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Life cycle (gap) analysis for advanced material recycling of PLA cups

Michael Dieterle*, Jannis Ginter

Fraunhofer Institute for Chemical Technology ICT, Joseph-von-Fraunhofer-Straße 7, 76327 Pfinztal, Germany

* Corresponding author. Tel.: +49-721-4640-621; fax: +49-721-4640-111. *E-mail address:* michael.dieterle@ict.fraunhofer.de

Abstract

This paper analyses and compares the LCA & LCC results of single-use PLA cups from a circular economy perspective using life cycle gap analysis and identifies potential optimizations to increase its eco-efficiency. Based on highlighted life cycle gaps of > 82 %, an advanced material recycling process chain for the recovery of secondary PLA is introduced, including washing, thermal treatment, milling and recompounding. Through the new end-of-life pathway, it is possible to recover PLA with virgin quality and to increase the energy efficiency of the mechanical recycling process. The results indicate positive effects from an environmental perspective, as well as from an economic perspective, as the eco-efficiency increases by > 88 %.

Keywords: Life Cycle Assessment (LCA); Life Cycle Costing (LCC); Circular Economy (CE); Life Cycle Gap Analysis (LCGA); PLA recycling; Thermoplastic recycling.

1. Introduction

Poly (lactic acid) - short PLA - is a bio-based polymer as it is generated from a regenerative feedstock (e.g. corn). The production of plastics based on renewable materials is increasing continuously, especially in the packaging sector. [1] At the same time, the main fractions of PLA are still incinerated within end-of-life (EoL) in order to recover thermal energy. [2] One reason for the incineration of PLA from an economic perspective is that the market volumes are still negligible compared to conventional polymers in the packaging sector, like polyethylene (PE) or polypropylene (PP). This hinders the economically feasible recovery of PLA. [3] Another reason from a technical perspective is that the conventional material recycling process chain (including sorting, shredding, washing, compounding and granulating) turned out to be not fully suitable for the recovery of thermoformed PLA cups, as the produced particles after mechanical shredding hinder further processability in terms of pourability and dosability. [4] Current research about mechanical recycling of PLA focuses on the quality of the recycled material. Studies on decrease of polymer chains [5-7] were performed as well as investigations on the effect of PLA in other recycling streams e.g. Poly(ethylene terephthalate) (PET) [3]. However, no study was found on methods of improving the efficiency of recycling itself.

This study analyses the potential environmental impacts and economic costs of single-use PLA cups – being used at concerts and cultural festivities, where reusable cup systems cannot be established easily - according to status quo recycling while using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). Life Cycle Gap Analysis (LCGA) is applied within the interpretation stage of the study in order to analyse potentials for further improvement from a Circular Economy (CE) perspective.

The following *chapter 2* provides insights into the materials and assessment methods applied in this study. *Chapter 3* analyses and compares the LCA & LCC results of two different EoL scenarios using LCGA. Based on the results of *chapter 3*, a discussion and conclusion is facilitated in *chapter 4*.

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2. Methodology

LCA according to the ISO 14040 series [8] and conventional LCC [9; 10] analyses the potential environmental impacts and economic costs related to the life cycle of a product, including raw material acquisition, production, transportation, use stage and EoL.

This contribution focuses on the application of the LCGA methodology within the interpretation phase in order to identify potentials for further improvement from a CE perspective. The basic idea of the LCGA methodology is to determine a life cycle gap (LCG) which results from the difference between the environmental impacts and economic costs of a product's initial manufacturing, including raw material acquisition and production, as well as environmental credits and economic revenues after recycling. The overall aim is to close existing LCGs (improve circularity) without ignoring burden shifting from one life cycle stage to another (improve sustainability). [11; 12] The application of the LCGA methodology requires to follow six iterative (and one optional) steps [12]:

- *Step 1*: Summarize the LCA results and the LCC results of a product system according to its status quo, subdivided into the phases of raw material acquisition, production, transportation, use and EoL - while considering environmental impacts and economics costs for recycling as well as environmental credits and economic revenues stemming from reusable or recycled goods of EoL.
- *Step 2*: Compare the environmental credits and economic revenues after recycling to environmental impacts and economic costs for manufacturing, as one particular focus of CE strategies is put on closing products' material and energy flows and minimizing resource input and waste, emissions, as well as energy leakages [13]. The difference equals the LCG, which can be expressed in absolute as well as in relative terms.
- *Step 3*: Identify options to improve the circularity (reduce existing LCGs).
- *Step 4*: Assess each option's (outcome of *step 3*) ability to narrow the LCG.
- *Step 5*: Assess the environmental impacts and economic costs of the new product system across the entire life cycle.
- *Step 6*: Compare the LCA results and LCC results of the new product system (results from *step 5*) with the product system status quo (results from *step 1*), while ensuring that total life cycle impacts and total life cycle costs are not increasing (avoid negative trade-offs).
- *Step 7 (optional)*: Assess a product's eco-efficiency in an eco-efficiency diagram using the economic and environmental area integral (*FI*) depending on $f(x_1, y_1) := 1$, whereby x_1 represents the economic dimension, and y_1 the environmental dimension. A reduction of the integral area within each framework (differentiated between a life cycle (*total*) and CE (*LCG*) perspective) indicates a relative increase in eco-efficiency (%) which is equivalent to a reduction of the area of a rectangle in a two-dimensional coordinate system.

3. Life cycle (gap) analysis of a PLA cup

Starting point for the application of the LCGA methodology are the LCA and LCC results of a single-use PLA cup, presented below according to the sequence of phases and steps defined in the ISO 14040 series [8]: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, (iv) interpretation (incl. LCGA application).

3.1. Goal and scope definition

Goal of this study is to analyse the potential environmental impacts and economic costs of a single-use PLA cup, while considering two different EoL scenarios, and to identify potentials for further improvement, while applying LCGA methodology. The whole life cycle is taken into account and divided into the phases of raw material acquisition, production of the PLA cup, transportation and use (consumption) at a cultural festival, as well as EoL. The following *figure 1* illustrates the product system according to status quo.

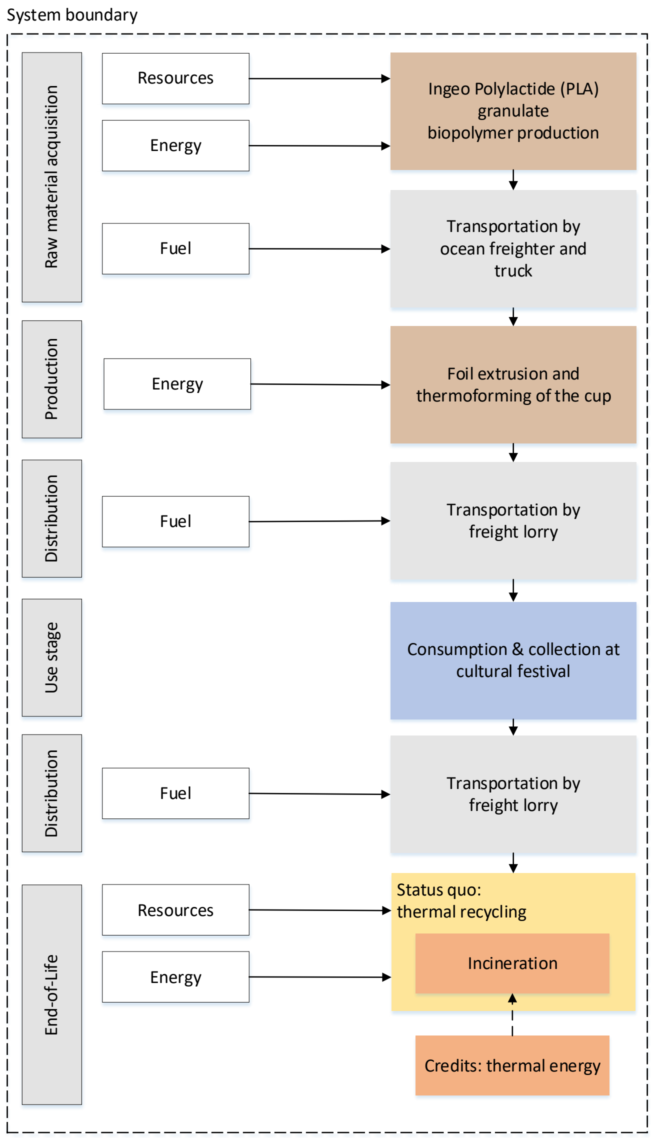

Fig. 1. Product system of a single-use PLA cup according to status quo.

The functional unit is defined as a single-use cup which has to "provide 400 ml of drinks". The environmental impact assessment focuses on climate change - global warming potential (GWP 100) in grams of carbon dioxide equivalents (g CO_2eq). The economic assessments are carried out for financial analysis of the producer and summarize all costs in EUR (€) cent associated with the life cycle of a PLA cup. All environmental impacts and economic costs are allocated to the PLA cup under study. Allocations within EoL follow the avoided burden approach and consider environmental credits and economic revenues for the recovery of secondary materials and energy depending on the quantity AND (*) quality (substitution of primary materials).

3.2. Inventory analysis

According to *figure 1*, Life Cycle Inventory (LCI) data of the initial product system (X_0) are summarized in *table 1*. Foreground data for the production were measured and calculated according to the weight of a single-use PLA cup. Data for the distribution distances were assumed based on a PLA raw material supply chain from US to Europe, as well as a transportation of the manufactured cups from gate to use to EoL.

Table 1. LCI of a single-use PLA cup (400 ml).

Flow	LCI data set GaBi professional	Amount	Unit	Additional information
Raw material: Ingeo Polylactide (PLA) granulate	US: Ingeo Polylactide (PLA) biopolymer production	10.0 *(2.0E-1)*	g *(EUR cent/g)*	Considered market price for PLA granulate [14]: 2 *EUR/kg*.
Acquisition: Transportation from US to Europe by ocean freighter and truck	US: Transport, ocean freighter, average fuel mix EU-28: Transport, truck (26 t total cap., 17.3t payload)	63,000 *(1.3E-7)* 17,000 *(3.5E-5)*	g*km *(EUR cent/ g*km)*	Assumed distances: 6,300 km by ocean freighter and 1,700 km by freight lorry; considered costs for shipping [15]: 0.0013 *EUR/t*km*; considered costs for road transport [15]: 0.348 *EUR/t*km*.
Production: Foil extrusion and thermo-forming	EU-28: Electricity grid mix (average power plants) (2020)	14.4 *(3.0E-2)*	Wh *(EUR cent/g)*	Use of 1.44 kWh/kg electricity for inline extrusion and thermoforming of plastic pellets [16]; no production losses considered; market price for electricity [17]: 0.21 *EUR/kWh*.
Distribution & use: Transportation by freight lorry from gate to use to EoL	EU-28: Lorry transport incl. fuel, Euro 0-6 mix	10,000 *(3.5E-5)*	g*km *(EUR cent/ g*km)*	Assumed distance: 1,000 km; considered costs for road transport [15]: 0.348 *EUR*tkm*.
End-of life: Thermal recycling	EU-28: Polylactic acid (PLA) in waste incineration plant	10.0 *(-3.0E-3)*	g *(EUR cent/g)*	Considered costs for incineration [18]: 170 *EUR/t*; revenues from LCI dataset: generation of 723 kWh/t electricity and 1,300 kWh/t of steam (natural gas savings 0.04 *EUR/kWh* [19]).

3.3. Impact and cost assessment

The environmental impact assessment (focusing on greenhouse gas emissions) is based on the Environmental Footprint (EF) 2.0 characterization factors within GaBi professional. The economic assessments were carried out using Microsoft Excel. The results are summarized in *table 2*.

Table 2. LCA and LCC results of a single-use PLA cup (400 ml).

Life cycle phases PLA cup (400 ml)	Environmental impacts *(g CO_2eq/cup)*	Economic costs *(EUR cent/cup)*
Raw material acquisition	27.9	2.6
Production	5.2	0.3
Distribution & use	0.8	0.3
Recycling	0.3	0.2
Credits	-6.1	-0.2
Total	*28.1*	*3.2*

Figure 2 illustrates the contribution of the different stages of the life cycle to the global warming potential of a single-use PLA cup according to status quo recycling.

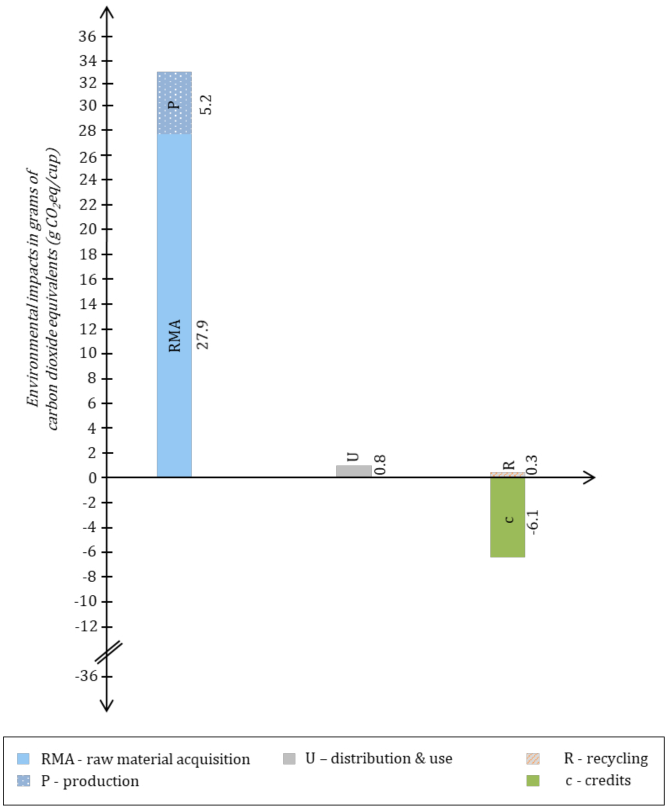

Fig. 2. LCA results of a single-use PLA cup according to status quo recycling.

The results show that 33.1 gCO_2eq and 2.9 EUR Cent arise from the manufacturing, 0.8 gCO_2eq and 0.3 EUR Cent from the distribution and use stage, as well as -5.8 gCO_2eq and plus minus null EUR Cent/cup (about -0.03 EUR Cent) from the EoL of a single-use PLA cup.

3.4. Interpretation using LCGA methodology

A detailed view on the overall results (see *table 2,* and also *figure 2* for the environmental impacts) illustrates that the manufacturing phase is the main driver with a share of higher than 80 % of the total impacts and costs and serves as the starting point for the application of the LCGA methodology (see *chapter 2*, *step 1*). According to *step 2* of the LCGA approach, it is now possible to determine the environmental LCG (I_{LCG}) (1) and economic LCG (C_{LCG}) (2) of the initial product system (X_0) and therefore the potential for further improvement from a CE perspective. The environmental credits and economic revenues after recycling are compared to the environmental impacts and economic costs for manufacturing. The difference equals the LCG.

$$I_{LCG}(X_0) = 27.9\ g\ CO_2eq + 5.2\ g\ CO_2eq - 6.1\ g\ CO_2eq = 27.0\ g\ CO_2eq \quad (1)$$

$$C_{LCG}(X_0) = 2.6\ EUR\ cent + 0.3\ EUR\ cent - 0.2\ EUR\ cent = 2.7\ EUR\ cent \quad (2)$$

Figure 3 illustrates the environmental LCG of a PLA cup according to status quo.

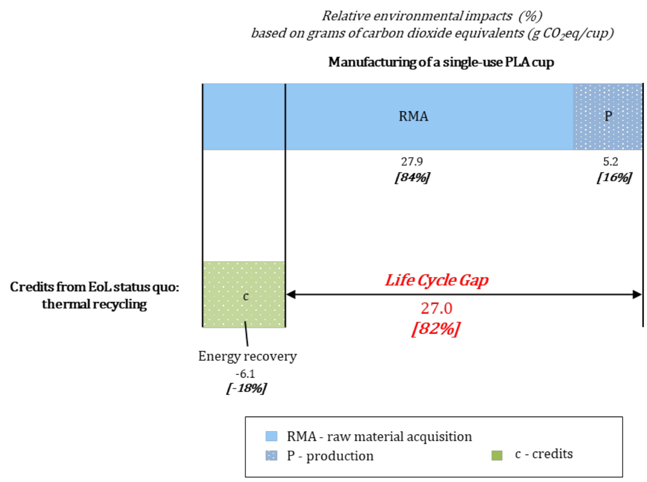

Fig. 3. LCG of a PLA cup according to status quo.

The results for the PLA cup show, despite the consideration of credits for energy recovery after incineration, a LCG of 82 % from an environmental perspective (see *figure 3*) and 93 % from an economic perspective, which underlines a significant potential for further improvement from a CE perspective.

Step 3 therefore focuses on a newly developed material recycling pathway [4] for the single-use PLA cup in order to recover secondary PLA (rPLA) granulate. *Figure 4* visualizes the modified product system. In comparison to common mechanical recycling chain for post-consumer waste, the newly developed EoL pathway was reorganized to washing, thermal treatment, shredding and compounding with granulating, which has certain advantages from an engineering perspective. A thermal treatment step before shredding does not only change the volume of the cups (reduced, in form of a disc), but also the anisotrophic properties to an isotrophic breakage behaviour. The obtained flakes have increased processability in the further process chain (improved pourability) and the overall energy efficiency of the recycling process has increased by 11 %, from 12.25 Wh/cup to 10.90 Wh/cup in comparison to common mechanical recycling chain (see *table 3*).

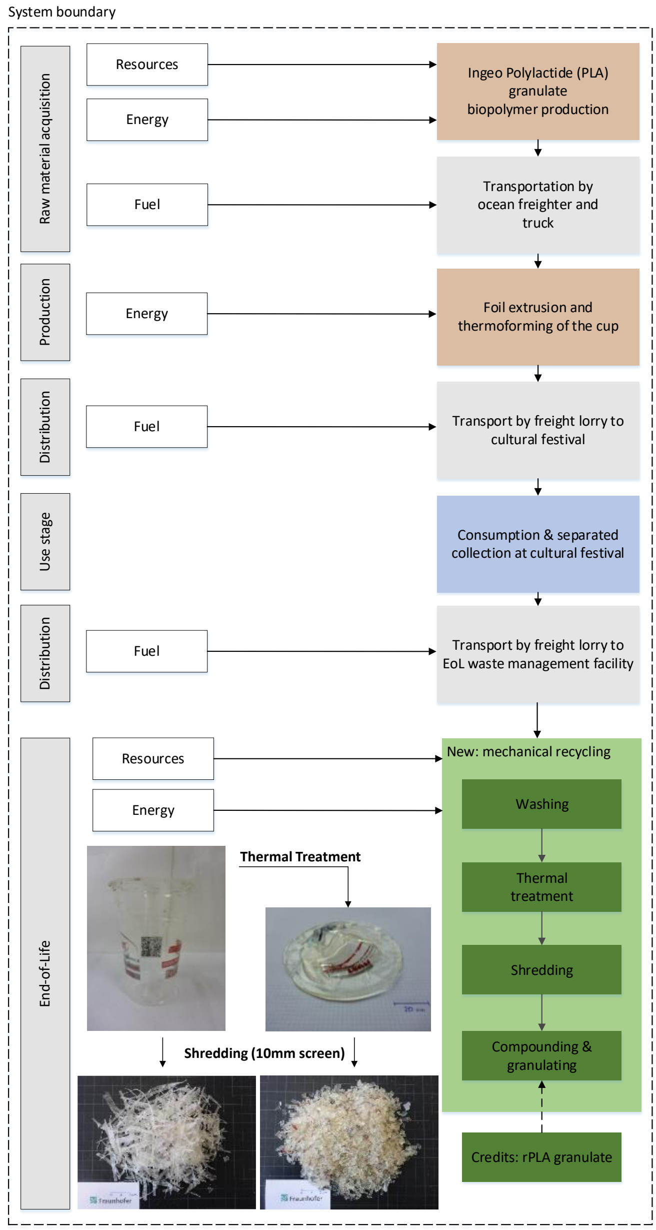

Fig. 4. Product system of a single-use PLA cup according to the newly developed EoL pathway.

Table 3. Energy demand* [4] for material recycling of a PLA cup (400 ml).

Processing steps	Without thermal treatment (*Wh/cup*)	With thermal treatment (*Wh/cup*)	Additional information
Washing	0.40	0.40	Use of 2 ml water** and 0.04 g detergent*** [4]
Thermal treatment	-	1.17	Considering a rPLA granulate recovery rate of 95% and 5 % mass losses during shredding (dust as mixed fraction incinerated; LCI data set see *table 1*).
Shredding	2.96	0.65	
Compounding & granulating	8.89	8.68	
total	*12.25*	*10.90*	

LCI data set GaBi professional; economic market prices:

* EU-28: Electricity grid mix; market price [17]: 0.21 *EUR/kWh*.

** EU-28: Process water from ground; market price [20]: 3.70 *EUR/t*.

*** EU-28: Sodium hydroxide mix; market price [21]: 5.00 *EUR/kg*.

Step 4: The new material recycling pathway with a rPLA granulate recovery rate of 95 % results in a reduction of the environmental LCG from $I_{LCG}(X_0) = 27.0$ g CO_2eq to $I_{LCG}(X_{NEW}) = 6.3$ g CO_2eq (3) (see *figure 5*), as the environmental credits increase from -6.1 g CO_2eq to -26.8 g CO_2eq, and in a reduction of the economic LCG from $C_{LCG}(X_0) = 2.7$ EUR cent to $C_{LCG}(X_{NEW}) = 0.4$ EUR cent (4), as the revenues increase from -0.2 EUR cent to -2.5 EUR cent.

$$I_{LCG}(X_{NEW}) = 27.9\ g\ CO_2eq + 5.2\ g\ CO_2eq - 26.8\ g\ CO_2eq = 6.3\ g\ CO_2eq \quad (3)$$

$$C_{LCG}(X_{NEW}) = 2.6\ EUR\ cent + 0.3\ EUR\ cent - 2.5\ EUR\ cent = 0.4\ EUR\ cent \quad (4)$$

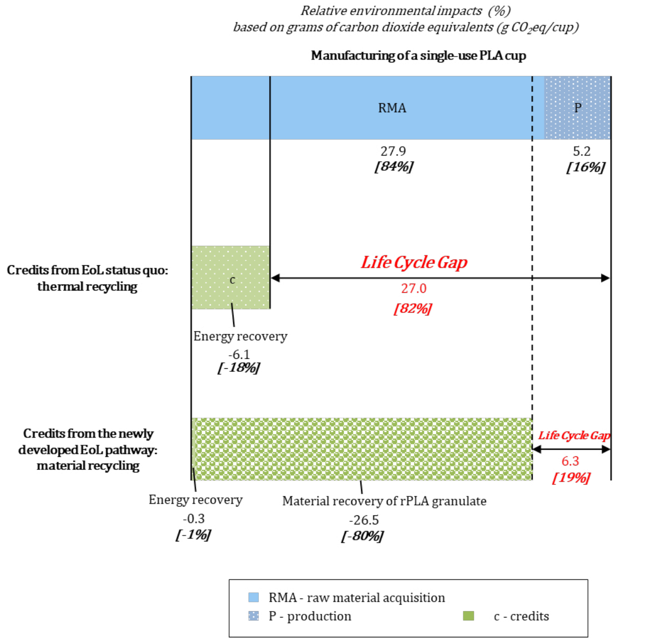

Fig. 5. LCG according to the newly developed EoL pathway for a PLA cup.

Step 5: Based on the demand of energy, water and detergent within material recycling (see *table 3*), environmental impacts and economic costs of the total balance change. The total life cycle impacts and life cycle costs of the new product system X_{NEW} are summarized in *table 4*.

Table 4. LCA and LCC results of a single-use PLA cup (400 ml) according to the newly developed EoL pathway.

Life cycle phases PLA cup (400 ml)	Environmental impacts (*g* CO_2*eq/cup*)	Economic costs (*EUR cent/cup*)
Raw material acquisition	27.9	2.6
Production	5.2	0.3
Distribution & use	0.8	0.3
Recycling	4.0	0.2
Credits	-26.8	-2.5
Total	*11.1*	*1.0*

A comparison of the overall results within *step 6* demonstrates that the defined restriction of the methodology is fulfilled, which ensures a net reduction of overall environmental impacts **AND** economic costs of the new mechanical recycling pathway (5), and hence an effective contribution towards sustainable development.

$$11.1\ g\ CO_2eq \leq 28.1\ g\ CO_2eq \ \land\ 1.0\ EUR\ cent \leq 3.2\ EUR\ cent \quad (5)$$

According to *step 7*, the eco-efficiency of the single-use PLA cup - considering the new material recycling pathway - is then:

- Life cycle framework

$$FI\ (total_0) = \int_0^{28.1\ g\ CO_2eq} \int_0^{3.2\ EUR\ cent} f(x_1, y_1)\, dx_1\, dy_1 = 89.9\ g\ CO_2eq * EUR\ cent$$

$$FI\ (total_{NEW}) = \int_0^{11.1\ g\ CO_2eq} \int_0^{1.0\ EUR\ cent} f(x_1, y_1)\, dx_1\, dy_1 = 11.1\ g\ CO_2eq * EUR\ cent \quad (6)$$

- CE framework

$$FI\ (LCG_0) = \int_0^{27.0\ g\ CO_2eq} \int_0^{2.7\ EUR\ cent} f(x_1, y_1)\, dx_1\, dy_1 = 72.9\ g\ CO_2eq * EUR\ cent$$

$$FI\ (LCG_{NEW}) = \int_0^{6.3\ g\ CO_2eq} \int_0^{0.4\ EUR\ cent} f(x_1, y_1)\, dx_1\, dy_1 = 2.5\ g\ CO_2eq * EUR\ cent \quad (7)$$

Figure 6 visualizes the economic and environmental results in the LCGA eco-efficiency diagram [12]. The green dotted area represents the increase in eco-efficiency (relative reduction of the area of each rectangle), while the remaining area (red) represents the potential for further improvement of the PLA cup from a life cycle and CE perspective.

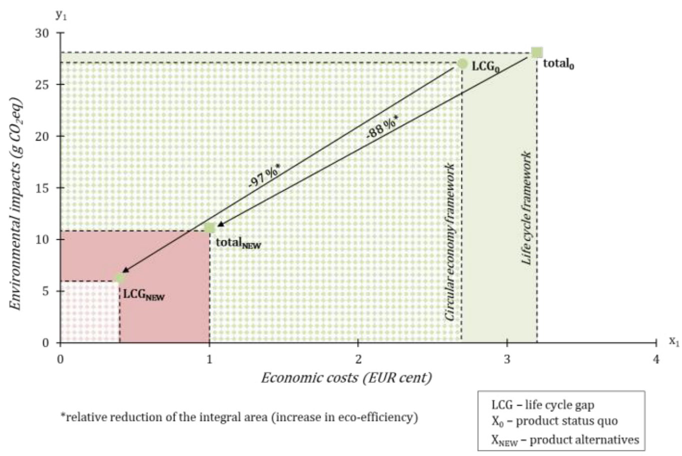

Fig. 6. Eco-efficiency of the PLA cup from a life cycle and CE perspective before and after optimization.

The results show that a reduction of impacts and costs within the (total) life cycle framework leads to a relative increase in the eco-efficiency of around 88 % - from $FI\ (total_0) = 89.9$ g CO_2eq*EUR cent to $FI\ (total_{NEW}) = 11.1$ g CO_2eq*EUR cent; and within the CE framework to a relative increase of 97 % - from $FI\ (LCG_0) = 72.9$ g CO_2eq*EUR cent to $FI\ (LCG_{NEW}) = 2.5$ g CO_2eq*EUR cent.

4. Discussion & Conclusion

This study analysed the potential environmental impacts and economic costs of a PLA cup using LCA and LCC and applied LCGA within interpretation stage. In comparison to common interpretation of the life cycle results (see for example *figure 2*), where (only) the manufacturing phase would be identified as a hot spot for single-use PLA cups, LCGA highlighted LCGs of > 82 % and hence significant potentials for further improvement from a CE perspective. The environmental and economic results of the newly developed mechanical recycling pathway show a positive contribution towards CE and sustainability, as LCGs were reduced by > 60 % and the eco-efficiency increased by > 88 %. Another finding from the assessment is that even after realizing the advanced material recycling system, there is still a potential for further improvement (see environmental LCG_{NEW} with 19 % in *figure 5* as well as red areas in *figure 6*). One key recommendation is hence to analyse barriers and challenges for introducing reuse systems of cups at concerts and festivals, including a comparison of life cycle impacts and costs with single-use cups in each specific case.

From an engineering point of view, the presented improvement within the mechanical recycling chain for post-consumer waste demonstrates how the molecular structure of a polymer is optimized before shredding. As this is achieved through an additional thermal treatment step, this technique could be tested on other thermoplastic polymers. Any thin-walled component in which a more orientated molecular structure is created during the forming process in production, like for example PET bottles, could undergo a thermal treatment step before shredding in order to achieve higher efficiency and to further reduce LCGs.

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