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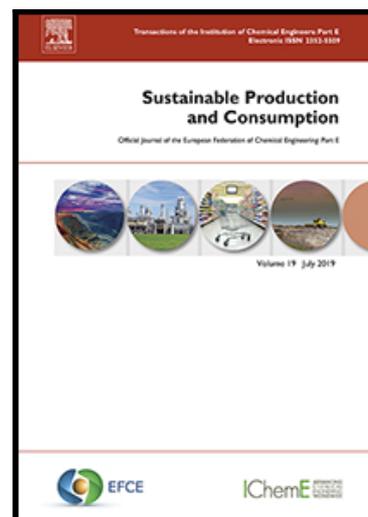
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# Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups

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## ABSTRACT

The Circular Economy introduced new research challenges to be faced. Linear and circular supply chain comparisons require general methodologies to obtain significant and scalable results. A two-step methodology is here proposed to facilitate the interpretation of results during a Life Cycle Assessment (LCA). Firstly, an LCA analysis has been conducted on four single-use - Polypropylene (PP), Polylactic acid (PLA), Polyethylene terephthalate (PET), and Cardboard+Polyethylene coat - and reusable - PP, PLA, PET, and glass - cups. Secondly, the analyzed midpoint impact categories have been aggregated into the three main life cycle phases: production, use and EoL. Then, they have been used to assess the environmental break-even point (BEP), i.e. the minimum number of uses necessary for a reusable cup to be preferable than a single-use cup, considering two End of Life (energy recovery, and recycling) and three use phase strategies (onsite handwashing, onsite and offsite washing). Considering offsite washing - transport distance of 20km and industrial washing machines - and energy recovery, findings highlight that reusable plastic cups reach a break-even point for climate change and non-renewable energy use for  $n < 150$ , while single-use PP cups are the best option in terms of acidification, eutrophication, and water scarcity indicator. With respect to PP single-use cups, for acidification, eutrophication, and water scarcity indicator, a BEP cannot be achieved, even in the case of infinite reuses. Results evidenced all the conditions for reaching a BEP, allowing to identify possible strategies to improve the efficiency of reusable products and to obtain an environmental benefit.

## 1. Introduction

1           Plastics are lightweight, durable, and cheap materials.  
2           Since the '60s, plastics, gradually substituting other  
3           materials such as wood, metal, and glass, have become  
4           the ubiquitous materials of the modern economy (Ellen MacArthur  
5           Foundation and World Economic Forum, 2016) due to their chemical  
6           properties and their low cost. Plastics production is regularly  
7           growing and, nowadays, global production reached 359 Mt in 2018  
8           and an industry turnover

12           of 355 billion euros in 2017 in Europe (Plastics Europe, 2019).  
13           On the other hand, plastic waste causes impactful consequences  
14           in the environment (Jiang, 2018), in terms of degradation of natural  
15           systems (Ryberg et al., 2019; Jambeck et al., 2015), a large  
16           quantity of greenhouse gas emissions, fossil feedstock depletion  
17           (Hopewell et al., 2009), and toxic additives circulation (Swan et al.,  
18           2015; Lien et al., 2015; Winton et al., 2020). The plastic issue  
19           has captured the attention of the public and private sectors around  
20           the world (European Commission, 2015; European Parliament, 2019;  
21           Ellen MacArthur Foundation, 2019). The industry is showing its  
22           inclination to gradually move away from today's linear  
23           

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26 take-make-dispose model (Ellen MacArthur Founda-  
 27 tion, 2016), by adopting innovative circular busi-  
 28 ness models. So, waste is designed out from the  
 29 linear model and resources are circulated back to  
 30 the soil (compostable plastic) (Razza et al., 2009),  
 31 to the producers (recycled plastic) (Accorsi et al.,  
 32 2020), or to the consumers (reusable plastic) (Chang-  
 33 wichan and Gheewala, 2020).

34 Today the efforts towards the increase of recy-  
 35 cling practices are remarkable, but still not suffi-  
 36 cient. The plastic packaging recycling rate in the  
 37 European Union cannot be considered satisfactory  
 38 at all, with an average percentage of 41% in EU  
 39 28+2 and a target for plastic packaging recycling of  
 40 50% by 2025 (Plastics Europe, 2018). At legislative  
 41 level, there is still a gap in terms of rules promoting  
 42 good practices of recycling. Some of them have al-  
 43 ready been identified by previous research (Mariotti  
 44 et al., 2019): taxes on the use of virgin plastics or  
 45 differentiated value-added taxes for recycled plas-  
 46 tics, the introduction of recycled content standards,  
 47 targeted public procurement requirements, or recy-  
 48 cled content labeling, just to name a few.

49 An increasing number of countries are taking  
 50 measures to reduce single-use plastic dispersion into  
 51 the natural environment and, in 2019, the European  
 52 Parliament approved the Directive 2019/904 on the  
 53 “reduction of the impact of certain plastics products  
 54 on the environment” to promote circular (European  
 55 Parliament, 2019). Cups are one of these. Despite  
 56 new recycling policies, promoting reuse remains the  
 57 main effective solution to reduce the accumulation  
 58 of plastic waste. In fact, to ensure reusability, the  
 59 first step is to encourage the deposit return systems  
 60 (Cottafava et al., 2019). Several European Union  
 61 (EU) countries already adopted national legislations  
 62 to increase the use of reusable plastic with deposit  
 63 return systems (CM Consulting Inc and Reloop Plat-  
 64 form, 2016). Although reusable products can suc-  
 65 cessfully limit the use of virgin materials and can  
 66 have a positive effect on the material extraction/produc-  
 67 tion, the impact could not be always positive by consid-  
 68 ering various environmental indicators. For instance,  
 69 two recent studies on supermarket (Edwards and Fry,  
 70 2011) and grocery (Bisinella et al., 2018) carriers  
 71 bags revealed how reusable cotton bags should be  
 72 used thousands of times, i.e. dozens years of inter-  
 73 sive use, to be environmentally better than equiv-  
 74 alent single-use bags, which is clearly an unrealis-

tic scenario. An effective approach for an objective  
 evaluation of these indicators is given by the use of  
 the Life Cycle Assessment (LCA) methodology.

LCA is one of the most adopted techniques to  
 evaluate the environmental impacts of products and  
 processes (Sonnemann et al., 2018). Several stud-  
 ies have evaluated the environmental effects arising  
 from the reuse of plastic products, by comparing the  
 same service offered by single-use products (Gar-  
 rido and Del Castillo, 2007; Almeida et al., 2018;  
 Tua et al., 2019; Paspaldzhiev et al., 2018). How-  
 ever, what emerges from each LCA analysis is a  
 snapshot of a precise situation, generally hard to be  
 generalized (Ekvall et al., 2007; Finnveden, 2000),  
 with specific boundary conditions, End of Life (EoL)  
 scenarios, or functional units. Indeed, nowadays,  
 an open debate within the Circular Economy (CE)  
 framework is emerging on how to model multi-cycle  
 circular processes, including reuse, repair, refurbish,  
 or remanufacturing (Amasawa et al., 2020).

Dealing with different kinds of electrical and elec-  
 tronic products, Ardente et al. (2018) highlighted  
 the importance to consider all the operations needed  
 to prepare an item for the reuse phase. Indeed, a  
 product, before being reused, could require minor  
 interventions, that influences the assessment of the  
 environmental impact. A similar study (Boldoczki  
 et al., 2020) came to the conclusion that reuse is  
 not always preferable to recycling. From an envi-  
 ronmental point of view, if the impacts arising dur-  
 ing a certain usage duration of a reused product are  
 smaller than those of a new product, reuse is better  
 than recycling. But this is not always the case: for  
 instance, the global warming potential, cumulative  
 energy demand, and water consumption impact cat-  
 egories, in the case of electric and electronic equip-  
 ments, mainly derive from the use phase. In the  
 same way, Simon et al. (2001), considering washing  
 machines, attributed 90% of the environmental im-  
 pacts to the use phase. In fact, the lifetime extension  
 to the repairing / remanufacturing / refurbishing  
 is not always the best option, especially for energy-  
 demanding products (Ardente and Mathieux, 2014).  
 Moreover, more durable products may imply higher  
 quality and amount of materials and, thus, a higher  
 environmental impact during the production phase  
 (Okumura et al., 2001). From the existing literature,  
 it is straightforward that there is no single choice  
 which is overall preferable in terms of single-use

124 versus reusable products. To point out such consid-  
 125 erations, in case of reuse, repair, remanufacturing,  
 126 refurbishing, several researchers proposed various  
 127 models to identify an environmental break-even point  
 128 (BEP) - i.e. the minimum no. of reuses after which  
 129 a reusable product is environmentally better than  
 130 the single-use equivalent one (Barletta et al., 2018).  
 131 For instance, Bobba et al. (2016) proposed a set of  
 132 environmental and economic indicators to evaluate  
 133 product durability, starting from the indicator pro-  
 134 posed by Ardente and Mathieux (2014), which takes  
 135 into account lifetime, energy consumptions, impacts  
 136 of lifetime extension and of the replacement prod-  
 137 uct. Boldoczki et al. (2020), instead, proposed a  
 138 simple linear model to compare the reuse of devices  
 139 with the purchase of new ones, by evaluating the en-  
 140 vironmental impact versus the usage duration (time).  
 141 With respect to plastics products, similar analyses  
 142 have been carried out by Almeida et al. (2018), who  
 143 compared a commercial reusable coffee cup with  
 144 single-use cups, with the aim of identifying the en-  
 145 vironmental BEP. From the relevant literature, a stan-  
 146 dard methodology does not exist yet and, thus, the  
 147 debate about robust formalisms to model multi-cycle  
 148 closed-loop processes is still open.

149 To face up this issue related to environmental  
 150 assessment through LCA, in this paper a novel method-  
 151 ology for the interpretation of results is proposed,  
 152 in order to facilitate comparisons between single-  
 153 use and reusable products. To easily identify the  
 154 environmental BEP, the product efficiency - the ef-  
 155 ficiency of the production and End of Life (EoL)  
 156 phases - and the use efficiency have been introduced.  
 157 The suggested formalism allows to decouple, in the  
 158 BEP assessment, the effect of the use from the pro-  
 159 duction and the EoL. This methodology has been  
 160 applied to a case study, comparing four single-use  
 161 cups with four reusable cups, by analyzing seven  
 162 impact categories in three different use phase sce-  
 163 narios and two EoL scenarios.

164 The following of the paper is structured as fol-  
 165 lows. In section 2, the novel methodology is de-  
 166 scribed by highlighting the differences with a tradi-  
 167 tional LCA analysis. In Section 3, the comparison  
 168 between reusable and single-use cups is discussed  
 169 in terms of the environmental break-even point. In  
 170 Section 4, main results are compared with previous  
 171 findings in the literature and some limitations of the  
 172 proposed methodology are pointed out. Finally, in

Section 5, main results are summarized.

## 2. Methodology

The adopted methodology consists of two steps to further advance the well-consolidated LCA analyses and to support the results' interpretation for multi-cycle closed-loop processes where reuse, repair, refurbish, or remanufacturing are introduced. The first step consists of a traditional LCA analysis. The aim of the second step is to aggregate single impacts into the three main life phases (production, use, EoL) and to analyze, in terms of the no. of uses "n", the environmental BEPs for each analyzed impact category.

### 2.1. Case Study

The suggested methodology has been tested on a case study related to reusable and single-use plastic cups. The relevance of the case study was provided by analyzing the most common materials used, within the European Union, for single-use and reusable plastic cups. Four single-use cups, different materials, i.e. Polypropylene (PP), Polylactic acid (PLA), Polyethylene terephthalate (PET), and Cardboard + Polyethylene (PE) coat, have been compared with four reusable cups, i.e. PP, PLA, PET, and glass.

Seven relevant midpoint impact categories - Climate Change (CC), Ozone Depletion (OD), Acidification (A), Photochemical Oxidant Creation (POC), Eutrophication (E), Non-Renewable Energy Use (NREU), and Water Scarcity Indicator (WSI) - have been considered. Among the many possibilities of impact categories, as reported in the Technical Report by the Joint Research Center (JRC) (Fazio et al., 2018), CC and OD are recommended and considered satisfactory; A, E, and POC are also recommended, although they are not yet considered fully mature and satisfactory. In fact, more precise and in-depth studies are still needed to evaluate the weight of all characterization factors. As the studied system here presents a direct consumption of chemicals, water and energy both in the use phase and in the cups production, despite the lower reliability of the results, it was considered appropriate to measure the impacts also relating to the WSI and NREU categories.

For a comprehensive comparison between the service offered by disposable cups and reusable cups,

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220 different scenarios related to the use phase and EoL  
 221 have been analyzed. Figure 1 shows a detailed scheme  
 222 of the system life cycle, highlighting the considered  
 223 scenarios. In particular, four scenarios for the use  
 224 phase - 0) single-use without loop (baseline), 1) on-  
 225 site washing, 2) offsite washing, and 3) onsite hand-  
 226 washing have been considered

227 The baseline 0) case consists of using the cup  
 228 once and then throwing it for disposal. The use  
 229 phases have been modeled according to Martin et al.  
 230 (2018) for 1) onsite handwashing, and 3) onsite wash-  
 231 ing with commercial washing machines. The onsite  
 232 washing is modeled for the real situation, when the  
 233 bars/pubs/restaurants directly wash the cups. The 2)  
 234 offsite washing refers to the use of industrial wash-  
 235 ing machines (primary data) and an increasing trans-  
 236 port distance. It models real situations, such as tem-  
 237 porary events, small bars without washing machines,  
 238 or catering for buffets during events.

239 Finally, with respect to the EoL phase, energy  
 240 recovery and recycling/composting have been com-  
 241 pared. Landfill scenario has been discarded as a  
 242 possible scenario, according to the Circular Eco-  
 243 nomy European Directive (European Parliament, 2020).  
 244 So, two scenarios have been considered: 1) 100%  
 245 energy recovery, and 2) full recycling or, in the case  
 246 of PLA cups, composting.

## 2.2. Life Cycle Assessment

247 LCA is defined by the International Organiza-  
 248 tion for Standardization (ISO) standards 14040 and  
 249 14044. According to ISO, the LCA methodology  
 250 consists of four conceptual phases: goal and scope  
 251 definition, life cycle inventory (LCI), life cycle im-  
 252 pact assessment (LCIA), and results' interpretation  
 253 (International Organization for Standardization, 2006).  
 254 The entire work was conducted with software SimaPro  
 255 8 and using the Ecoinvent v.3.3 database.

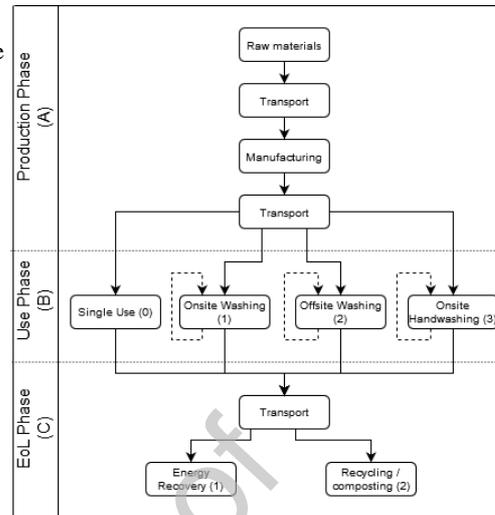


Figure 1: Overview of the analyzed scenarios.

### 2.2.1. Goal and scope definition

256 The aim of this work is to assess the environ-  
 257 mental BEP of deposit back systems for cups, by  
 258 identifying the minimum number of uses a reusable  
 259 cup needs in order to be considered preferable than  
 260 a single-use cup. To achieve this goal, the LCA  
 261 analysis was applied to the case of disposable and  
 262 reusable cups in order to identify the main environ-  
 263 mental impacts. These were later used to determine  
 264 the break-even point between the two service deliv-  
 265 ery strategies.

266 The chosen functional unit was serving 0.4 liters  
 267 of  
 268 draught beverages in one go, which allows to collect  
 269 the data relating to the service in a single supply.  
 270 These data constitute the starting point for model-  
 271 ing and studying the function of serving beverages  
 272 repeated  $n$  times over time (function performed by  
 273 disposable and reusable cups). The system bound-  
 274 ary has been defined considering the whole life cycle  
 275 from the extraction of raw materials up to the  
 276 EoL phase, as shown in Figure 1.

### 2.2.2. Life cycle inventory.

277 The weights of the cups considered in the study  
 278 are summarized in Table 1. Weight of the single-  
 279 use and reusable plastic cups, as well as of the glass  
 280 reusable cups and single-use PE-coated cardboard

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284 cups, has been calculated as an average of available  
285 commercial products in Europe. 324

	Reusable cup [gr]				Single-use cup [gr]				Card
	PP	PLA	PET	Glass	PP	PLA	PET	Card	
Min	35	150	60	330	6	7.5	8	7.5	
Avg	40	175	70	360	7	8.5	9	8.5	
Max	45	200	80	390	8	9.5	10	9.5	

**Table 1**  
331 Minimum, maximum, and average weight of the ana-  
332 lyzed single-use and reusable cups. 333

286 The sources from which all inventory values were  
287 derived or measured are indicated in Table 1 in sec-  
288 tion B of the Supplementary Information (SI). Input-  
289 output data for the production, use and the EoL phases,  
290 are specified in Tables 2, 3, 4, 5, and 6 in sections B  
291 of the SI. 340

292 The production of the plastic cups was modeled  
293 using the thermoforming and injection moulding pro-  
294 cesses for single use and reusable respectively (Craw-  
295 ford and Martin, 2020; Changwichan and Gheewala,  
296 2020). Given the lack of specific data related to the  
297 production of PET cups, the system was modeled  
298 in a similar way to PP cups, taking into account the  
299 different physical-chemical properties of the poly-  
300 meric materials. 348

301 The input data for the packaging refer to reusable  
302 cups. As no specific data were obtained for the dis-  
303 posable cups, the system was left unchanged in the  
304 two cases. 352

305 To simplify the study and not to add variables  
306 that are not directly measurable, a distance of 100  
307 km was assumed for the transport of raw materials  
308 to the production site of the cups. For the same rea-  
309 son, a distance of 1000 km between cup producer  
310 and place of use was considered. The latter is the  
311 average distance that allows covering the transport  
312 within single countries and between neighboring states  
313 in a territory such as Europe. Both transports have  
314 been modeled assuming a road service that uses freight  
315 lorries of 16-32 tons. Instead, the transport in the  
316 use phase (Table 4 in section B of the SI), used in  
317 the offsite washing scenario, takes place with a light  
318 commercial vehicle.

319 The use phase has been modeled with reference  
320 to three different types of washing for reusable cups:  
321 hand washing, dishwasher, and industrial washing  
322 (offsite). The data used to model hand washing and

dishwasher were obtained from Martin et al. (2018);  
the usage data of water, detergents, and energy were  
reported. The data for modeling an industrial wash-  
ing were directly measured in an Italian crockery  
washing company. In the case of industrial washing,  
the contribution of round-trip transport was also con-  
sidered.

The EoL scenario of incineration has been mod-  
eled for the cups in PP, PLA, PET, and cardboard+PE;  
as process output, the production of an amount of  
energy, specific for each material, was assumed. The  
alternative EoL's scenario considers the recycling  
of PP, PET, glass; to model the recycling process,  
the avoided production of a specific amount of raw  
materials, according to the percentages reported in  
the literature was taken in account, i.e. 85% of recy-  
cled polymer for PP and PET (Franklin Associates,  
2018) and 89% of recycled material for glass (Gaines  
and Mintz, 1994). PLA is not recycled, but it can be  
composted according to Vercalsteren et al. (2007).

### 2.2.3. Life cycle impact assessment

In this study, the environmental impacts are ex-  
pressed as midpoint results and the considered im-  
pact categories are CC, OD, A, POC, E, NREU, and  
WSI.

The results of the first five impact categories were  
obtained using the EPD 2018 method (Environdec,  
2019). In order to calculate the impacts, it refers di-  
rectly to the CML-IA baseline method (for E, CC,  
OD) and CML-IA non-baseline method (for A). The  
EPD method was selected because of units of im-  
pact categories. In fact, for some raw materials (PP,  
PLA, PET, PE), the environmental impacts are usu-  
ally obtained by the respective eco-profiles published  
in the literature, whereas eco-profiles calculated with  
the EPD method can be used directly. The results  
relative to the NREU impact category were obtained  
with the Cumulative Energy Demand (CED) method,  
which accounts for gross energy requirements (Frischknecht  
et al., 2007). For the WSI assessment, the Pfister  
et al. (2009) method has been adopted. This method  
allows to obtain geographically representative and  
accurate results.

### 2.2.4. Results' interpretation

For the last phase, interpretation of the results,  
an assessment based on the environmental BEP has  
been conducted, as described in the next subsection.

In particular, the proposed approach supports the interpretation of results phase of LCA analyses. The introduction of the environmental BEP, the product efficiency and the use phase efficiency, as it will be described in next subsection, allows to decouple the effects of a change in the production phase (it affects only “when” the BEP is achieved) or in the use phase (it affects “if” the BEP is reached) by facilitating the comparison among reusable and single-use products.

### 2.3. Break-even point assessment

To evaluate the BEP, according to Figure 1, let us define:

1.  $A$  = production,  $B$  = use, and  $C$  = EoL phase impact;
2.  $X$  = single-use, and  $Y$  = reusable product life cycle impact;
3. the subscripts 0, 1, 2, 3 refer to the different scenarios;
4. the subscripts also highlight the product material.

With this notation, for instance,  $B_{PLA,Y_1}$  is the impact of the use phase for the reusable PLA cup for onsite washing. The subscript 0, for the use phase, represents the baseline, i.e. the use phase for the reusable product without loop.

Thus, the environmental impact of the whole cycle is denoted in general, skipping, for now, the materials' subscripts and considering only the baseline scenario without closed-loop (0), as  $X$ , for a single-use product, and  $Y_0$ , for a reusable product without loop. Thus,  $X$  and  $Y_0$  are equal to:

$$X = A_X + B_X + C_X \quad (1)$$

$$Y_0 = A_Y + B_{Y_0} + C_Y \quad (2)$$

The use phase impact for the baseline, i.e. the life cycle without loop, has been considered equal to zero ( $B_X, B_{Y_0} = 0$ ). According to this notation, three Key Performance Indices (KPIs) for a reusable product can be defined, as described in the following.

#### 2.3.1. Product efficiency

The *environmental product efficiency for reusable products* KPI is defined as:

$$\eta_p = \frac{Y_0}{X} \quad (3)$$

$\eta_p$  is, in other words, the no. of single-use products which impacts as much as the reusable product and it represents the efficiency of the production and EoL process of the reusable product, with respect to a reference single-use product life cycle impact. Indeed, according to Okumura et al. (2001), a more durable product, such as a reusable one, implies a larger amount of materials and, thus  $\eta_p > 1$ . The larger is  $\eta_p$ , the less efficient is the reusable product related to the single-use one. If,  $\eta_p < 1$ , instead, it implies that the reusable product impacts less than the single-use product and it represents a very efficient production and EoL process.

#### 2.3.2. Use phase efficiency

The *environmental use phase efficiency for reusable product* KPI is defined as:

$$\eta_{u,j} = \frac{B_{Y_j}}{X} \quad (4)$$

where  $B_{Y_j}$  is the impact of the use phase for the reusable product for the use scenario  $j$ .  $\eta_{u,j} > 1$  means that the use phase for the reusable product  $B_{Y_j}$  impacts more than the whole life cycle of the single-use product  $X$ ; thus,  $\eta_{u,j} > 1$  represents an inefficient use phase. On the contrary, if  $\eta_{u,j} < 1$ , the use phase impact for the reusable product is lower than the single-use product life cycle and the smaller is  $\eta_{u,j}$ , the more efficient is the reusable product use phase with respect to the single-use product life cycle.

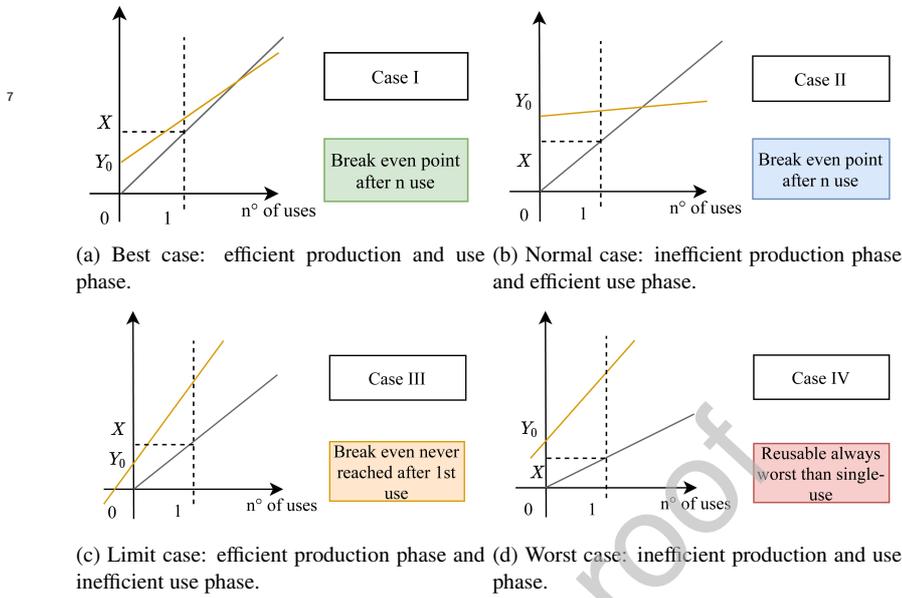
#### 2.3.3. Environmental break-even point

The *environmental break-even point* KPI is calculated as:

$$n_j = \frac{Y_0}{X - B_{Y_j}} \quad (5)$$

where  $n_j$  is properly the environmental BEP for the reusable product, considering the reuse loop scenario  $j$ .  $n_j$  represents the minimum no. of reuses necessary to balance the impact of the reusable product with respect to the same no. of single-use product usages. The proof and rationale of Eq. 5 is explained in section A.1 of the SI.

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**Figure 2:** Environmental break-even point representation of the four possible cases comparing reusable and single-use products. The y-axis represents the related midpoint impact category. Gray lines refer to the single-use product, while yellow ones to the reusable product. Horizontal dashed lines show the impact  $X$  related to the whole life cycle of one single-use product, while the vertical ones refer to one use, i.e.  $n = 1$ .

448 By substituting Eq. 3 and 4 into Eq. 5, the environmental  
 449 environmental BEP can be expressed in terms of the  
 450 product efficiency  $\eta_p$  and the use efficiency  $\eta_{u,j}$   
 451 according to:

$$n_j = \frac{\eta_p}{1 - \eta_{u,j}} \quad (6)$$

452 From equation 5, two cases emerge. If  $X > B_{Y_j}$   
 453  $B_{Y_j} \Rightarrow n_j > 0$ ; thus,  $n_j$  represents the minimum  
 454 no. of reuses in order to obtain an environmental  
 455 benefit for the reusable product with respect to the  
 456 single-use. Otherwise, if  $X < B_{Y_j} \Rightarrow n_j < 0$ ; thus,  
 457 the reusable product does never reach an environ-  
 458 mental BEP, since a negative number of usages is  
 459 not possible.

460 **2.3.4. Mapping cases**

461 From Eq. 3, Eq. 4 and Eq. 5 (or Eq. 6) four  
 462 possible cases may be identified which explain the  
 463 behavior of the reusable with respect to the single-  
 464 use product life cycle impacts. Figure 2 shows the

four possible cases to compare reusable vs single-  
 use products. The representation in Fig. 2 describes  
 the environmental impact as function of the number  
 of uses  $n$ . The slope of the straight line for the  
 single-use product is given by  $X$ , while for the reusable  
 product it is given by  $B_{Y_j}$ . With this formalism,  
 the single-use line passes from the origin while the  
 reusable line crosses the y-axis at  $Y_0$ , and if  $X =$   
 $B_{Y_j}$ ,  $n_j$  tends to infinite, as the two straight lines are  
 parallel.

Cases	Environmental break-even point	Product efficiency	Use phase efficiency
Case I	$n_j > 0$	$0 < \eta_p < 1$	$0 < \eta_u < 1$
Case II	$n_j > 0$	$\eta_p > 1$	$0 < \eta_u < 1$
Case III	$n_j < 0$	$0 < \eta_p < 1$	$\eta_u > 1$
Case IV	$n_j < 0$	$\eta_p > 1$	$\eta_u > 1$

**Table 2**  
 Four cases and relationships with the  $n$ ,  $\eta_p$ , and  $\eta_u$

## Assessment of the environmental break-even point for deposit return systems

475 According to Table 2, each case corresponds to  
476 a precise condition for  $n_j$ ,  $\eta_p$  and  $\eta_u$  such as:

- 477 1. *Case I: Best case.* This solution happens when  
478  $n_j > 0$  (or  $0 < \eta_u < 1$ ) AND  $0 < \eta_p < 1$ ; it  
479 implies that the reusable product is better than  
480 the single-use product after  $n_j$  reuses when  
481  $\eta_p > 1 - \eta_u$ , while if  $\eta_p < 1 - \eta_u$ , the reusable  
482 product is always better.
- 483 2. *Case II: Normal case.* This case occurs when  
484  $n_j > 0$  (or  $0 < \eta_u < 1$ ) AND  $\eta_p > 1$ ; it  
485 means that the reusable product is better than  
486 the single use only after  $n_j$  reuses.
- 487 3. *Case III: Limit case.* This one represents the  
488 transition case and it occurs when  $n_j < 0$  (or  
489  $\eta_u > 1$ ) AND  $0 < \eta_p < 1$ ; it corresponds to a  
490 particular condition when the reusable prod-  
491 uct is better only before the first use phase.
- 492 4. *Case IV: Worst case.* Finally, this last case  
493 refers to  $n_j < 0$  (or  $\eta_u > 1$ ) AND  $\eta_p > 1$  and  
494 it means that the reusable product is always  
495 worse than the single-use product.

496 Negative environmental BEP  $n_j < 0$  has no real  
497 physical meaning but it is a useful KPI to classify  
498 the results within the discussed formalism.

499 The four cases described in Table 2, if plotted, in  
500 logarithmic scale, in a scatter plot, correspond ex-  
501 actly to the four quadrants, i.e. best case ( $\log(\eta_u) >$   
502  $0$ ;  $\log(\eta_p) < 0$ ), normal case ( $\log(\eta_u) < 0$ ;  
503  $\log(\eta_p) > 0$ ), limit case ( $\log(\eta_u) > 0$ ;  $\log(\eta_p) <$   
504  $0$ ) and worst case ( $\log(\eta_u) > 0$ ;  $\log(\eta_p) > 0$ ).

## 505 2.4. Case study analysis

### 506 2.4.1. Materials

507 First, the four reusable cups (PP, PLA, PET, glass)  
508 have been compared with the four single-use cups  
509 (PP, PET, PLA, PE+cardboard) with respect to the  
510 seven impact categories (CC, OD, A, POC, E, NREIJ,  
511 and WSI). The considered EoL for all plastics cups  
512 and for single-use Cardboard+PE cups refers to 100%  
513 energy recovery (Vercalsteren et al., 2007), while  
514 for reusable glass cups EoL reflects recycling of 89%  
515 of the used materials (Gaines and Mintz, 1994). The  
516 use phase refers to scenario 2 of Figure 1, i.e. offsite  
517 washing with 20km of transport roundtrip distance  
518 (10km+10km).

### 519 2.4.2. Transport distance

520 With the same EoL scenario (i.e. 100% energy  
521 recovery for plastic and cardboard cup, recycling of

89% of the used materials for glass), three different  
use phase scenarios for the reusable cups have been  
analyzed:

1. onsite handwashing (Martin et al., 2018);
2. onsite washing with commercial washing ma-  
chines (Martin et al., 2018);
3. offsite washing with industrial washing ma-  
chines and increasing transport distance.

An upper distance limit, i.e. the maximum num-  
ber of km  $n_{km,max}$  during the use phase to have a  
positive environmental BEP, for an infinite number  
of reuses, has been calculated by decomposing  $B_{Y_2}$   
with respect to the washing impact  $B_{Y_2,washing}$  and  
the transport impact per cup per km  $B_{Y_2,km}$  accord-  
ing to:

$$n_{km,max} = \frac{X - B_{Y_2,washing}}{B_{Y_2,km}} \quad (7)$$

Eq. 7 (rationale in section A.2 of the SI) shows  
how  $n_{km,max}$  does not depend on the production and  
EoL phase of the reusable cups (since it's a con-  
straint for the slopes). Thus, for all reusable plastic  
cups (with the same weight) the  $n_{km,max}$  is the same.

Finally, the area of interest, in terms of the dis-  
tance, was defined according to the following classi-  
fication - 1) city (5km), 2) metropolitan area (30km),  
3) district (80km), 4) region (200-300km), and 6)  
country (>400km).

### 524 2.4.3. Dispersion Rate

525 The dispersion rate  $d$  was also briefly analyzed  
526 with the same use scenario (i.e. offsite washing with  
527 a roundtrip of 20km) and EoL scenario (100% en-  
528 ergy recovery for plastic and cardboard cups, recy-  
529 cling for glass cups).  $d$  is defined as the average  
530 number of reuses before a reusable cup is dispersed  
531 and is substituted with a new one. Dispersed means  
532 that the use phase loop, whatever use strategy con-  
533 sidered, immediately ends up, and the production of  
534 a new cup is considered. For the sake of simplicity,  
535 the EoL was considered the same as declared for the  
536 "not dispersed".

### 537 2.4.4. EoL

538 Two EoL scenarios have been compared for the  
539 three - PP, PLA, PET - plastic cups: 1) 100% energy  
540 recovery, and 2) recycling. Composting, instead of

recycling, has been considered for PLA. The variation in the EoL scenario has been analyzed for the use phase scenario  $j = 2$ , i.e. offsite washing with a roundtrip of 20km. The EoL for cardboard and glass cups has not been changed. Thus, 100% energy recovery and recycling of 89% of the used materials have been considered for cardboard and glass cups respectively.

In order to analyze EoL scenarios is necessary to analyze distinctly a variation in the EoL of single-use cups and a variation in the EoL of reusable cups. In this subsection, subscripts refer to the EoL scenario. Thus, the use phase subscripts are omitted. A simultaneous variation of the EoL scenario of single-use and reusable products is out of the scope of this study.

*Variation of EoL scenario of reusable products*  
First, if only reusable product EoL ( $C_Y$ ) varies, this change affects only the product efficiency  $\eta_p$  (Eq. 3), since the use phase efficiency  $\eta_u$  (Eq. 4) does not depend on  $C_Y$  or  $Y_0$ . Thus, a change in the reusable product EoL, from  $C_{Y_1}$  to  $C_{Y_2}$ , induces a variation in the product efficiency according to:

$$\Delta\eta_{p,1\rightarrow 2} = \eta_{p,2} - \eta_{p,1} = \frac{\Delta Y_{0,1\rightarrow 2}}{X} = \frac{\Delta C_{Y_{0,1\rightarrow 2}}}{X} \quad (8)$$

where  $\Delta Y_{0,1\rightarrow 2} = Y_{0,2} - Y_{0,1}$  is the variations in  $Y_0$  from EoL scenario 1 (energy recovery) to 2 (recycling), while  $\Delta C_{Y_{0,1\rightarrow 2}}$  and  $\Delta\eta_{p,1\rightarrow 2}$  the corresponding variations, respectively in the EoL phase and in the product efficiency. The last step is allowed since without a variations in the production phase scenario,  $A_Y$ ,  $\Delta Y_{0,1\rightarrow 2} = \Delta C_{Y_{0,1\rightarrow 2}}$ . Consequently, if  $\Delta C_{Y_{0,1\rightarrow 2}} > 0 \Rightarrow \eta_{p,2} > \eta_{p,1}$ ; in other words, as greater the EoL impacts is ( $C_{Y_{0,2}} > C_{Y_{0,1}}$ ), as less efficient the product efficiency is. Finally, a change in  $C_{Y_0}$  affects only when the BEP  $n$  is achieved but it does not affect if this is achieved or not, i.e. it does not modify the sign of  $n$  from positive to negative (or viceversa).

*Variation of EoL scenario of single-use products*  
Similarly, a change in the EoL scenario of single-use product  $\Delta C_{X_{1\rightarrow 2}}$  can be described in terms of a variation of the product efficiency  $\Delta\eta_{p,1\rightarrow 2}$  and the use phase efficiency  $\Delta\eta_{u,1\rightarrow 2}$ . In this case, both values vary. Indeed, since  $\eta_u$  is inversely proportional

with respect to  $X$ :

$$\Delta\eta_{u,1\rightarrow 2} = \eta_{u,2} - \eta_{u,1} = B_Y \left( \frac{1}{X_2} - \frac{1}{X_1} \right) = -B_Y \frac{\Delta C_{X_{1\rightarrow 2}}}{X_1 X_2} \quad (9)$$

an increase in the EoL impact for single-use products,  $\Delta C_{X_{1\rightarrow 2}} > 0$ , implies a reduction in the use efficiency

$\Delta\eta_{u,1\rightarrow 2} < 0$ , while  $\Delta C_{X_{1\rightarrow 2}} < 0 \Rightarrow \Delta\eta_{u,1\rightarrow 2} > 0$ . The same inversely proportionality holds for the product efficiency, according to

$$\Delta\eta_{p,1\rightarrow 2} = -Y_0 \frac{\Delta C_{X_{1\rightarrow 2}}}{X_1 X_2} \quad (10)$$

In terms of environmental BEP  $n$ , a change in the use phase efficiency implies that  $n$  can change sign and in some cases a BEP cannot be achieved anymore, or on the contrary it can be achieved, depending on the relative differences ( $X_1 - B_Y$ ), or ( $X_2 - B_Y$ ). A detailed discussion of results for these cases goes beyond the scope of this work.

Since a change in sign in  $n$  between the two EoL scenarios 1 and 2 occurs if and only if  $\frac{n_1}{n_2} < 0$ , a quick indicator is the ratio

$$\frac{n_1}{n_2} = \frac{Y_1 (X_2 - B_Y)}{Y_2 (X_1 - B_Y)} < 0 \Rightarrow \frac{(X_2 - B_Y)}{(X_1 - B_Y)} < 0 \quad (11)$$

because  $Y_2, Y_1 > 0$  by hypothesis.

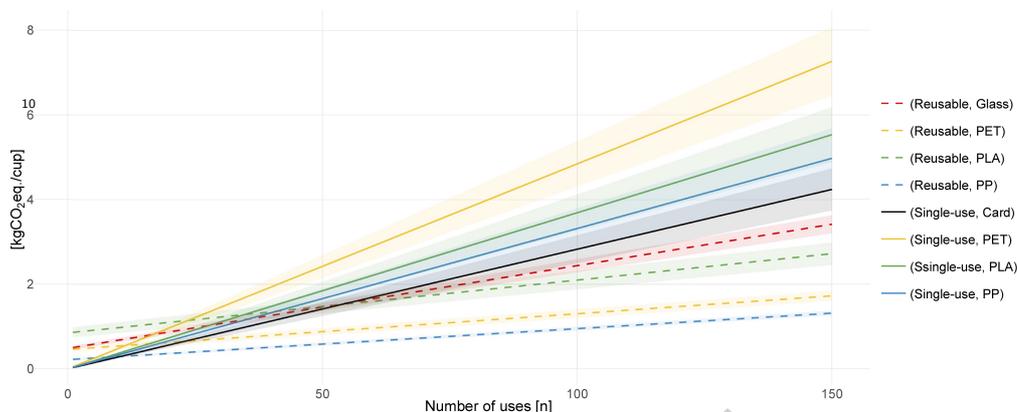
### 3. Results

All midpoint impact categories for the production, use and EoL phases are reported in Table 7a, 7b and 7c in section C of the SI.

#### 3.1. Materials analysis

Figure 3 shows the linear trend (lines) for the CC and the uncertainty due to the differences in the cup weights (shaded area), highlighting how the BEPs lie between 10 and 50 reuses in terms of CC depending on the material and the cup weight. Based on the relative position and the slope of the lines, the best single-use cup is the cardboard+PE coat, followed by the PP and PLA ones, while the worst one results to be the PET one. The cardboard+PE, PP, and PLA single-use cups CC impacts are very similar and the

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**Figure 3:** Climate Change (CC) for the offsite washing scenario with a transport distance of 20km during the use phase and energy recovery at EoL for plastic materials and recycling for glass. The shaded areas represent the uncertainty due to the minimum and maximum weights, while the line represent the average ones according to Table 1. Dashed lines refer to the reusable cups while the solid ones refer to the single-use cups.

average impact (i.e. the solid lines) lie in the uncertainty shaded area. In particular, the PP single-use cup is comparable with both the cardboard+PE and PLA single-use, while the cardboard+PE can be considered better than the PLA one. With respect to the reusable cups, instead, after 50 uses, the best one is the PP cup and the worst the glass cup, even if its production and EoL impact is better than the PLA reusable cups and it is comparable with the PET cups, as shown in Figure 3. The PET (2nd best reusable cup) and the PLA (3rd one) cups lie in-between the PP and the glass cups. The slope differences among dashed lines mainly reflect the weight differences of the reusable cups (see Table 1), as a consequence of the carrying capacity during the transport of the use phase. Although the transport noteworthy affects the use phase, all reusable cups achieve the BEP for the CC impact category for less than 50 uses.

Table 3 summarize the BEP for the current section. Next impact categories are presented in Figure 1 in section D.1 of the Supplementary Information. Fig. 1a in the SI shows that only PET cups have a not negligible OD impact. The transport does not affect OD and such a big impact mainly derives from the production phase of the PET granulate (Plastics Europe, 2020). For this impact category, it turned out that the BEP for PET reusable

		Number of uses to achieve the break-even point (BEP)						
Single-use cups	Reusable cups	CC	OD	A	POC	E	NREU	WSI
PP	PP	8	9	-29	61	-4	9	-5
	PLA	41	57	-121	-164	-73	39	-61
	PET	18	472	-70	-2631	-21	21	-49
	Glass	35	80	-46	-30	-16	42	-17
PLA	PP	7	6	2	2	1	10	3
	PLA	35	35	34	33	36	43	41
	PET	16	324	7	19	8	23	29
	Glass	28	31	35	24	13	50	15
PET	PP	5	0	5	1	12	6	1
	PLA	24	1	143	15	1571	22	16
	PET	11	8	22	10	74	13	12
	Glass	17	0	-630	9	-78	18	5
Cardboard +PE	PP	10	25	6	8	7	23	9
	PLA	54	667	181	350	284	151	184
	PET	23	1472	25	82	39	54	109
	Glass	55	-60	-285	-67	-320	-235	106

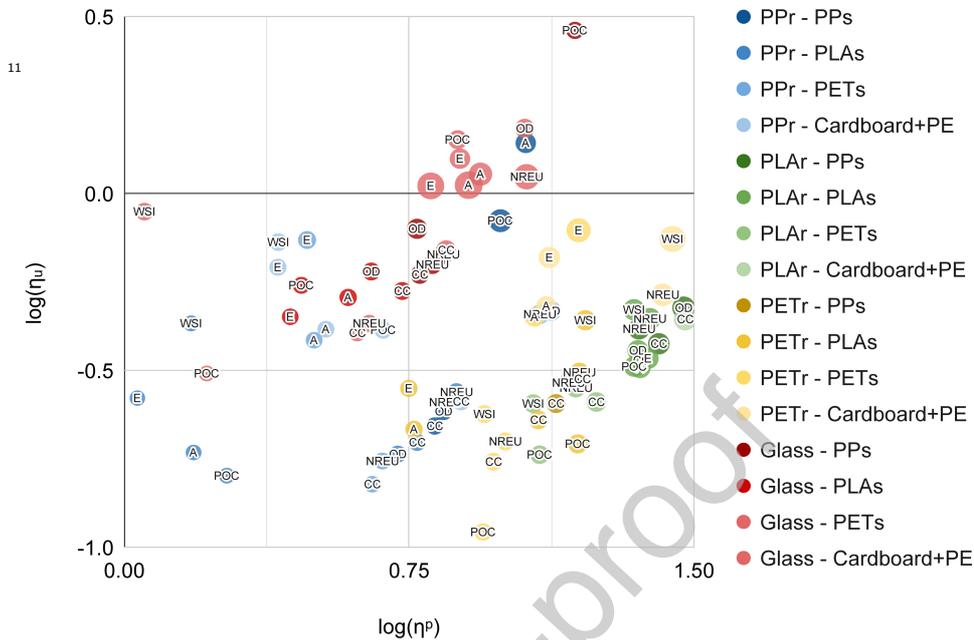
**Table 3**

Break-even point related to the offsite washing use phase and 100% energy recovery for plastic and cardboard cups and 89% material recycling for glass cups.

cups is achieved for less than 10 uses.

The best solution with respect to the A impact category (Fig. 1b in the SI) is the single-use PP cup for any number of uses, while the worst solution, for high no. of uses, is the single-use PLA cup. A impacts for single-use PET and cardboard+PE cups are comparable, as evidenced by corresponding solid lines within the uncertainty shaded areas.

## Assessment of the environmental break-even point for deposit return systems



**Figure 4:** Zoom for  $-0.5 < \eta_u < 0.5$  and  $0 < \eta_p < 1.5$  of the scatter plot of the use efficiency  $\eta_u$  vs the product efficiency  $\eta_p$  related to the material analysis. Midpoint impact categories refer to offsite washing and energy recovery EoL strategy.

676 Regarding the reusable cups, the best performance  
 677 refers to the PP cups, followed by the PET cups,  
 678 while the glass and PLA reusable cups are the worst  
 679 ones. The bad performance of glass and PLA reusable  
 680 cups is due both by a high impact during the pro-  
 681 duction and EoL phase (see corresponding values  
 682 at  $n=0$ ) and by their high weight, which affects the  
 683 use phase and thus the slope of the line. For this im-  
 684 pact category, PP and PET reusable cups achieved  
 685 the BEP for  $n < 20$  with respect to all single-use cup  
 686 types (avoiding the PP single-use cup), while PLA  
 687 and glass reusable cups perform better than PLA  
 688 single-use cup after 40 uses. Finally, PLA reusable  
 689 cups, in comparison with the cardboard+PE and PET  
 690 single-use cups, achieve the BEP after a large num-  
 691 ber of reuses ( $n > 150$ ). 711

692 With respect to POC impact category (Fig. 1c  
 693 in the SI) the best solutions for any  $n$  are the single-  
 694 use and reusable PP cups. The PP reusable cups  
 695 in comparison with the PP single-use cups, achieve

the BEP after about 50 uses. After 50 uses, the 2nd,  
 3rd and 4th best solutions for reusable cups are re-  
 spectively the PET, PLA and glass cups, while for  
 $n < 50$  the glass reusable cups perform better than  
 the PLA reusable cups and for  $n < 10$  they are even  
 better than PET reusable cups. The PET reusable  
 cup achieves the BEP for  $n < 100$  with respect all  
 single-use cup types (avoiding PP), while PLA and  
 glass cups behave better than PLA and PET single-  
 use cups (for  $n > 30$ ). Finally, PLA reusable cups  
 reach a BEP with respect to cardboard+PE cup only  
 after a very large number of reuses ( $n > 350$ ).

In terms of eutrophication (E), Fig. 1d in the SI  
 points out that single-use PP are always better than  
 reusable cups for any number of reuses. Reusable  
 PP and PET cups, with respect all single-use cups,  
 reach a BEP respectively, after less than five uses,  
 and around 60 uses. PLA is very impactful in terms  
 of eutrophication impact category and it is the worst  
 one, even if due to the difference in weight glass

## Assessment of the environmental break-even point for deposit return systems

716 reusable cups perform better only for less than 150  
717 reuses. 765

718 The behaviour of the NREU impact category  
719 (Fig. 1e in the SI) is similar to that of the CC impact  
720 category. Reusable plastic cups reach the BEP for  
721  $n < 50$  versus all types of single-use cups, with the  
722 only exception that the cardboard+PE cups perform  
723 slightly better than in the CC case. 771

724 Finally, according to Fig. 1f in the SI, the best  
725 solution for the WSI is the single-use PP cup which  
726 is always better than any other solution. With respect  
727 to reusable cups, the best cup material is again  
728 the PP, while the worst one is the PLA. All reusable  
729 cups achieve a BEP (avoiding the PP single-use cup)  
730 for  $n < 50$  vs the PLA and PET single-use solutions  
731 and for  $n < 150$  vs the cardboard+PE cups. 779

732 In conclusion, single-use PP cups are the best  
733 solution with respect to A, POC (for  $n < 100$ ), E,  
734 and WSI, while reusable PP cups are the best ones  
735 among the other reusable solutions with respect to all  
736 midpoint impact categories. PET and PLA reusable  
737 cups are, respectively, the 2nd and the 3rd best choice  
738 among reusable cups except for the OD, E, and WSI  
739 impact categories. In fact, PET is the unique ma-  
740 terial with a not negligible OD impact (i.e. it is  
741 the worst material), and, PLA, due to the impact  
742 during the production phase, is the worst solution  
743 with respect to E and WSI impact categories. Re-  
744 garding single-use cups, the cardboard+PE cups are  
745 the best considering the CC and NREU impact cat-  
746 egories, while, for all the other impact categories,  
747 the PP single-use cup solution performs better. For  
748 all categories, PLA and PET single-use solutions,  
749 generally, impact more than PP and cardboard+PE.  
750 On the contrary, reusable plastic (PP, PET, PLA)  
751 cups reach a BEP for all the impact categories (ex-  
752 cept for the above-mentioned cases against single-  
753 use PP cups) after a variable number of reuses, gen-  
754 erally lower than 150. Finally, for all the impact  
755 categories, because of the high weight, the glass  
756 cups are strongly affected by the transport phase  
757 and even if the production and EoL phases, in some  
758 cases, is better than reusable plastic cups, the im-  
759 pact for large  $n$  is always the worst. Thus, a more  
760 detailed analysis of transport distance is presented  
761 in the next paragraph. 808

762 *Use and product efficiency: scatter plot* The  
763 material analysis are also reported in the scatter plots  
811

(as discussed in Section 2 according to Table 2), in  
Figure 2 in section D.1 of the SI, where Fig. 2a  
shows all results in a unique graph. Fig. 4, instead,  
zooms in results in the range  $-0.5 < \eta_u < 0.5$  and  
 $0 < \eta_p < 1.5$ . Different colours represents differ-  
ent materials for the reusable cups, while differ-  
ent gradients of the same colour point out the com-  
parison of the same material for the reusable cups  
with the different materials for single-use cups. The  
size of each point is proportional to the BEP  $n$  for  
 $\log(\eta_u) < 0$ , while for  $\log(\eta_u) > 0$  represents a  
negative  $n$ . The graph straightforwardly shows, for  
any case, if, and when, the BEP is achieved simul-  
taneously for all analyzed impact categories. The  
reusable glass cups (red series) are the worst per-  
forming solution since many impact categories lie  
in the worst case quadrant ( $\log(\eta_u), \log(\eta_p) > 0$ )  
and  $\log(\eta_u)$  is generally closer to 0 than the other  
materials. In terms of product efficiency, the PLA  
is the worst performing plastic material for reusable  
cups (green series) for almost all impact categories  
since  $\log(\eta_p)$  is generally larger with respect to PP  
(blue series) and PET (yellow series) reusable cups.  
Regarding PET reusable cups, the large size of POC  
and OD points shows that the BEP is achieved only  
after a large number of reuses. This result is simply  
explained by Eq. 6; indeed, as  $\eta_u \rightarrow 1$  (i.e.  $B_{x,j} \rightarrow$   
 $X$ ), or  $\log(\eta_u) \rightarrow 0$ ,  $n \rightarrow \pm\infty$ . PP reusable cups  
are slightly better than PLA and PET reusable cups  
for the production and EoL phases. With respect  
to the use efficiency  $\eta_u$ , all three types of reusable  
plastic cups achieve a BEP, since points lie in the  
third and fourth quadrant ( $\log(\eta_u) < 0$ ) for all im-  
pact categories except for A, POC, E, and WSI with  
respect to the PP single-use cups.

### 3.2. Use phases and transport distance analysis

Since PP reusable cups, from the previous sec-  
tion analysis, perform better than the other reusable  
cups for almost all impact categories, in this section  
results and graphs are presented referred mainly to  
PP reusable cups and the average weights. Figure  
5 shows the results for the CC impact category re-  
lated to the PP reusable cups and the four types of  
single-use cups with respect to the three use scenar-  
ios. The graph highlights how, for the use phase,  
the best washing scenario is the *offsite washing* with  
a distance lower than 50km, then the *onsite wash-*

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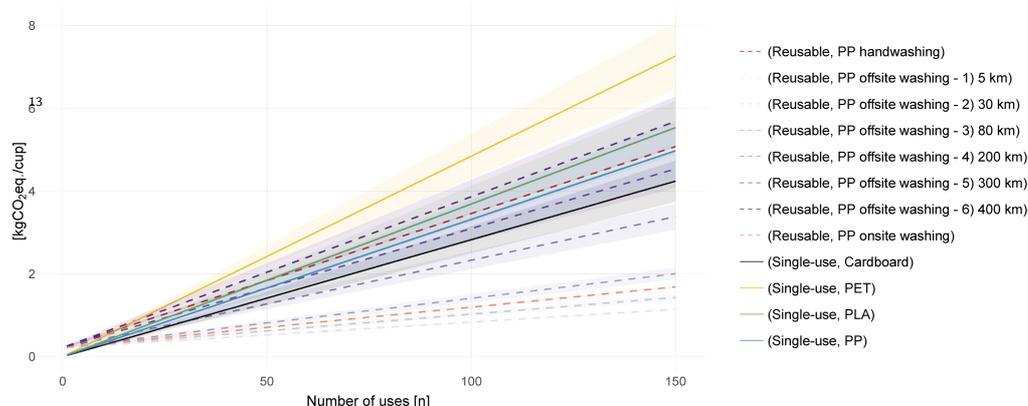


Figure 5: CC of reusable PP cups for onsite handwashing/washing (dashed lines), and offsite washing (dotted lines) VS single-use (continuous lines).

ing, subsequently the *offsite washing* with a distance lower than 350km, and, finally, the *handwashing* scenario. With a transport distance greater than 350km the *offsite washing* is always the worst scenario. In each scenario of the use phase: handwashing, dishwasher, and industrial dishwasher (for a distance of 10+10 km), the impacts are due, for a percentage higher than 75%, to the electricity consumed. The optimization of the system, achieved at an industrial level, allows to considerably reduce energy consumption and therefore limit impacts.

With respect to the single-use cups, the *onsite handwashing scenario* never achieves an environmental BEP, in terms of CC, vs the cardboard+PE and PP cups (although the line for onsite handwashing lies on the uncertainty shaded area of the PP cups) while the onsite washing scenario (or the offsite washing with equivalent CC impact) achieves the environmental BEP with a number of reuses lower than 20.

According to the area of interest classification, it emerges that local entities or institutions are necessary to manage the use phase. Indeed, for instance, CC impacts for the reusable plastic cups are lower than single-use cups if and only if distances are lower than 30-50km, thus, if a local entity in each City/Metropolitan Area is set up.

Table 4 points out how  $n_{km,max}$  is negative, with respect to single-use PP cup, for Acidification, Eutrophication, and WSI midpoint impact categories.

Maximum distance  $n_{km,max}$  [km] for the use phase for PP reusable cups

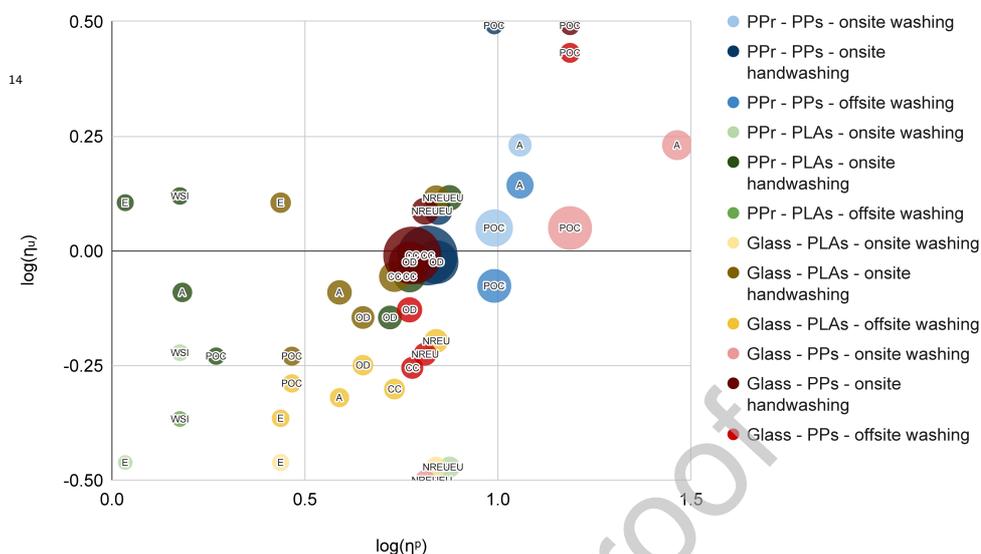
Midpoint impact category	Maximum distance $n_{km,max}$ [km]			
	PP	PLA	PET	Cardboard
CC	357	406	556	293
OD	239	332	12217	100
A	-6	423	166	150
POC	33	364	681	113
E	-198	658	101	161
NREU	339	311	539	152
WSI	-528	986	2413	290

Table 4

Maximum distance [km] for the offsite washing scenarios in the use phase  $n_{km,max}$ , i.e. for infinite number of reuse, for PP reusable cups vs four different single-use cups. The use phase does not depend on the material of the reusable cup but only on its weight.

The negative numbers represent the case when the environmental BEP is not achieved either for an infinite number of reuses. Although a negative number does not represent a real situation, it is still a useful indicator. Indeed, when a negative number is close to zero (e.g. the case of A for PP cups) it means that with a slight improvement in the washing process for that impact category the environmental BEP can be achieved. Excluding the negative numbers, the minimum value of maximum allowed km occurs for the POC impact category in the case of PP single-use cups (33km). All the other

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**Figure 6:** Zoom for  $-0.5 < \eta_u < 0.5$  and  $0 < \eta_p < 1.5$  of the scatter plot (logarithmic scale) of the use efficiency  $\eta_u$  vs the product efficiency  $\eta_p$  with different use phases. The acronyms CC, OD, A, POC, E, NREU, and WSI represent respectively: global warming, ozone depletion, acidification, photochemical oxidant creation, eutrophication, non renewable energy use, and, water scarcity indicator impact categories.

854 values are greater than 100km, which means that, for an infinite number of reuses, if the distance during the use phase is lower than 100km an environmental BEP is always reached (excluding the impact categories above mentioned).

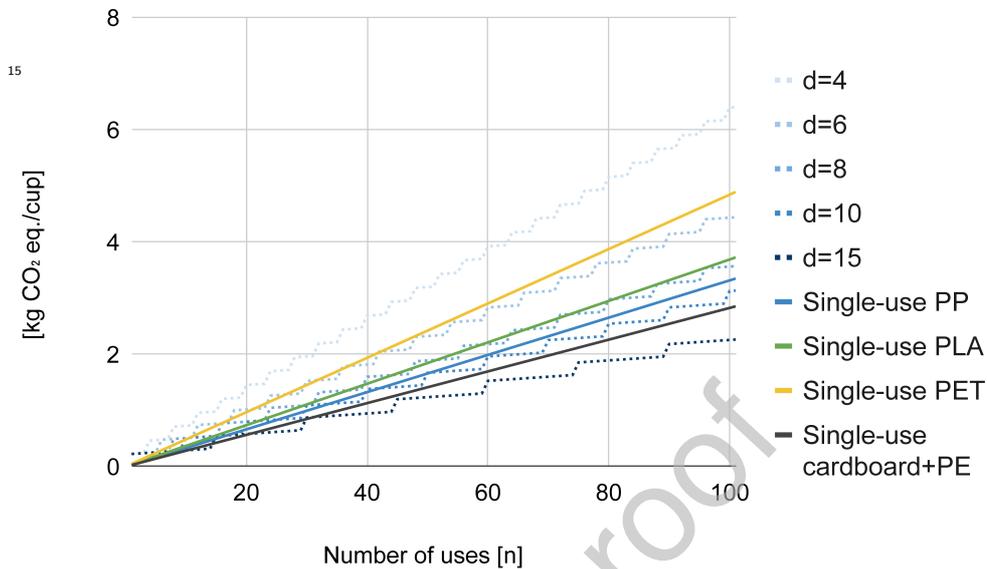
859 Finally, the same results can be obtained for the other reusable cups simply by multiplying the  $n_{km}$  in Table 4 by a scaling factor due to the difference in weight between the cups. For instance, for glass cups the scaling factor, according to Table 1, is 0.11 (40/360 = 0.11) because of the glass cup weight (360gr) and the PP cup weight (40gr). Thus, the maximum number of allowed km for the glass reusable cups to achieve an environmental BEP, for all non-negative values in Table 4, is much lower, i.e. less than 15km.

870 *Use phases and transport distance analysis* Finally, the best and the worst performing reusable cups, i.e. PP and glass cups, have been selected in order to analyze the different use phases. Results,

in terms of use ( $\eta_u$ ) and product efficiency ( $\eta_p$ ) are plotted in Figure 3 in section D.2 of the SI. Fig. 6 presents the zoom for the range  $-0.5 < \eta_u < 0.5$  and  $0 < \eta_p < 1.5$ . Colors represent the comparison between a different couple of materials (e.g. reusable PP cups vs PLA single-use cups) while the color gradients highlight the different use phases for the same couple of materials.

Handwashing, as previously discussed, is the worst solution for all analyzed midpoint impact categories and the BEP in many cases is not reached. On the contrary, offsite washing for PP reusable cups is the best solution and the BEP is achieved with respect to PLA single-use cups for all impact categories. Comparing PP reusable and single-use cups, instead, the BEP is not achieved for A, E, and WSI. Reusable glass cups, again, are the worst-performing solution. The BEP is achieved, in terms of CC, OD, and NREU (vs PP single-use cups) and of CC, OD, A, POC, E, and NREU (vs PLA single-use cups).

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**Figure 7:** CC of reusable PP cups for offsite washing (dotted lines) vs single-use (continuous lines) with different dispersion rate.

### 3.3. Dispersion Rate

Figure 7 shows the CC for reusable PP cups (dotted lines) vs single-use cups (continuous lines) with an increasing dispersion rate  $d$ .  $d$  is the average number of reuses before a reusable cup is dispersed and is substituted with a new one. Thus, after  $d$  uses, the production and EoL impacts of a new reusable cup are taken into account; in Figure 7 this effect corresponds to a “jump” in the impact. Previous studies analyzed these scenarios comparing different dispersion rates for reusable cups (Vercauteren et al., 2007) or for reusable plastic crates (Tua et al., 2019). Figure 7 shows how this is a “false” problem since the dispersion rate can be easily mapped into the environmental BEP  $n$ . Thus, for  $d < n$  (see the case with  $d = 4$  in Fig. 7) the environmental BEP is never reached, for  $d \gg n$  (e.g.  $d = 15$  in Fig. 7) once achieved the BEP the reusable cups are always better than the single-use cups, while for  $d \sim n$  every time a reusable cup is dispersed into the environment the next usages of the reusable cup are environmentally worse up to the BEP is reached again (e.g.  $d = 8$  in Fig. 7).

### 3.4. EoL scenarios: recycling vs energy recovering

In order to show the rationale of the proposed methodology Table 8a in section D.3 of the SI summarizes the EoL environmental impact variations between the two EoL scenarios (recycling vs energy recovering) for PP and PET single-use and reusable products. For the PLA cups, composting has been considered instead of recycling. Table 8a shows how recycling is always better than energy recovery for reusable cups, in terms of CC since  $\Delta C_{Y_{0,1 \rightarrow 2}} < 0$ , for any considered material (PP, PLA or PET). Moreover, recycling is better in terms of POC and NREU for PP reusable cups, while PLA composting is worst for all midpoint impact categories (excluding CC) than energy recovery. Finally, PET recycling, for reusable cups, is better than energy recovery for all impact categories (excluding OD). On the contrary, for single-use cups, results have to be considered with the opposite meaning and when a negative sign occurs, i.e.  $\Delta C_{X_{1 \rightarrow 2}} < 0$ , both the product and the use phase efficiency are negatively affected.

940 Finally, Table 8b and 8c must be read simultane-  
 941 ously and quickly show when a change in EoL  
 942 strategy for single-use products induces a change  
 943 in the sign for  $n$ , and, thus, the environmental BEP is  
 944 now reached or not.

945 Thus, Table 8b and 8c show that by compar-  
 946 ing recycling  $C_{X_2}$  with energy recovery  $C_{X_1}$  strat-  
 947 egy for single-use in few cases the BEP is no more  
 948 achieved. In particular, in the case of onsite wash-  
 949 ing, with respect to CC for PP cups, the environ-  
 950 mental BEP is no longer achieved when single-use  
 951 cups are recycled instead of incinerated, while for  
 952 PET single-use cups the BEP is no longer achieved  
 953 for A, E, and WSI impact categories. With respect  
 954 to PLA cups, instead, there is no change in the sign  
 955 for any impact category (Table 8b) for  $n$  by chang-  
 956 ing the EoL strategy for single-use. In the case of  
 957 offsite washing, instead, there is only one change in  
 958 sign (for Eutrophication for PP cups) but in this case  
 959 it's a positive change in sign, thus, the BEP is now  
 960 achieved. Again, for PLA there is no change in the  
 961 sign for  $n$ , and for PET as well. Thus, by analyzing  
 962 the two best use phase scenarios for reusable cups,  
 963 i.e. onsite washing and offsite washing, in a scenario  
 964 where single-use cups are 100% recycled the  
 965 environmental benefits are no longer maintained  
 966 ther for the CC.

#### 967 4. Discussion

968 By adopting this approach based on the envi-  
 969 ronmental BEP, the product and use efficiency, as a  
 970 standard functional unit, i.e. one single-use, can be  
 971 used, simplifying comparisons among LCA stud-  
 972 ies. Such an approach may be particularly suitable  
 973 for monitoring the performance of an organization  
 974 in the most recent framework of the Organizational  
 975 LCA (OLCA) (Martínez-Blanco et al., 2015) but  
 976 further studies are needed to homogenize results' in-  
 977 terpretation according to UNEP (Blanco et al., 2015)  
 978 guidelines and to the most recent ISO/TS 14072:  
 979 2014 (International Organization for Standardiza-  
 980 tion, 2014).

981 In next subsections, findings of the present work  
 982 are compared with previous studies, highlighting  
 983 and discussing limitations and advantages of the pro-  
 984 posed methodology.

#### 4.1. Comparison of results with literature

In the last decade, the comparison of environ-  
 mental performance between reusable and dispos-  
 able cups has been the subject of several studies.  
 Studies often have shown the difficulty of complet-  
 ing an effective and objective comparison. For in-  
 stance, van der Harst and Potting (2013) compared  
 ten disposable cups, showing that, due to the differ-  
 ent methodological choices and differences in leg-  
 islative rules, it was not feasible a reliable compar-  
 ison. Vercalsteren et al. (2010), instead, analyzed  
 four types of cups - reusable polycarbonate and single-  
 use polypropylene, PE-coated cardboard, and poly-  
 lactide cups - in large and small events thanks to a  
 comparative LCA study. To compare reusable ver-  
 sus single-use cups, they introduced the *trip rate*,  
 i.e. the mean number of uses for a reusable cup.  
 They concluded that none of the cases is always bet-  
 ter neither at small nor large events. Garrido and  
 Del Castillo (2007) compared single-use and reusable  
 cups for large events in Spain concluding that the  
 minimum number of uses to have a smaller impact  
 is 10. A similar result was also determined in the  
 present study by referring to the global warming  
 category, in fact for a number of reuses between  
 10 and 50 times all types of reusable cups show  
 fewer impacts than single-use cups. Although Gar-  
 rido and Del Castillo (2007) reported that reusable  
 cups with respect to ozone layer depletion, heavy  
 metals, and carcinogenic compounds, are always worse  
 than single-use due to the impact during the wash-  
 ing phase. The comparison between reusable and  
 single-use coffee cups - made of different materi-  
 als - were performed in a work by Almeida et al.  
 (2018). Polypropylene and glass reusable cups, pro-  
 duced by a specific company, were compared with  
 generic PP and bamboo reusable cups and with pa-  
 per and PLA single-use cups. From this study it  
 emerges that PP and glass are the best materials for  
 cups; in particular reusable cups - made of these ma-  
 terials - are better than disposable alternatives af-  
 ter around 10-20 uses. These results are partially in  
 agreement with what we obtained from our analy-  
 sis. The main difference is represented by the result  
 of the glass cups in fact in the work of Almeida et  
 al. the cups weight does not affect the impacts of  
 the use phase because the study hypothesizes that  
 the cups are used and washed in a home context  
 (therefore without the need of any kind of trans-

port). In another work, Potting and van der Haast (2015) compared three disposable cups - polystyrene, biobased, and compostable polylactic acid (PLA) and bio-paper - with polystyrene reusable cups (hand-washed or dish-washed). Again, no overall preference was possible neither among the different disposable cups nor among the disposable ones and the reusable cups. More precisely, reusable cups with dishwashing (4 uses before washing) are worse than disposable polystyrene cups for four midpoint impact categories - terrestrial ecotoxicity, ozone layer depletion, human toxicity, marine aquatic ecotoxicity - out of the eleven considered impact categories while, with handwashing, all impact categories were worse.

In recent years, to facilitate comparison between single-use and reusable products, the European Commission reported a thorough "life cycle inventories" of single-use plastic products and their alternatives (Paspaldzhiev et al., 2018) for single-use plastic products (e.g. cigarette butts, drinks bottles, cutlery, straws, food containers, drinks cups, ..), with suggestions about some non-plastic reusable alternatives.

From the report, it emerged that washing impacts are strongly affected by the technology used and by ecodesign criteria but the report does not provide results in terms of the number of usages. The effect on the final impacts of the technology used to model the system in the use phase emerges from the comparison with the recent work by Changwichan and Gheewala (2020); as reported in this study, the impacts generated by handwashing are considerably lower than those obtained when using a dishwasher. Other aspects to keep in mind - when examining similar works - concern the geographical region and the technology used to model the production phase of the cups. In fact, Changwichan and Gheewala (2020) suggest how reusable steel cups show better environmental performance than PP, PET and PLA single use cups, for different impact categories. Thus, results from previous works show that they are all closely linked to the specific situation and the assumptions examined.

## 4.2. Limitations and advantages

Although results obtained from this study also depend on specific assumptions and boundary conditions due to the system itself, the proposed ap-

proach may facilitate the phase of interpretation of results in LCA analyses. In particular, the introduction of the environmental BEP  $n$  allows to easily analyze close-loop scenarios, by maintaining a simple functional unit (i.e. serving 0.4 liters of draught beverages in one go) instead of more complex ones (e.g. hundreds of uses). Moreover, by studying the environmental impacts in terms of the proposed KPIs, i.e. the environmental BEP  $n$ , the use phase efficiency  $\eta_u$  and the product phase efficiency  $\eta_p$ , it is possible to decouple the effects of a variation in the production phase, or in the use phase, of a reusable product. Indeed, a variation on the use phase may affect the achievement, or not, of an environmental BEP for a reusable product, while a variation on the production and EoL phases of the reusable product only affects when the BEP is achieved (i.e. the minimum number of reuses). Thus, depending on the values of  $\eta_u$  and  $\eta_p$ , possible strategies (Table 5) may be easily identified, to improve the efficiency of a reusable product and to achieve an environmental benefit with a reasonable number of reuses.

On the contrary, a few limitations emerged. First, the environmental BEP assessment allows the simultaneous comparison of different midpoint impact categories, since the two KPIs for the use and product efficiency are dimensionless by definition, but the usual midpoint impact category weighting process towards common endpoints still remains a challenge. Second, the results obtained for the use phase are strongly affected by electricity consumption. Indeed, more than 75% of the impact is due to energy consumption. Further investigations are needed to evaluate differences in assumptions for the electricity mix (e.g. 100% renewable energy) or for the soap and detergent composition, such as the detailed study conducted by Tua et al. (2019) on reusable plastic crates. Third, the discussed EoL scenario needs an ad-hoc analysis with primary data from specific companies and plants to evaluate uncertainties and the results' accuracy. Furthermore, EoL implications have to be further investigated in order to simplify the analysis of the effects both on the product and the use efficiency, when different single-use product EoL processes have to be compared. Fourth, in this study an uncertainty analysis on the cup weight is discussed, by presenting the effects of a variation of weight with respect to an average value. Although this assumption represents the

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**Table 5**

Strategy to improve the reusable products impact in order to achieve an environmental benefit for reusable products.

Cases	Use efficiency	Product efficiency	Break-even point	Strategy
Best Case	$0 < \eta_u < 1$	$0 < \eta_p < 1$	$n > 0$	1) Improve the use phase if $n \gg 1$
Normal Case	$0 < \eta_u < 1$	$\eta_p > 1$	$n > 0$	1) Improve the use phase if $n \gg 1$ 2) Improve reusable product production or change material for reusable product
Limit Case	$\eta_u > 1$	$0 < \eta_p < 1$	$n < 0$	1) Improve the use phase to reach a break-even point
Worst Case	$\eta_u > 1$	$\eta_p > 1$	$n < 0$	1) Improve the use phase to reach a break-even point 2) Improve reusable product production or change material for reusable product

most common cup weight found in European marketplace, further investigations are needed to cover the high variability in weight. Indeed, by varying the weight, the material ranking, i.e. best or worst performing cups, may change significantly. Thus, a full market analysis should be necessary in order to identify the best solution for reusable or single-use cups and to define boundary assumptions (e.g. weight). Finally, due to lack of primary data for the whole supply chain, this study relies on secondary data obtained from the literature; thus, for future studies specific analyses on production, use or EoL processes may be needed to improve obtained results.

*Simultaneous variation of EoL scenario of single-use and reusable products.* If one wants to compare different EoL scenarios both for single-use and reusable products a more complex case arises for product efficiency  $\eta_p$ . Indeed, by defining  $\eta_{p,1} = \frac{Y_1}{X_1}$  and  $\eta_{p,2} = \frac{Y_2}{X_2}$ , the variation in the product efficiency depends on a mixed comparison of impacts of reusable and single-use products, according to

$$\Delta\eta_{p,1 \rightarrow 2} = \frac{X_1 Y_2 - Y_1 X_2}{X_1 X_2} \quad (12)$$

Since  $X_1, X_2 > 0$  by hypothesis, Eq. 12 means that

$$\Delta\eta_{p,1 \rightarrow 2} > 0 \Rightarrow \frac{X_1}{X_2} > \frac{Y_1}{Y_2} \quad (13)$$

and a full analysis is necessary to understand the impact of the variations of the EoL scenarios. On the contrary, the use phase efficiency and thus the sign of the environmental BEP still depends only on EoL impact for single-use product  $C_X$ .

## 5. Conclusion

The present study introduced a novel methodology for the interpretations of results from comparative LCA analyses in order to evaluate reusable versus single-use products. The methodology lies on three main KPIs: 1) the *product phase efficiency* ( $\eta_p$ ), 2) the *use phase efficiency* ( $\eta_u$ ), and 3) the *environmental break-even point* (BEP) ( $n$ ).  $n$  represents the minimum number a reusable product has to be used in order to become environmentally better than an equivalent number of uses of a single-use product.

Four single-use cups (PP, PLA, PET, and Cardboard+PE coat) have been compared with four reusable cups (PP, PLA, PET, and glass) with respect to seven midpoint impact categories - Climate Change (CC), Ozone Depletion (OD), Acidification (A), Photochemical Oxidant Creation (POC), Eutrophication (E), Water Scarcity Indicator (WSI) and Non-Renewable Energy Use (NREU) - taking into account two EoL strategies (energy recovery and recycling) and three use phase strategies for reusable cups (onsite handwashing, onsite washing and offsite washing). Composting, instead of recycling, has been considered for PLA.

Considering offsite washing use phase - i.e. transport distance of 20km and industrial washing machines - and energy recovery EoL phase, results highlight that reusable plastic (PP, PET, PLA) cups reach a break-even point for CC and NREU for  $n < 150$ , with respect to all analyzed single-use cups. On the contrary, in terms of A, E, and WSI, single-use PP cups are the best option. Reusable glass cups are worse than any other solutions due to transport during the use phase. Generally, reusable cups midpoint impact categories are strongly affected by the distance during the use phase. A limit result has

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1197 been quantified in terms of the maximum distance  
 1198 (km) allowed during the use phase in order to achieve  
 1199 an environmental break-even point after an infinite  
 1200 number of reuses. With respect to PP single-use  
 1201 cup, the environmental break-even point is never achieved  
 1202 for A, E, and WSI, while for PET, PLA, and card-  
 1203 board single-use cup the environmental break-even  
 1204 point is attained for all midpoint impact categories.  
 1205 Excluding also POC impact category with respect  
 1206 to PP single-use cups, in all the other cases a break-  
 1207 even point is always achieved for a transport dis-  
 1208 tance during the use phase lower than 100km. Fi-  
 1209 nally, onsite handwashing is the worst solution while  
 1210 onsite washing is an intermediate solution. For  
 1211 stance, in terms of CC, they are comparable with  
 1212 offsite washing with a distance of 350km and 50km  
 1213 respectively.

1214 By considering recycling as EoL scenario the  
 1215 impacts are lower both for reusable and single-use  
 1216 products, while are worse for composting (for PLA).  
 1217 Thus, considering single-use cups recycling, the break-  
 1218 even points are negatively affected. Indeed, when  
 1219 single-use cups are recycled and reusable cups are  
 1220 energy recovered, for the onsite washing, the break-  
 1221 even point is no more achieved either for CC for PP  
 1222 cups and for A, E, and WSI for PET cups, while for  
 1223 the offsite washing with 20km transport distance no  
 1224 noteworthy differences emerged.

1225 Within the current transition to the circular econ-  
 1226 omy, the presented methodology may be adopted  
 1227 by manufacturers of reusable products, as well as  
 1228 by researchers, practitioners, and decision-makers  
 1229 to evaluate the introduction of new circular prod-  
 1230 ucts, or circular business models, and to correctly  
 1231 identify if, and under which conditions, a reusable  
 1232 product is environmentally better than an equivalent  
 1233 single-use product. Future studies related  
 1234 the discussed case study on reusable and single-use  
 1235 cups should focus on the comparison of different  
 1236 End of Life scenarios and in collecting up to date  
 1237 primary data related to the production and End of  
 1238 Life phase. More in general, the proposed method-  
 1239 ology should be homogenized with the most recent  
 1240 framework of the Organizational Life Cycle Asses-  
 1241 sment introduced by the ISO/TS 14072:2014.

**Disclosure statement**

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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