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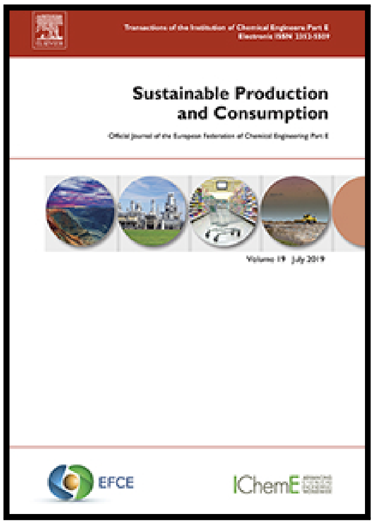

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Assessment of the environmental break-even point for deposit return systems through an LCA analysis of single-use and reusable cups

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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

Plastics are lightweight, durable, and cheap materials.
Since the '60s, plastics, gradually substituting other materials such as wood, metal, and glass, have become the ubiquitous materials of the modern economy (Ellen MacArthur Foundation and World Economic Forum, 2016) due to their chemical properties and their low cost. Plastics production is regularly growing and, nowadays, global production reached 359 Mt in 2018 and an industry turnover of 355 billion euros in 2017 in Europe (Plastics Europe, 2019). On the other hand, plastic waste causes impactful consequences in the environment (Jiang, 2018), in terms of degradation of natural systems (Ryberg et al., 2019; Jambeck et al., 2015), a large quantity of greenhouse gas emissions, fossil feedstock depletion (Hopewell et al., 2009), and toxic additives circulation (Swan et al., 2015; Lien et al., 2015; Winton et al., 2020). The plastic issue has captured the attention of the public and private sectors around the world (European Commission, 2015; European Parliament, 2019; Ellen MacArthur Foundation, 2019). The industry is showing its inclination to gradually move away from today's linear

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take-make-dispose model (Ellen MacArthur Foundation, 2016), by adopting innovative circular business models. So, waste is designed out from the linear model and resources are circulated back to the soil (compostable plastic) (Razza et al., 2009), to the producers (recycled plastic) (Accorsi et al., 2020), or to the consumers (reusable plastic) (Changwichan and Gheewala, 2020).

Today the efforts towards the increase of recycling practices are remarkable, but still not sufficient. The plastic packaging recycling rate in the European Union cannot be considered satisfactory at all, with an average percentage of 41% in EU 28+2 and a target for plastic packaging recycling of 50% by 2025 (Plastics Europe, 2018). At legislative level, there is still a gap in terms of rules promoting good practices of recycling. Some of them have already been identified by previous research (Mariotti et al., 2019): taxes on the use of virgin plastics or differentiated value-added taxes for recycled plastics, the introduction of recycled content standards, targeted public procurement requirements, or recycled content labeling, just to name a few.

An increasing number of countries are taking measures to reduce single-use plastic dispersion into the natural environment and, in 2019, the European Parliament approved the Directive 2019/904 on the *"reduction of the impact of certain plastics products on the environment"* to promote circular (European Parliament, 2019). Cups are one of these. Despite new recycling policies, promoting reuse remains the main effective solution to reduce the accumulation of plastic waste. In fact, to ensure reusability, the first step is to encourage the deposit return system (Cottafava et al., 2019). Several European Union (EU) countries already adopted national legislations to increase the use of reusable plastic with deposit return systems (CM Consulting Inc and Reloop Platform, 2016). Although reusable products can successfully limit the use of virgin materials and can have a positive effect on the material extraction/production, the impact could not be always positive by considering various environmental indicators. For instance, two recent studies on supermarket (Edwards and Fry, 2011) and grocery (Bisinella et al., 2018) carriers bags revealed how reusable cotton bags should be used thousands of times, i.e. dozens years of intensive use, to be environmentally better than equivalent single-use bags, which is clearly an unrealistic 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 studies have evaluated the environmental effects arising from the reuse of plastic products, by comparing the same service offered by single-use products (Garrido and Del Castillo, 2007; Almeida et al., 2018; Tua et al., 2019; Paspaldzhiev et al., 2018). However, 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 electronic 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 environmental point of view, if the impacts arising during 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 categories, in the case of electric and electronic equipments, mainly derive from the use phase. In the same way, Simon et al. (2001), considering washing machines, attributed 90% of the environmental impacts to the use phase. In fact, the lifetime extension due 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

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versus reusable products. To point out such considerations, in case of reuse, repair, remanufacturng, refurbishing, several researchers proposed various models to identify an environmental break-even point (BEP) - i.e. the minimum no. of reuses after which a reusable product is environmentally better than the single-use equivalent one (Barletta et al., 2018). For instance, Bobba et al. (2016) proposed a set of environmental and economic indicators to evaluate product durability, starting from the indicator proposed by Ardente and Mathieux (2014), which takes into account lifetime, energy consumptions, impacts of lifetime extension and of the replacement product. Boldoczki et al. (2020), instead, proposed a simple linear model to compare the reuse of devices with the purchase of new ones, by evaluating the environmental impact versus the usage duration (time). With respect to plastics products, similar analyses have been carried out by Almeida et al. (2018), who compared a commercial reusable coffee cup with single-use cups, with the aim of identifying the environmental BEP. From the relevant literature, a standard methodology does not exist yet and, thus, the debate about robust formalisms to model multi-cycle closed-loop processes is still open.

To face up this issue related to environmental assessment through LCA, in this paper a novel methodology for the interpretation of results is proposed, in order to facilitate comparisons between single-use and reusable products. To easily identify the environmental BEP, the product efficiency - the efficiency of the production and End of Life (EoL) phases - and the use efficiency have been introduced. The suggested formalism allows to decouple, in the BEP assessment, the effect of the use from the production and the EoL. This methodology has been applied to a case study, comparing four single-use cups with four reusable cups, by analyzing seven impact categories in three different use phase scenarios and two EoL scenarios.

The following of the paper is structured as follows. In section 2, the novel methodology is described by highlighting the differences with a traditional LCA analysis. In Section 3, the comparison between reusable and single-use cups is discussed in terms of the environmental break-even point. In Section 4, main results are compared with previous findings in the literature and some limitations of the 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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different scenarios related to the use phase and EoL have been analyzed. Figure 1 shows a detailed scheme of the system life cycle, highlighting the considered scenarios. In particular, four scenarios for the use phase - 0) single-use without loop (baseline), 1) onsite washing, 2) offsite washing, and 3) onsite handwashing have been considered

The baseline 0) case consists of using the cup once and then throwing it for disposal. The use phases have been modeled according to Martin et al. (2018) for 1) onsite handwashing, and 3) onsite washing with commercial washing machines. The onsite washing is modeled for the real situation, when the bars/pubs/restaurants directly wash the cups. The 2) offsite washing refers to the use of industrial washing machines (primary data) and an increasing transport distance. It models real situations, such as temporary events, small bars without washing machines, or catering for buffets during events.

Finally, with respect to the EoL phase, energy recovery and recycling/composting have been compared. Landfill scenario has been discarded as a possible scenario, according to the Circular Economy European Directive (European Parliament, 2020). So, two scenarios have been considered: 1) 100% energy recovery, and 2) full recycling or, in the case of PLA cups, composting.

2.2. Life Cycle Assessment

LCA is defined by the International Organization for Standardization (ISO) standards 14040 and 14044. According to ISO, the LCA methodology consists of four conceptual phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and results' interpretation (International Organization for Standardization, 2006a,b). The entire work was conducted with software SimaPro 8 and using the Ecoinvent v.3.3 database.

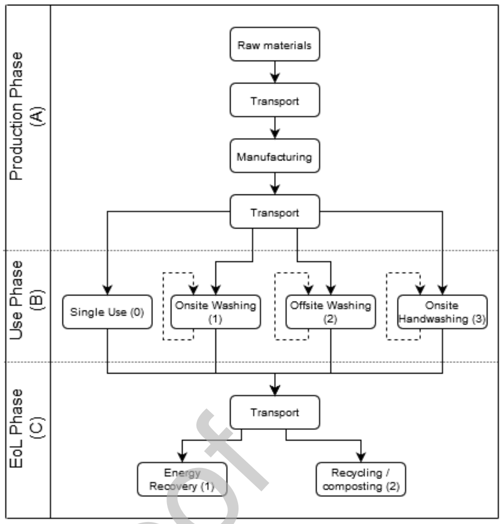

Figure 1: Overview of the analyzed scenarios.

2.2.1. Goal and scope definition

The aim of this work is to assess the environmental BEP of deposit back systems for cups, by identifying the minimum number of uses a reusable cup needs in order to be considered preferable than a single-use cup. To achieve this goal, the LCA analysis was applied to the case of disposable and reusable cups in order to identify the main environmental impacts. These were later used to determine the break-even point between the two service delivery strategies.

The chosen functional unit was serving 0.4 liters of draught beverages in one go, which allows to collect the data relating to the service in a single supply. These data constitute the starting point for modeling and studying the function of serving beverages repeated *n* times over time (function performed by disposable and reusable cups). The system boundary has been defined considering the whole life cycle from the extraction of raw materials up to the EoL phase, as shown in Figure 1.

2.2.2. Life cycle inventory.

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

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

5	Reusable cup [gr]				Single-use cup [gr]			
	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
Minimum, maximum, and average weight of the analyzed single-use and reusable cups.

The sources from which all inventory values were derived or measured are indicated in Table 1 in section B of the Supplementary Information (SI). Input-output data for the production, use and the EoL phases, are specified in Tables 2, 3, 4, 5, and 6 in section B of the SI.

The production of the plastic cups was modeled using the thermoforming and injection moulding processes for single use and reusable respectively (Crawford and Martin, 2020; Changwichan and Gheewala, 2020). Given the lack of specific data related to the production of PET cups, the system was modeled in a similar way to PP cups, taking into account the different physical-chemical properties of the polymeric materials.

The input data for the packaging refer to reusable cups. As no specific data were obtained for the disposable cups, the system was left unchanged in the two cases.

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

The use phase has been modeled with reference to three different types of washing for reusable cups: hand washing, dishwasher, and industrial washing (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 washing were directly measured in an Italian crockery washing company. In the case of industrial washing, the contribution of round-trip transport was also considered.

The EoL scenario of incineration has been modeled 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 recycled 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 expressed as midpoint results and the considered impact 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 directly 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 impact categories. In fact, for some raw materials (PP, PLA, PET, PE), the environmental impacts are usually 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.

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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 affect only *"when"* the BEP is achieved) or in the use phase (it affect *"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, letâĂŹs 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:

$$X = A_X + B_X + C_X \tag{1}$$

$$Y_0 = A_Y + B_{Y_0} + C_Y \tag{2}$$

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:

$$\eta_p = \frac{Y_0}{X} \tag{3}$$

η_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 η_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:

$$\eta_{u,j} = \frac{B_{Y_j}}{X} \tag{4}$$

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:

$$n_j = \frac{Y_0}{X - B_{Y_j}} \tag{5}$$

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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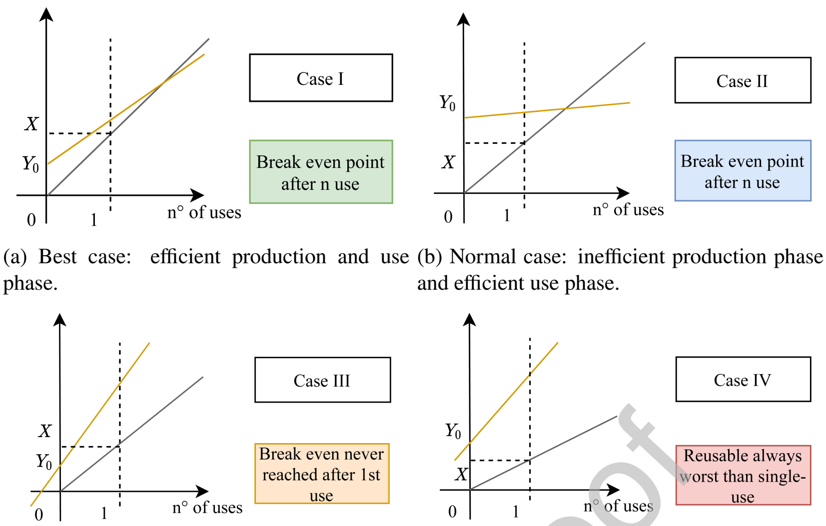

(a) Best case: efficient production and use phase.

(b) Normal case: inefficient production phase and efficient use phase.

(c) Limit case: efficient production phase and inefficient use phase.

(d) Worst case: inefficient production and use phase.

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. $n = 1$.

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

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

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

2.3.4. Mapping cases

From Eq. 3, Eq. 4 and Eq. 5 (or Eq. 6) four possible cases may be identified which explain the behavior of the reusable with respect to the single-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, η_p, and η_u

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According to Table 2, each case corresponds to a precise condition for n_j, η_p and η_u such as:

1. *Case I: Best case.* This solution happens when $n_j > 0$ (or $0 < \eta_u < 1$) AND $0 < \eta_p < 1$; it implies that the reusable product is better than the single-use product after n_j reuses when $\eta_p > 1 - \eta_u$, while if $\eta_p < 1 - \eta_u$, the reusable product is always better.
2. *Case II: Normal case.* This case occurs when $n_j > 0$ (or $0 < \eta_u < 1$) AND $\eta_p > 1$; it means that the reusable product is better than the single use only after n_j reuses.
3. *Case III: Limit case.* This one represents the transition case and it occurs when $n_j < 0$ (or $\eta_u > 1$) AND $0 < \eta_p < 1$; it corresponds to a particular condition when the reusable product is better only before the first use phase.
4. *Case IV: Worst case.* Finally, this last case refers to $n_j < 0$ (or $\eta_u > 1$) AND $\eta_p > 1$ and it means that the reusable product is always worse than the single-use product.

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

The four cases described in Table 2, if plotted, in logarithmic scale, in a scatter plot, correspond exactly to the four quadrants, i.e. best case ($\log(\eta_u) < 0$; $\log(\eta_p) < 0$), normal case ($\log(\eta_u) < 0$; $\log(\eta_p) > 0$), limit case ($\log(\eta_u) > 0$; $\log(\eta_p) < 0$) and worst case ($\log(\eta_u) > 0$; $\log(\eta_p) > 0$).

2.4. Case study analysis

2.4.1. Materials

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

2.4.2. Transport distance

With the same EoL scenario (i.e. 100% energy 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 machines (Martin et al., 2018);
3. offsite washing with industrial washing machines and increasing transport distance.

An upper distance limit, i.e. the maximum number 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 $B_{Y_{2,km}}$ according to:

$$n_{km,max} = \frac{X - B_{Y_{2,washing}}}{B_{Y_{2,km}}} \tag{7}$$

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 constraint 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 distance, was defined according to the following classification - 1) city (5km), 2) metropolitan area (30km), 3) district (80km), 4) region (200-300km), and 6) country (>400km).

2.4.3. Dispersion Rate

The dispersion rate d was also briefly analyzed with the same use scenario (i.e. offsite washing with a roundtrip of 20km) and EoL scenario (100% energy recovery for plastic and cardboard cups, recycling for glass cups). d is defined as the average number of reuses before a reusable cup is dispersed and is substituted with a new one. Dispersed means that the use phase loop, whatever use strategy considered, immediately ends up, and the production of a new cup is considered. For the sake of simplicity, the EoL was considered the same as declared for the "not dispersed".

2.4.4. EoL

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

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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 η_p (Eq. 3), since the use phase efficiency η_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:

$$\Delta\eta_{p,1\to2} = \eta_{p,2} - \eta_{p,1} = \frac{\Delta Y_{0,1\to2}}{X} = \frac{\Delta C_{Y_{0,1\to2}}}{X} \quad (8)$$

where $\Delta Y_{0,1\to2} = Y_{0,2} - Y_{0,1}$ is the variations in Y_0 from EoL scenario 1 (energy recovery) to 2 (recycling), while $\Delta C_{Y_{0,1\to2}}$ and $\Delta\eta_{p,1\to2}$ 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, $\Delta Y_{0,1\to2} = \Delta C_{Y_{0,1\to2}}$. Consequently, if $\Delta C_{Y_{0,1\to2}} > 0 \Rightarrow \eta_{p,2} > \eta_{p,1}$; 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 $\Delta C_{X_{1\to2}}$ can be described in terms of a variation of the product efficiency $\Delta\eta_{p,1\to2}$ and the use phase efficiency $\Delta\eta_{u,1\to2}$. In this case, both values vary. Indeed, since η_u is inversely proportional with respect to X:

$$\Delta\eta_{u,1\to2} = \eta_{u,2} - \eta_{u,1} = B_Y\left(\frac{1}{X_2} - \frac{1}{X_1}\right) = -B_Y\frac{\Delta C_{X_{1\to2}}}{X_1X_2} \quad (9)$$

an increase in the EoL impact for single-use products, $\Delta C_{X_{1\to2}} > 0$, implies a reduction in the use efficiency

$\Delta\eta_{u,1\to2} < 0$, while $\Delta C_{X_{1\to2}} < 0 \Rightarrow \Delta\eta_{u,1\to2} > 0$. The same inversely proportionality holds for the product efficiency, according to

$$\Delta\eta_{p,1\to2} = -Y_0\frac{\Delta C_{X_{1\to2}}}{X_1X_2} \quad (10)$$

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

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

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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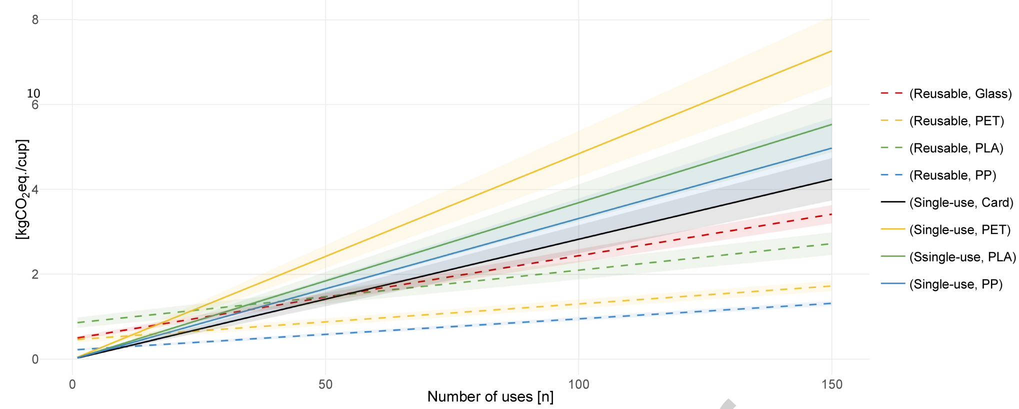

Figure 3: Climate Change (CC) for the offsite washing scenario with a transport distance of 20km during the use phase and energy recovery at EoL for plastic materials and recycling for glass. The shaded areas represent the uncertainty due to the minimum and maximum weights, while the line represent the 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 cups is achieved for less than 10 uses.

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.

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.

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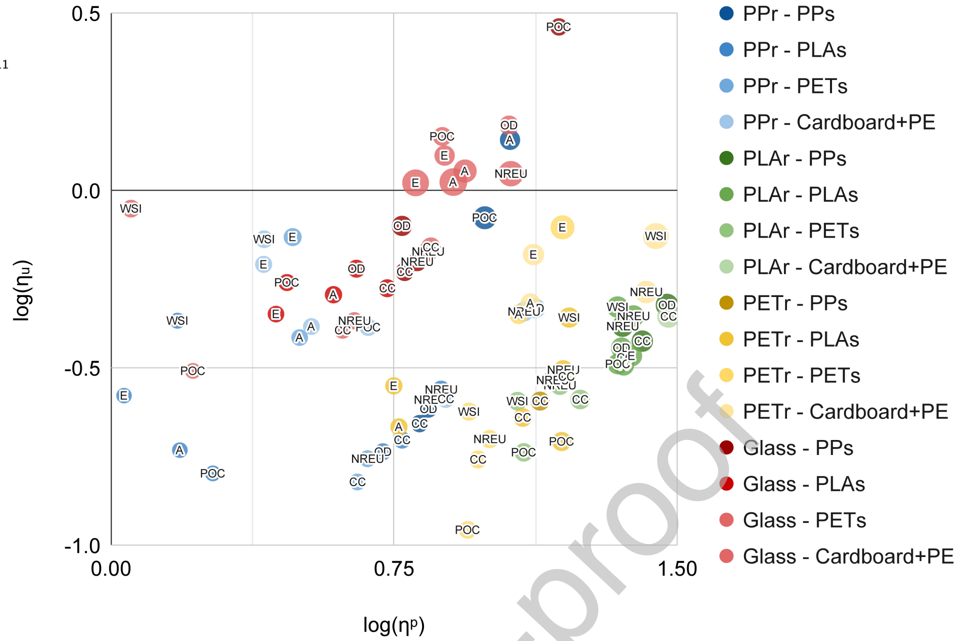

Figure 4: Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$ of the scatter plot of the use efficiency η_u vs the product efficiency η_p related to the material analysis. Midpoint impact categories refer to offsite washing and energy recovery EoL strategy.

Regarding the reusable cups, the best performance refers to the PP cups, followed by the PET cups, while the glass and PLA reusable cups are the worst ones. The bad performance of glass and PLA reusable cups is due both by a high impact during the production and EoL phase (see corresponding values at n=0) and by their high weight, which affects the use phase and thus the slope of the line. For this impact category, PP and PET reusable cups achieved the BEP for $n < 20$ with respect to all single-use cup types (avoiding the PP single-use cup), while PLA and glass reusable cups perform better than PLA single-use cup after 40 uses. Finally, PLA reusable cups, in comparison with the cardboard+PE and PET single-use cups, achieve the BEP after a large number of reuses ($n > 150$).

With respect to POC impact category (Fig. 1c in the SI) the best solutions for any n are the single-use and reusable PP cups. The PP reusable cups, 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 respectively 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 carboard+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

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reusable cups perform better only for less than 150 reuses.

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

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

In conclusion, single-use PP cups are the best solution with respect to A, POC (for $n < 100$), E, and WSI, while reusable PP cups are the best ones among the other reusable solutions with respect all midpoint impact categories. PET and PLA reusable cups are, respectively, the 2nd and the 3rd best choice, among reusable cups except for the OD, E, and WSI impact categories. In fact, PET is the unique material with a not negligible OD impact (i.e. it is the worst material), and, PLA, due to the impact during the production phase, is the worst solution with respect to E and WSI impact categories. Regarding single-use cups, the cardboard+PE cups are the best considering the CC and NREU impact categories, while, for all the other impact categories, the PP single-use cup solution performs better. For all categories, PLA and PET single-use solutions, generally, impact more than PP and cardboard+PE. On the contrary, reusable plastic (PP, PET, PLA) cups reach a BEP for all the impact categories (except for the above-mentioned cases against single-use PP cups) after a variable number of reuses, generally lower than 150. Finally, for all the impact categories, because of the high weight, the glass cups are strongly affected by the transport phase, and even if the production and EoL phases, in some cases, is better than reusable plastic cups, the impact for large n is always the worst. Thus, a more detailed analysis of transport distance is presented in the next paragraph.

Use and product efficiency: scatter plot The material analysis are also reported in the scatter plots (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 different materials for the reusable cups, while different gradients of the same colour point out the comparison 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 simultaneously for all analyzed impact categories. The reusable glass cups (red series) are the worst performing 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 $\eta_u \to 1$ (i.e. $B_{x,j} \to X$), or $\log(\eta_u) \to 0$, $n \to \pm\infty$. PP reusable cups are slightly better than PLA and PET reusable cups for the production and EoL phases. With respect to the use efficiency η_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 impact 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 section 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 related to the PP reusable cups and the four types of single-use cups with respect to the three use scenarios. 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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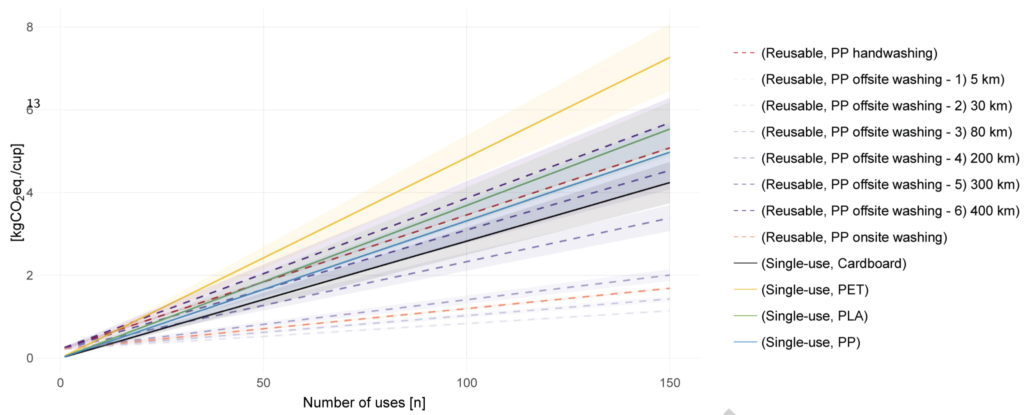

Figure 5: CC of reusable PP cups for onsite handwashing/washing (dashed lines), and offsite washing (dotted lines) VS single-use (continuous lines).

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	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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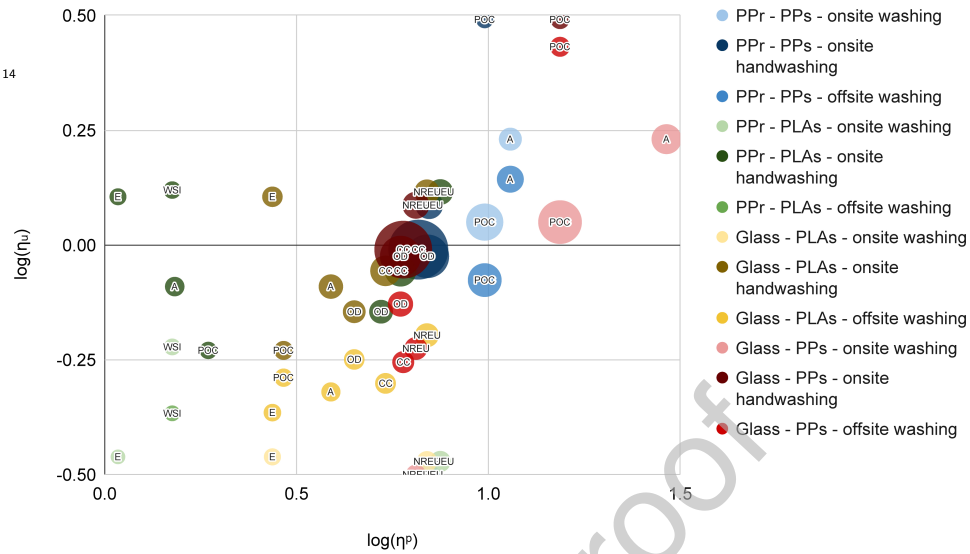

Figure 6: Zoom for $-0.5 < \eta_u < 0.5$ and $0 < \eta_p < 1.5$ of the scatter plot (logarithmic scale) of the use efficiency η_u vs the product efficiency η_p with different use phases. The acronyms CC, OD, A, POC, E, NREU, and WSI represent respectively: global warming, ozone depletion, acidification,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

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).

Finally, the same results can be obtained for the other reusable cups simply by multiplying the $n_{km,max}$ 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.

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 (η_u) and product efficiency (η_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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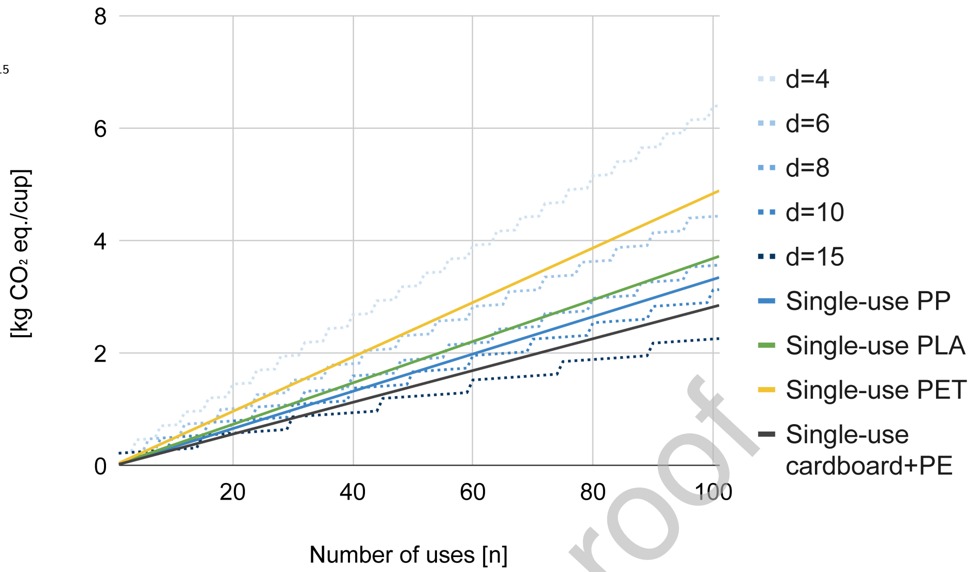

Figure 7: CC of reusable PP cups for offsite washing (dotted lines) vs single-use (continuous lines) with different dispersion rate.

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 (Vercalsteren 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.

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Finally, Table 8b and 8c must be read simultaneously and quickly show when a change in EoL strategy for single-use products induces a change in the sign for *n*, and, thus, the environmental BEP is now reached or not.

Thus, Table 8b and 8c show that by comparing recycling C_{X_2} with energy recovery C_{X_1} strategy for single-use in few cases the BEP is no more achieved. In particular, in the case of onsite washing, with respect to CC for PP cups, the environmental BEP is no longer achieved when single-use cups are recycled instead of incinerated, while for PET single-use cups the BEP is no longer achieved for A, E, and WSI impact categories. With respect to PLA cups, instead, there is no change in the sign for any impact category (Table 8b) for *n* by changing the EoL strategy for single-use. In the case of offsite washing, instead, there is only one change in sign (for Eutrophication for PP cups) but in this case it's a positive change in sign, thus, the BEP is now achieved. Again, for PLA there is no change in the sign for *n*, and for PET as well. Thus, by analyzing the two best use phase scenarios for reusable cups, i.e. onsite washing and offsite washing, in a scenario where single-use cups are 100% recycled the environmental benefits are no longer maintained neither for the CC.

4. Discussion

By adopting this approach based on the environmental BEP, the product and use efficiency, a standard functional unit, i.e. one single-use, can be used, simplifying comparisons among LCA studies. Such an approach may be particularly suitable for monitoring the performance of an organization in the most recent framework of the Organizational LCA (OLCA) (Martínez-Blanco et al., 2015) but further studies are needed to homogenize results' interpretation according to UNEP (Blanco et al., 2015) guidelines and to the most recent ISO/TS 14072: 2014 (International Organization for Standardization, 2014).

In next subsections, findings of the present work are compared with previous studies, highlighting and discussing limitations and advantages of the proposed methodology.

4.1. Comparison of results with literature

In the last decade, the comparison of environmental performance between reusable and disposable cups has been the subject of several studies. Studies often have shown the difficulty of completing an effective and objective comparison. For instance, van der Harst and Potting (2013) compared ten disposable cups, showing that, due to the different methodological choices and differences in legislative rules, it was not feasible a reliable comparison. Vercalsteren et al. (2010), instead, analyzed four types of cups - reusable polycarbonate and single-use polypropylene, PE-coated cardboard, and polylactide cups - in large and small events thanks to a comparative LCA study. To compare reusable versus 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 better 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 Garrido 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 washing phase. The comparison between reusable and single-use coffee cups - made of different materials - were performed in a work by Almeida et al. (2018). Polypropylene and glass reusable cups, produced by a specific company, were compared with generic PP and bamboo reusable cups and with paper 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 materials - are better than disposable alternatives after around 10-20 uses. These results are partially in agreement with what we obtained from our analysis. 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-

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port). In another work, Potting and van der Harst (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 are 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 plastics 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 approach 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 η_u and the product phase efficiency η_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 η_u and η_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 the product efficiency η_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

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

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

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

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* (η_p), 2) the *use phase efficiency* (η_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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been quantified in terms of the maximum distance (km) allowed during the use phase in order to achieve an environmental break-even point after an infinite number of reuses. With respect to PP single-use cup, the environmental break-even point is never achieved for A, E, and WSI, while for PET, PLA, and cardboard single-use cup the environmental break-even point is attained for all midpoint impact categories. Excluding also POC impact category with respect to PP single-use cups, in all the other cases a break-even point is always achieved for a transport distance during the use phase lower than 100km. Finally, onsite handwashing is the worst solution while onsite washing is an intermediate solution. For instance, in terms of CC, they are comparable with offsite washing with a distance of 350km and 50km, respectively.

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

Within the current transition to the circular economy, the presented methodology may be adopted by manufacturers of reusable products, as well as by researchers, practitioners, and decision-makers, to evaluate the introduction of new circular products, or circular business models, and to correctly identify if, and under which conditions, a reusable product is environmentally better than an equivalent single-use product. Future studies related on the discussed case study on reusable and single-use cups should focus on the comparison of different End of Life scenarios and in collecting up to date primary data related to the production and End of Life phase. More in general, the proposed methodology should be homogenized with the most recent framework of the Organizational Life Cycle Assessment introduced by the ISO/TS 14072:2014.

Disclosure statement

No potential conflicts of interests were reported by the authors.

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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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