠA BUKUROV** [1]*, **JELENA STANKOVIĆ**[1]
[1] University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, 21000 Novi Sad, Serbia
[2] University of Novi Sad, Faculty of Technology, Bul. cara Lazara 1, 21000 Novi Sad, Serbia
[3] Polytechnic – School of New Technologies, Bul. Zorana Djindjica 152a, 11000 Belgrade, Serbia

The study compares the environmental impacts of 500 mL water bottles produced from corn-based polylactide (PLA) and PET. The results of cradle-to-bottle factory gate assessment revealed that the usage of PLA granules instead of PET granules would reduce the net global warming potential and cumulative non-renewable energy demand of bottles by 30.9% and 32%, respectively. However, if no credits are given for atmospheric CO_2 *fixed by corn, and the energy in corn-feedstock is accounted for, the advantages of PLA would be largely diminished.*

Keywords: polylactide, PET, bottles, life cycle assessment

The worldwide production of plastics exceeded 300 million tons in 2013 [1]. A significant share of these plastics turns to solid waste and cause disposal problem since they are mostly non-degradable under natural environment [1,2]. The disposal problem, jointly to other environmental concerns associated with petroleum-based plastics, has raised the demand for bio-based polymers [3].

Polylactide (PLA), with annual production of over 180,000 tons [4], is one of the main drivers of the advances of bio-based polymers (BPs) on the market. PLA is biodegradable thermoplastic aliphatic polyester derived from renewable resources, such as corn starch, cassava, or sugarcane [5-9] and can be used to alleviate the waste disposal problem [10]. It is also one of the most versatile materials and – in contrast to most other available BPs – is also suitable for more sophisticated applications like beverage and food packaging [5]. It has been showed that PLA can successfully replace polyethylene terephthalate (PET) in the production of clamshell containers, trays and bottles [5,11,12].

PLA is often considered to be more environmentally friendly compared to its petroleum-based counterparts due to its biodegradability and renewability of raw materials used for its production. Nevertheless, the production of PLA also requires non-renewable energy sources. Fossil fuel is used to power farm machinery, to produce fertilisers and pesticides, to transport crops and crop products to processing plants, to process raw materials, and ultimately to produce the PLA granules. Therefore, to comprehensively evaluate the environmental profile of bio-based products it is paramount to carry out a life-cycle based study, as being bio-based is not sufficient to be considered environmentally friendly [7].

Several life cycle assessment (LCA) studies of PLA have been carried out recently with varying and often contradictory conclusions [5,13-17]. Variation in LCA results of PLA is expected due to different local climatic and soil conditions for crop production and different production technologies along the production chain of PLA granules and products. Certain variation in LCA results is expected due to different system boundaries and inventory data sets. Therefore, the results of previous LCAs are only valid for the specific geographical and temporal scope and main methodological assumptions implemented in the specific study.

This paper aims to evaluate the environmental performance of PLA bottles produced from corn starch in comparison with PET bottles, based on the life cycle approach. It is assumed that corn production, as well as the PLA production plant, is located in Vojvodina, Serbia. The results will highlight the potential variations in LCA results of PLA arising from regional differences in production practices and inventory data.

Experimental part

Material and methods

Environmental impact of PET and PLA bottles is evaluated using the attributional life cycle assessment (LCA) method (ISO 14040:2006). LCA is based on the results of the life cycle inventory (LCI) analysis which include information on all of the elementary flows (i.e. emissions and natural resources) emitted or consumed in the life cycle of a product or service. The total quantity of specific elementary flow i (E_i) in the life cycle of PLA and PET bottles was calculated using equation (1):

$$E_i = \sum_{j=1}^{n} I_j \cdot E_{i,j}$$

where: I_j – the quantity of product flow j in the life cycle of bottle (e.g. kg corn per functional unit); $E_{i,j}$ – the quantity of emission or natural resource i in the life cycle of product flow j (e.g. kg CO_2 per kg corn); n – number of product flows in the life cycle of bottle.

Type and quantity of product flows (I_j) as well as their LCI data ($E_{i,j}$) are described in the following sections.

Functional unit and system boundaries

The functional unit (FU) is defined as 1000 units of 500 mL PLA or PET bottles which are intended to be filled with drinking water. One unit of 500 mlL PET or PLA bottle weighs 12.20 g [15] and 11.28 g, respectively. Difference in weights is due to the different densities of PLA and PET (1.23 g . cm^{-3} and 1.33 g . cm^{-3} [5], respectively) and the same thickness and forms of bottles assumed in this study.

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* *email: mbukurov@uns.ac.rs; Tel.: +381 21 4852387*

The study is a cradle-to-gate LCA. This means, that it covers all relevant process steps from raw material sourcing, through PLA and PET polymer production up to the bottle factory gate. However, distribution of finished bottles from the production facility to the consumers, as well as processes and flows associated with the usage of bottles and their end-of-life treatment were outside of system boundaries.

A general simplified process flow diagram is given in figure 1, including an indication of the system boundaries and the main product flows of the product systems studied. Each stage of the production chain is discussed in more detail bellow.

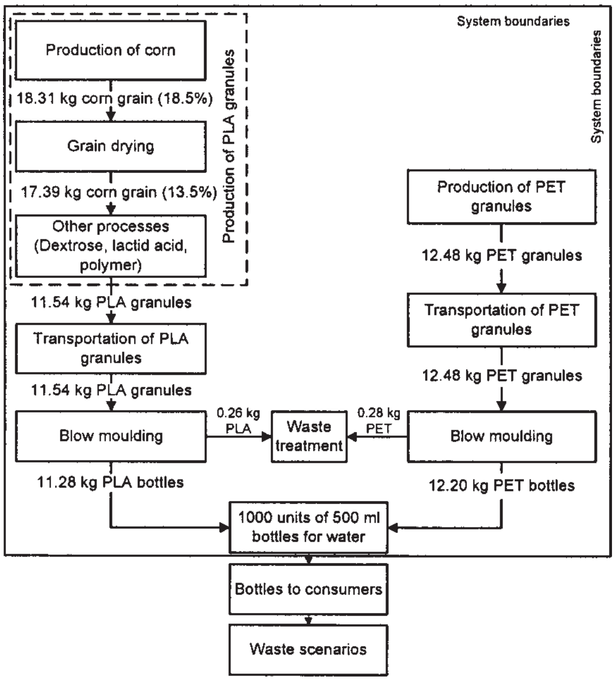

Fig. 1. Main processes and product flows in the production chain of PLA and PET bottles

Life cycle inventory of PLA bottles

As showed on figure 1 the life cycle of PLA bottles begins with corn growing and harvesting. Data on corn yield and material and fuel inputs are average values obtained from six agricultural enterprises in Vojvodina, Serbia for the years 2013 and 2014. In the observed period the average annual yield of corn was 8560 kg per hectare. The average inputs of corn seed, fertilisers, pesticides and diesel fuel normalized in terms of functional unit (i.e. 18.31 kg corn; fig. 1) is showed in table 1. In addition, the LCI of corn production includes CO_2 absorbed by corn grain through the photosynthesis process (1.34 kg $CO_2 . kg^{-1}$ corn [18]), energy content of corn grain (16 MJ per 1 kg corn [18]) and nitrous oxide (N_2O) field emissions. N_2O field emission is associated with the application of nitrogenous fertilizers [19] and it was estimated to be 31 g per kg of N (or 3.99 kg N_2O per hectare) using the BioGrace software [20].

The harvested corn is transferred by diesel truck for 40 km to the grain dryer to reduce the moisture content from the initial 18.5% to the required 13.5%. The drying process takes place at a vertical gravity dryer with an average energy consumption of 5 MJ of light fuel oil and 0.05 kWh of electricity per 1 kg of water evaporated [21].

In the next step the dried corn is sent to the PLA production facility. LCI of PLA production from corn is available from the Ecoinvent v. 2.2 database [14]. The main inventory data were derived from the eco-profile of PLA produced in 2006 [13] at the world's largest PLA production facility NatureWorks® in Blair, Nebreska. The PLA production process includes the following sub-processes: the conversion of corn into dextrose by wet milling, processing of dextrose into lactic acid by fermentation, conversion of lactic acid into lactide, and polymerization of lactide into polylactide [7,13]. The Ecoinvent v. 2.2 dataset considers electricity and natural gas consumption in PLA production, plant infrastructure and waste treatment processes. However, chemicals, enzymes and other auxiliary materials used in the PLA production process are not included in the database. In the original Ecoinvent v. 2.2 dataset the environmental profile of electricity is described by UCTE (Union for the Co-ordination of

Table 1
LIFE CYCLE INVENTORY OF 1000 UNITS OF 500 mL PLA DRINKING WATER BOTTLES

Life cycle phase	Process/Product flow (I_j)	Unit	Quantity	LCI data (from Ecoinvent v. 2.2) ($E_{i,j}$)
Corn production	Calcium ammonium nitrate	g N	26.74	Calcium ammonium nitrate, as N/RER
	Mono ammonium phosphate	g P_2O_5	128.34	Monoammonium phosphate, as P2O5/RER
	Potassium chloride fertilizer	g K_2O	85.56	Potassium chloride, as K2O/RER
	Urea	g N	245.99	Urea, as N/RER
	Herbicide (nikosulfuron)	g	0.11	[sulfonyl]urea-compounds, at regional storehouse/CH
	Herbicide (dicamba)	g	0.51	Dicamba, at regional storehouse/RER
	Sowing seeds	kg	0.39	Maize seed IP, at storehouse/CH
	Fuel in agricultural machinery	MJ	6.93	Energy, from diesel burned in machinery/RER
	Transport to dryer	tkm	0.73	Transport, lorry >16t, fleet average/RER
Corn drying	Light fuel oil for process heating	MJ	4.60	Light fuel oil, burned in industrial furnace 1MW/CH
	Electricity	kWh	0.046	Electricity, low voltage, at grid/CS
Other processes (corn to PLA)	Production of PLA granules	kg	11.54	Polylactide, granulate, at plant/GLO*
Transport	Transport to bottle producer	tkm	2.31	Transport, lorry >16t, fleet average/RER
Blow moulding	Bottle production and packaging	kg	11.54	Blow moulding/RER
	Waste treatment	kg	0.26	Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH

**modified Ecoinvent v. 2.2 process. See related text above.*

Transmission of Electricity) electricity mix. In this study it is assumed that PLA is produced in Vojvodina, Serbia; therefore, instead of the UCTE data, the environmental impact of electricity was modelled with LCI data representing the Serbian electricity (process “Electricity, low voltage, production CS” in the Ecoinvent v. 2.2 database).

PLA granules are converted in 500 mL bottles using a blow moulding technology at a plant assumed to be within 200 km from the polymer production facility. The LCI of blow moulding is available from the Ecoinvent v. 2.2 database and includes electricity used in the process and packaging materials. It is assumed that the material loss during the processing from polymer granules to bottles is the same regardless if PET or PLA is used. This loss is approximately 2% of the weight [11, 15].

Table 1 gives an overview of processes included in the LCI of PLA bottles with specification of product flows (I_j) for each of the subsystems, and LCI data of the specific product flow ($E_{i,j}$).

Life cycle inventory of PET bottles

The LCI of bottle grade PET granules is available from the Ecoinvent v. 2.2 database under the process name: “Polyethylene terephthalate, granulate, bottle grade, at plant/RER”. The Ecoinvent database uses data from the eco-profiles of the Association of Plastics Manufactures (PlasticsEurope) and represents average LCI of PET granules manufacturing at several European production plants in 1999/2000.

It is assumed that PET granules are transported 200 km to the bottle production facility. LCI datasets used for transportation and blow moulding modelling are the same as for PLA and are described in table 1.

Life cycle impact assessment

LCA is limited to the assessment of global warming potential (GWP) and cumulative energy demand (CED) of PET and PLA bottles. These impact categories are chosen since reductions of greenhouse gas (GHG) emissions and fossil fuel depletion are the main driving forces for the development of bio-based alternatives of the petroleum-based products. GWP (in terms of kg $CO_{2eq.}$. FU^{-1}) is calculated with the Greenhouse gas protocol method (ISO 14064-1:2006), while the CED (in terms of MJ . FU^{-1}) is evaluated using the cumulative energy demand method [23]. Both life cycle impact assessment (LCIA) methods, as well as the Ecoinvent v. 2.2 LCI database, are integrated in the SimaPro 8 LCA software [24] which was used for calculations of LCI and LCIA results.

Results and discussions

Cradle-to-gate impacts

The contributions of individual life cycle steps to the total life cycle environmental impacts of the PLA and PET bottles are summarized in tables 2 and 3. The PLA system shows advantages compared to petroleum-based PET system in terms of cumulative energy demand and net global warming impact. The usage of PLA granules instead of PET granules in bottle manufacturing would reduce the net GWP and CED of bottles by 30.9 and 9.7%, respectively (tables 2 and 3). It is important to note, however, that net GWP takes into account the fixation of CO_2 during biomass production and, therefore, does not express the full extent of GHG emissions from process operations. If the positive impact of CO_2 fixation is not taken into account the PLA-based bottles would have around 15% higher GWP compared to the PET-based alternative (60.9 kg CO_{2eq} . FU^{-1} compared to 52.6 kg $CO_{2\,eq}$. FU^{-1}, respectively; tables 2 and 3).

The granules production step is predominant in the total global warming impact of PLA and PET bottles. In the PLA system the major GHG emissions (about 68%) came from the “corn-to-PLA” step due to energy consumption, including steam and grid electricity. Corn production and drying is also a significant source of GHG emissions, accounting for 28.42% of the overall GWP of PLA bottles. In the corn cultivation stage almost 80% of impacts associated with GHG emissions are related to the production chain of fertilizers and N_2O emission from N-fertilizers (Fig. 2). In contrast to the transport of PLA and PET granules, which has negligible influence on the indicator results, bottle production is a major source of GHG emissions both in terms of PLA and PET. The small difference in the cumulative impact of GHG emissions associated with blow moulding is related to different amount of granules required per unit of bottle produced (fig. 1). Environmental impacts of bottle production step are mainly related to the use of electrical energy in extrusion and blow moulding processes. However, materials used for packaging of finished bottles are also important contributors to the process’s GWP (ca. 27%; fig. 2). Bottle production also contributes to CO_2 uptake due to biomass-based materials (i.e. cardboard) used in the packaging of PLA and PET bottles.

When comparing the energy required for PLA bottles with PET bottles, the results showed that PLA bottles had lower CED than PET bottles (tables 2 and 3). The CED for 1000 units of PLA and PET bottles was 1265 MJ and 1401 MJ, respectively. Production of PLA granule (cradle-to-resin) requires 74 percent of the total energy needed to make the

Table 2
CRADLE-TO-GATE IMPACTS OF 1000 UNITS OF 500 mL PLA BOTTLES (kg $CO_{2\,EQ}$ OR MJ)

Impact category	Granules production		Transport	Bottle production	Total
	Corn production	Corn to PLA			
GWP, GHG emission	4.94	41.42	0.29	14.23	60.89
GWP, CO_2 uptake	-23.44	-0.10	0.00	-5.20	-28.74
GWP, net	-18.50	41.32	0.29	9.04	32.14
CED, non-renewable	37.46	581.01	4.91	259.48	882.86
CED, renewable, biomass	276.76	1.02	0.01	57.10	334.88
CED, renewable, other	0.11	34.97	0.06	12.36	47.50
CED, total	314.33	617.00	4.97	328.93	1265.24

Table 3
CRADLE-TO-GATE IMPACTS OF 1000 UNITS OF 500 ML PET BOTTLES (kg $CO_{2\,eq}$ OR MJ)

Impact category	Granules production	Transport	Bottle production	Total
GWP, GHG emission	36.94	0.31	15.39	52.64
GWP, CO_2 uptake	-0.47	0.00	-5.62	-6.09
GWP, net	36.47	0.31	9.77	46.55
CED, non-renewable	1022.43	5.31	280.58	1308.31
CED, renewable, biomass	5.91	0.01	61.74	67.66
CED, renewable, other	12.46	0.06	13.36	25.88
CED. total	1040.80	5.38	355.68	1401.86

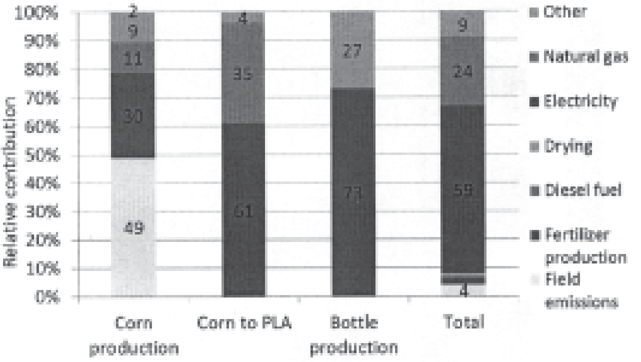

Fig. 2. Contribution of life cycle processes to GWP of PLA Lottles

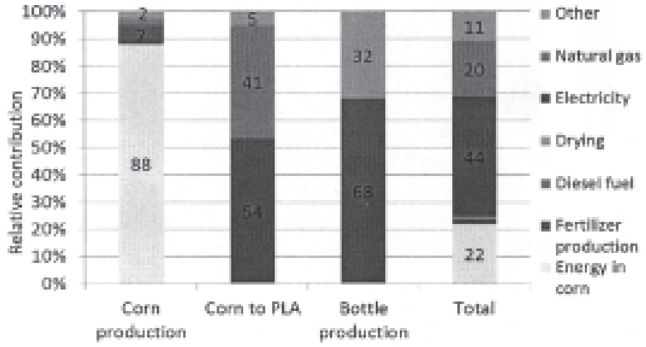

Fig. 3. Contribution of life cycle processes to CED of PLA bottles

water bottles; whereas, the resin transportation and blow molding require 26 percent of the total energy (table 3). This is also true for the PET water bottle with no end-of-life considered. An important difference between PLA and PET systems is the share of non-renewable energy sources in their CEDs. Around 30 percent of the total energy required for the PLA water bottle system comes from renewable energy sources, while renewable energy sources have a share of less than 10 percent in the total energy demand of the PET water bottles. Most of the renewable energy in the PLA systems represents the energy content of corn used as raw material (table 2, fig. 3).

Concerning GWP of different polymers, several studies [5, 13 - 17] have shown that PLA produced from corn and sugar beet had lower GWP than petroleum-based polymers such as PET (fig. 4), which is in good agreement with our study. When comparing our results with a similar cradle-to-gate studies of PLA granules [5-13 -16], they reported GHG emissions of 1.09 – 2.02 kg $CO_{2\ eq.}$ per kg corn-based PLA granules. These are in general lower than the value obtained in our study, which was 1.98 kg $CO_{2\ eq.}$ per kg PLA granules. Main difference comes from different LCI data used to model the electricity supply. The Serbian grid electricity, assumed to be the supplier of PLA production facilities in this study, has higher GWP compared to the USA average or Mid-continent Area Power Pool (MAPP) electricity used to model the environmental impact of PLA granules in most of the previous studies.

The fossil energy consumption obtained in our study was shown to be quite close to the value reported by Vink et al. [13]. However, the value obtained in our study was higher in comparison with other LCA studies of corn-based PLA [5,14-16] mainly because of the higher CED of the Serbian grid electricity compared to other electricity suppliers assumed in previous LCAs.

Limitations and uncertainties

In some cases the differences between PLA and PET options are small and it is important to highlight a number of uncertainties when interpreting the results. The modified Ecoinvent process “Polylactide, granulate, at plant/GLO” is based on LCI data of Vink et al. [13] which refer to PLA production practice at NatureWorks®, Nebreska in 2005. In the meantime, the energy efficiency of the process has been improved and consequently the non-renewable CED and the net GWP of PLA were reduced by 16% and 35% [14], respectively. It is reasonable to assume that PLA impacts are overrated in this study. Furthermore, unlike the PET production technologies, which have reached maturity and processes have been largely optimized [6], further improvements are expected in PLA production technology with favourable impacts on the product`s eco-profile.

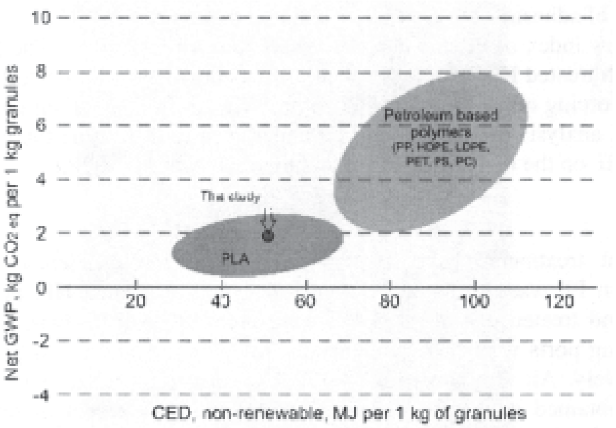

Fig. 4 Previous results on cradle-to-gate environmental impacts of PLA [5, 13-17] and petroleum-based polymers [25]
(Notes: PP – polypropylene, HDPE – High density polyethylene, LDPE – Low density polyethylene, PS – polystyrene, PC – polycarbonate)

Similarly to many previous LCAs of PLA, this study does not take into account environmental flows associated with the product‘s end-of-life (e.g., land filling, incineration, etc.). Given the non-toxic and biodegradable nature of PLA granules and products further comparable advantages may be expected in a cradle-to-grave perspective. Nevertheless, due to significant uncertainties associated with various end-of-life options of PLA this aspect is yet to be investigated.

There are uncertainties regarding some methodological assumptions as well. In general, cradle-to-gate LCAs studies of PLA give credits to atmospheric carbon fixed by plant in the process of photosynthesis. The fixed amount of CO_2 is usually subtracted from the gross impact of life cycle GHG emissions. However, the carbon is released into the atmosphere at the end-of-life of the PLA product in form of CO_2 and CH_4 (CH_4 has 23 times higher GWP than CO_2 on an equal mass basis); thus, the assumption of CO_2 neutrality of PLA is an oversimplification. Another important aspect is whether to include energy in biomass feedstock into CED of biomass-based products such as PLA. Most of the previous comparable LCA of PLA and PET consider only fossil and/or non-renewable life cycle energy demands; an approach clearly favouring the biomass-based option. However, corn is a combustible biomass material which may find other applications in energy sector (e.g., heat production, bioetanol industry) if not used for PLA manufacturing. Therefore, we found reasonable to include corn-feedstock energy in CED of PLA.

An important aspect yet to be considered in LCAs of PLA is the GWP associated with indirect land use change (iLUC). Indirect LUC occurs when land used for food production becomes rededicated and used for biomass production for non-food purposes. This, in turn, can lead to a situation where non-agricultural land (e.g. forest) is transformed into agricultural land somewhere else to counterweight the loss of food production. The process of a natural land transformation is usually followed by significant GHG emissions [26]. Although agreement on the most appropriate way to assess and include iLUC related impacts into LCAs is yet to be reached, it was showed on many cases that inclusion of iLUC effects in LCA of biomass-based products can significantly alter LCAs results and conclusions [27,28].

Conclusions

Comparable LCA assessment of PLA and PET bottles has showed that the biomass-based alternative is beneficial, both in terms of net GWP and CED. The usage of PLA granules instead of PET granules in bottle manufacturing would reduce the net GWP and CED of bottles by 30.9 and 9.7%, respectively.

Processes associated with conversion of corn into PLA granules are responsible for 68% of the overall GWP associated with GHG emissions, and require 66% of the total non-renewable energy needed to make the water bottles. Electricity consumed in the process is the largest contributor to environmental impacts of PLA bottles, indicating the importance of the adequate choice of electricity supplier. LCA results of PLA show a reduction in environmental impacts over time, thanks to phenomena of learning curves and implementation of energy efficient technologies and cleaner fuel sources. Unlike the PET production technologies, which are already largely optimized, in the case of PLA production further improvements might be expected.

There are still significant uncertainties associated with LCAs of PLA. These are related to inherent data uncertainties, choice of system boundaries (cradle-to-gate vs. cradle-to-grave perspective), and some calculation assumptions (e.g., consideration of CO_2 uptake, iLUC and energy content of biomass feedstocks). The choice of approaches to deal with these issues may significantly influence the outcome of LCAs.

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Manuscript received: 18.06.2015