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# Comparative life cycle analysis of disposable and reusable tableware: The role of bioplastics

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ABSTRACT

Annually, 115.000 tons of plastic tableware are used in Italy. The end of life of these objects is particularly troubled because no efficient way of recycling or reusing exist. Studies performed by the European Union demonstrate that about 80% of sea waste is made of plastic, representing a danger to human health and ecosystem. The aim of this paper is to analyse substitutes to disposable plastic tableware using the Life Cycle Assessment methodology. The alternatives are objects made of bio compostable plastic, both disposable and reusable. This article compares single-use and multi-use tableware made of a Polylactic acid (PLA) - Polybutylene succinate (PBS) blend with traditional disposable tableware made of polypropylene and of polystyrene. In order to perform an effective assessment, the objects are grouped in place settings, each made of a cup, a plate and cutlery. The use of tray mat and napkin is also taken into account. It was assumed that the fossil-based items are sent to landfill whereas the bio-based ones are sent to a compost plant. The functional unit chosen was “the service of 1000 meals”. The impact categories taken into account are Global Warming 100a, Ozone Depletion, Ozone Formation (Vegetation), Acidification, Aquatic Eutrophication, Human Toxicity water and Ecotoxicity water chronic. The results show that the compostable table sets have lower impact than the sets made of fossil-based plastic in all the categories except in Ozone Depletion and in Aquatic Eutrophication. In the categories of Human Toxicity water and Ecotoxicity water chronic, fossil-based materials have higher impact than multi-use one mainly due to the landfill scenario chosen as end of life. Disposable and reusable systems give a different contribution to total impact in different life stages. For disposable systems, the production and the end of life are the critical stages in terms of environmental burden, whereas for reusable systems washing is the most impactful phase. Further improvements can be obtained in the production of bio-based materials by using renewable energy to power the facilities whereas the washing phase can be improved by adopting certified ecopower. The impact of the reusable system strongly depends on the assumptions made on the number of reuses and on the washing modality.

## 1. Introduction

Although in recent times the Corona Virus pandemic has momentarily altered daily needs with the introduction of Smart Working, collective catering is a fundamental element for many workers who find themselves forced to eat at least one meal a day away from home. The use of non-biodegradable disposable items is highly widespread in this sector: it is estimated that in Italy the consumption of plastic tableware is 115,000 tons per year with a production value of approximately 960 million euros (Moronese, 2018). The problems linked to the abandonment of single-use plastic in favor of reusable items are not few. Single-use provides high levels of safety and hygiene and helps to maintain the freshness of packaged food, reducing food waste (ANGEM, 2020). A valid substitute could be bioplastics but, as pointed out by ANGEM (National Association of Canteens and Services), their introduction presents some obstacles. The production of bioplastics is currently not comparable in quantity to that of fossil plastics, so it is not sufficient to fully meet the demand of the sector. In addition, the current price of bioplastics is higher than for non-compostable alternatives and its adoption would lead to an increase in the price of meals that public and private users are often unwilling to pay. The debate on the adoption of alternatives to the current system based on plastics of fossil origin is,

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**Table 1**
Reference flow of the studied systems.

| | PLA set | | PP set | | PS set | | Multi-use set |
|---|---|---|---|---|---|---|---|
| 1000 | Disposable plate made of PLA-PBS | 1000 | Disposable plate made of Polypropylene | 1000 | Disposable plate made of Polystyrene | 1 | Multi-use plate made of PLA-PBS |
| 1000 | Disposable cup made of PLA-PBS | 1000 | Disposable cup made of Polypropylene | 1000 | Disposable cup made of Polystyrene | 1 | Multi-use cup made of PLA-PBS |
| 1000 | Disposable cutlery made of PLA-PBS | 1000 | Disposable cutlery made of Polystyrene | 1000 | Disposable cutlery made of Polystyrene | 1 | Multi-use cutlery made of PLA-PBS |
| 1000 | Tray mat and napkin | 1000 | Tray mat and napkin | 1000 | Tray mat and napkin | 1000 | Tray mat and napkin |
| | | | | | | 1000 | Washing |

therefore, very complicated and transcends the strictly environmental topic, involving economic, political and social matters. The issue is now of capital importance due to the approval of the EU Directive 2019/904, which aims to ban and disincentivize production and marketing of specific single-use plastic items. European Commission points out that more than 80% of the waste found in the sea is made of plastic (The European Parliament and The Council, 5 june 2019). Due to its slow decomposition process, it accumulates in seas, oceans and beaches, representing a serious danger to marine fauna and, through the food chain, also to man. The creation of a circular economy for plastic requires an intervention aimed at promoting the adoption of reusable or recyclable items, or the introduction of more sustainable materials. In the present study, the alternatives to fossil-based plastics taken into account are items made of bioplastic, both reusable and disposable. Biodegradability under composting conditions is determined by applying the standard EN 13432 (EN13432, 2000), according to which biodegradable items degrade by at least 90% in 6 months when subjected to a carbon-rich environment. Due to the presence of food residues, no efficient form of recycling fossil-based items is currently widely in use. Currently, incineration and landfill are the most popular alternatives to decrease the quantity of polypropylene waste (Mannheim and Simenfalvi, 2020). Therefore, the compostable objects represent a great chance to design a new, green, cleaner world. The fundamental role of tableware in everyday life justifies the necessity of an evaluation from an environmental point of view. Using the LCA methodology, several comparisons were made involving different alternatives. Vercalsteren et al. (2010) considered different raw materials for cups and the possibility of adopting reusable fossil-based items. Garrido and Alvarez del Castillo (2007) focused on fossil-based cups, calculating the minimum number of uses for a reusable system to be environmentally equivalent to a disposable one. The possibility of adopting reusable non-compostable systems was also assessed for takeaway food (Gallego-Schmid et al., 2018) and for the aviation catering sector (Blanca-Alcubilla et al., 2020). For food service (Fieschi and Pretato, 2017), put the attention on disposable systems, assessing the environmental burden of biodegradable items over traditional ones. In this study, the focus concerned the neglected topic of the evaluation of disposable over reusable bioplastic items. The comparison is carried out by considering different table place compositions, each including the main items that are usually needed during a meal. Also, fossil-based systems are considered, in order to analyze the world of tableware on a broad scale.

## 2. Methodology and data

The study is made following the Life Cycle Assessment methodology, using the SimaPro 9 (SimaPro, s.d.) software, developed by PRé Consultants, to perform the calculation. As prescribed by the ISO 14040 series, the following phases are presented.

- Goal and scope definition
- Life cycle Inventory
- Life cycle assessment
- Life cycle interpretation

### 2.1. Goal and scope definition

The aim of this analysis is to perform a Life Cycle Assessment of the main types of kitchenware and cutlery used in food catering by comparing different place settings. Each place setting is made of a plate, a cup, the cutlery, a tray mat and a napkin. In detail, the following systems are compared in this analysis.

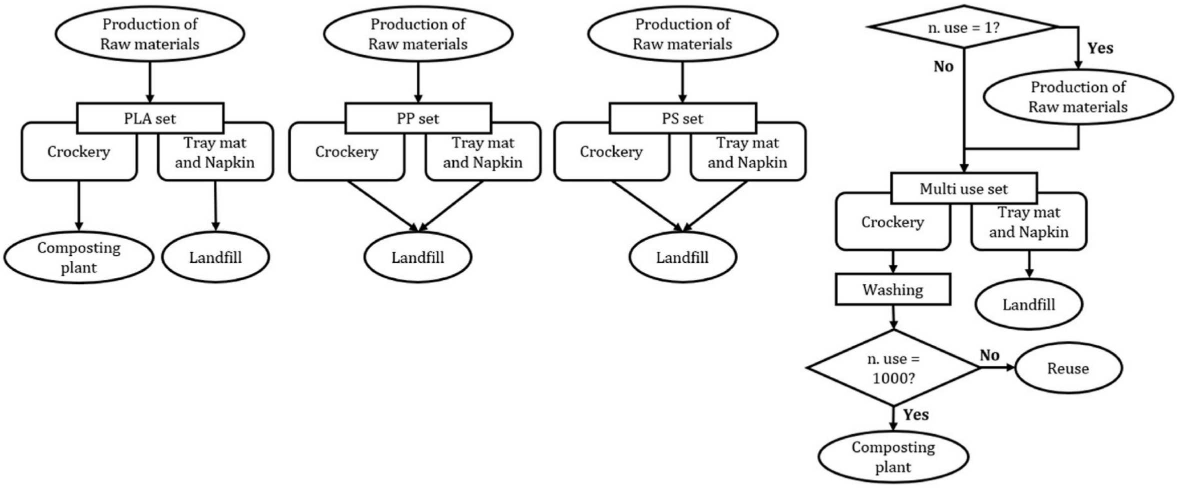

**Fig. 1.** Unit processes involved in serving one meal.

**Table 2**
Impact categories and unit of measure.

| Impact category | Unit |
|---|---|
| Global Warming 100a | kg CO$_2$ eq |
| Ozone depletion | kg CFC11 eq |
| Ozone formation (Vegetation) | m$^2$.ppm.h |
| Acidification | m$^2$ |
| Aquatic eutrophication EP(N) | kg N |
| Human toxicity water | m$^3$ |
| Ecotoxicity water chronic | m$^3$ |

- The *PLA set*, made of Polylactic acid (PLA) - Polybutylene succinate (PBS) crockery and cutlery, a paper tray mat and a paper napkin. All the items are disposable.
- The *PP set*, made of Polystyrene (PS) cutlery, Polypropylene (PP) crockery, a paper tray mat and a paper napkin. All the items are disposable.
- The *PS set,* made of Polystyrene (PS) crockery and cutlery, a paper tray mat and a paper napkin. All the items are disposable.
- The *Multi-use set*, made of Polylactic acid (PLA) - Polybutylene succinate (PBS) crockery and cutlery, a paper tray mat and a paper napkin. The crockery can be reused after being washed whereas the tray mat and the napkin are disposable.

### 2.2. *Functional unit*

The functional unit used in this study is “the supply of 1000 meals” (Fieschi and Pretato, 2017), (Pro.mo/Unionplast, 2015). The reference flow, sufficient to fulfill the functional unit, is quantified in Table 1. The assumption made is that the multi-use set is washed after every use.

### 2.3. *System boundaries and assumptions*

The analysis is made on “cradle to grave” systems. The production of raw materials is included in the system, but the following converting processes to get the disposable and the reusable items are excluded, as they do not change significantly the results. In the multi-use system, a washing process is also included. After being used, the compostable items are sent to a composting plant whereas the tray mat, the napkin and all the fossil-based items are sent to landfill. In fact, among the approaches for decreasing the amount of polypropylene waste, incineration and landfill are the most popular alternatives (Mannheim and Simenfalvi, 2020).

A schematic representation of the systems as described is provided in Fig. 1. The unit processes shown are referred to one meal served, so a thousand of them must be considered to fulfill the functional unit. Usually, no recycling is possible because of the food residues on the objects, so this scenario was not taken into account. Furthermore, no transport was included because no detailed information was available. The considered systems are a simplification of the real ones thus the results should be interpreted in this perspective.

### 2.4. *Impact categories*

The impact categories analysed in this paper are chosen among the PEF (European Commission (EC), July 17, 2012) suggested ones. The EDIP2003 method was chosen for the evaluation, since this method is one of the most faithful to the IPPC (Intergovernmental Panel on Climate Change) and WMO (World Meteorological Organization) principles (Masoni & Scimìa, s.d.). In Table 2 all the chosen categories and their unit of measure are provided.

### 2.5. *Inventory*

The data used in life cycle inventory are gathered from different and various sources.

**Table 3**
Composition and mass of compostable items.

| Disposable PLA-PBS plate | Mass: 12.9g | Multi-use PLA-PBS plate | Mass: 62.5g |
|---|---|---|---|
| Talc | 12% | Talc | 12% |
| PLA (poly-lactic acid) | 70.4% | PLA (poly-lactic acid) | 70.4% |
| PBS (poly butylene succinate) | 17.6% | PBS (poly butylene succinate) | 17.6% |
| **Disposable PLA-PBS cup** | **Mass: 4.4g** | **Multi-use PLA-PBS cup** | **Mass: 25g** |
| PLA (poly-lactic acid) | 25% | PLA (poly-lactic acid) | 25% |
| PBS (poly butylene succinate) | 45% | PBS (poly butylene succinate) | 45% |
| Talc | 30% | Talc | 30% |
| **Disposable PLA-PBS cutlery** | **Mass: 7.6g** | **Multi-use PLA-PBS cutlery** | **Mass: 37.5g** |
| Talc | 30% | Talc | 30% |
| PLA (poly-lactic acid) | 56% | PLA (poly-lactic acid) | 56% |
| PBS (poly butylene succinate) | 14% | PBS (poly butylene succinate) | 14% |

**Table 4**
Composition and mass of some item of PP set.

| Polypropylene Plate | Mass: 15g |
|---|---|
| Polypropylene | 64.3% |
| PP Compound (70% calcium carbonate) | 37.5% |
| **Polypropylene Cup** | **Mass: 6g** |
| Polypropylene | 100% |
| **Polystyrene Cutlery** | **Mass: 7.6g** |
| Polystyrene | 100% |

**Table 5**
Composition and mass of some item of PS set.

| Polystyrene Plate | Mass: 15g |
|---|---|
| Polystyrene – High Impact | 56.7% |
| Polystyrene (PS) | 7.6% |
| PS Compound (70% calcium carbonate) | 35.7% |
| **Polystyrene Cup** | **Mass: 6g** |
| Polystyrene | 100% |
| **Polystyrene Cutlery** | **Mass: 7.6g** |
| Polystyrene | 100% |

The modelling of compostable items combines composition data obtained from the company Bioware S.R.L (Bioware S.R.L, s.d.) with mass value obtained from literature research (Fieschi and Pretato, 2017). In Table 3 composition and mass are provided for each object.

SimaPro’s database was not used for the material listed in Table 3. As talc was not present in any of the provided library, Feldspar was used instead, since they have a comparable impact (Hill and Norton, 2018). To model Poly-lactic acid (PLA), the ecoprofile provided by NatureWorks was used, referred to 2006 production (Vink et al., 2007). The modelling of PBS is based on the production process of hybrid poly butylene succinate (Moussa, 2014). The PBS synthesis is achieved from 1,4-butanedion and succinic acid (Cok et al., 2014). The end of life of the compostable items is modelled as *Biowaste {CH}| treatment of, composting*, using the Ecoinvent library (Wernet et al., 2016).

The tray mat and the napkin are modelled using the Ecoinvent track *Tissue paper {GLO}| market for*. Their total mass is assumed to be 7.8g (Fieschi and Pretato, 2017).

Composition and mass of Polypropylene and Polystyrene items are derived from literature (Pro.mo/Unionplast, 2015) and are provided in Table 4 and in Table 5.

The different weight shown in Table 3and in Table 4 is due to the different thickness of the PLA objects compared to the PP ones, in particular the PLA dishes appear thinner than the PP ones. (Bioware S.R.L, s.d.)

**Table 6**
Ecoinvent traces used for the fossil-based tableware modelling.

| Material | Ecoinvent reference |
|---|---|
| Polystyrene | Polystyrene, general purpose {GLO}\| market for |
| Polystyrene – high impact | Polystyrene, high impact {GLO}\| market for |
| Calcium carbonate | Calcium carbonate, precipitated {RER}\| market for |
| Polypropylene | Polypropylene, granulate {GLO}\| market for |

**Table 7**
Washing consumption per place setting - dishwasher.

| Resource | Amount per place setting |
|---|---|
| Electricity | 0,018 kWh |
| Water | 0,21 l |
| Detergent | 0,0006 kg |

**Table 8**
Composition of the detergent.

| Ingredient | Quantity |
|---|---|
| Potassium tripolyphosphate solution, 50% (mass fraction) | 20% |
| Potassium hydroxide, 50% (mass fraction) | 36% |
| Sodium silicate (water glass) | 23% |
| Oxidizing agent | 0–4% |
| Deionised water | 17–21% |

The materials listed in Tables 4 and 5 were modelled using Ecoinvent library. For reasons of confidentiality, the information on the formula of the compounds is to be considered as indicative. For this study, the compounds were modelled by adding calcium carbonate to the main plastic material, according to the given percentage. In detail, the traces of the Ecoinvent database used are provided in Table 6.

The landfill scenario is modelled as *Municipal solid waste (waste scenario) {CH}| Treatment of municipal solid waste, landfill*, using the Ecoinvent library.

The washing process of the multi-use items is modelled by quantifying the amount of water, detergent and electricity needed (Paspaldzhiev et al., 2018). Data are provided per item. It is assumed that a place setting is made of three items, so the values used for this analysis are represented in Table 7. The consumptions are referred to a dishwasher with a 2014 technology level.

Electricity was modelled using the Italian energy production mix, provided by the Ecoinvent database. The detergent composition is a representative reference of detergents commonly used in European market (Rüdenauer et al., 2011). All the ingredients, provided in Table 8, are modelled using Ecoinvent library.

## 3. Results and discussion

### 3.1. Impact assessment results

The environmental impact of “supplying 1000 meals” is represented in Fig. 2. For greater usability, the results are shown in terms of percentages. For each category, the most impactful system is given the

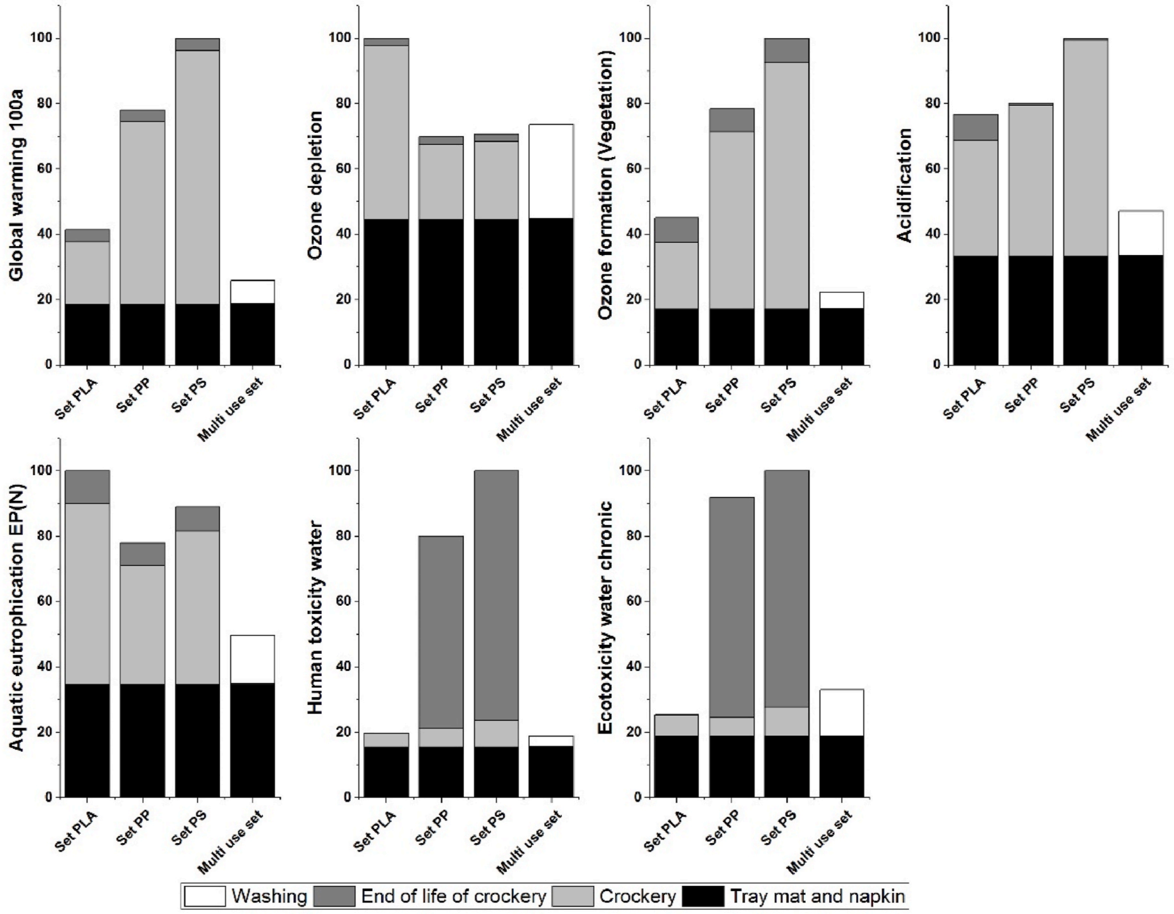

**Fig. 2.** Impact assessment of the baseline analysis- Global Warming Potential, Ozone Depletion, Ozone Formation, Acidification, Aquatic Eutrophication, Human Toxicity water, Ecotoxicity water chronic.

value of 100 and all the other systems are represented proportionally. A contribution analysis is also provided to better understand the role of the elements of each system. The label "Tray mat and napkin" represents the whole life cycle of the tray mat and the napkin, which is separated from the crockery. The label "Crockery" represents the impact of raw material production. It is introduced to visualize the contribution of bio-based plastic versus fossil-based plastic.

The bio-based systems, disposable or reusable, have lower impact in most categories. In Human toxicity and Ecotoxicity, fossil-based systems have higher impact due to the end of life of crockery. In fact, the landfill scenario gives a very strong contribution to toxicity of the fossil-based systems whereas the impact of compost can be considered negligible. In the reusable system, production and end of life of crockery have unimportant impact compared to the correspondent phases of disposable systems. Besides the tray mat and napkin, for this set the washing process gives the greatest contribution in all the considered categories.

With regard to disposable systems, the impact value of most categories found in the present study is aligned with the results obtained in the comparison of various disposable place settings used in quick service restaurants, contract catering and events reported in Fieschi and Pretato (2017). Furthermore, the trend herein observed can be found also for plastic bottles (Gironi and Piemonte, 2010). In this case, the environmental burden of a PLA bottle is compared to a fossil-based bottle made of PET. The advantages of adopting compostable items over non-biodegradable ones was also demonstrated for cutlery (Razza et al., 2009). The impact of the Tray mat and napkin, shown in Fig. 2, is always greater than the end of life of crockery in all impact categories except in Human Toxicity water and in Ecotoxicity water chronic.

In Global warming potential and Ozone formation, fossil-based systems keep on having higher impact due to production of the raw materials necessary for the fabrication of the crockery. Limited to the category of Global warming potential, the higher impact of the fossil-based systems over compostable ones was also reported in the literature for several items, especially for landfilling. The use of PLA to produce deli containers, envelope window film, foam meat trays and water bottles leads to lower emission in terms of $CO_2$ equivalents compared to fossil-based alternatives (Franklin Associates, 2006). The same result can be obtained by comparing carton-based cups coated in polyethene or polylactide to PET cups (Häkkinen and Vares, 2010). Studies on packaging films have demonstrated that also landfilling is an effective end of life for PLA items (Choi et al., 2018). In fact, the PLA film in landfill had a better performance compared to fossil-based film and PLA blend film. If it is assumed that the carbon embodied in PLA is fully sequestered in landfill, PLA and PP are equivalent in terms of greenhouse gas emissions, as demonstrated for food packaging (Bohlmann, 2004). Considering different end-of-life scenarios can lead to different performances. In fact, landfill system is the worst waste management option and significant improvements con be introduced by undertaking energy recycling (Cherubini et al., 2009). However, it was shown that the emissions in terms of $CO_2$ of landfill scenario are almost comparable to the ones of a scenario where items are 40% recycled, 30% incinerated and 30% landfilled (Madival et al., 2009).

In terms of Ozone Depletion and Aquatic Eutrophication, the disposable bio-based system has the highest impacts, this being ascribable to the necessary steps to grow the sugar cane or the other raw materials necessary to the fabrication of the bioplastics. In particular, during feedstock's cultivation, the use of fertilizer leads to higher eutrophication potential (Changwichan et al., 2018). Feedstock's cultivation and lactic acid production stage have an influence on Acidification too. This is mainly due to the production of the chemicals used, to transportation of raw materials and to energy generation for the process (Morão and Bie, 2019). The high impact of biopolymer production in these three categories is also confirmed by (Tabone et al., 2010). The impact of this life stage may be reduced by using renewable electricity to power the facilities (Vink et al., 2007).

In the category of Acidification, PLA set and PP set have comparable impact. This is due not only to the influence of feedstock's cultivation but also to the strong contribution given by the composting process. In fact, gaseous emissions from composting and anaerobic digestion increase the impact in terms of Acidification. It could be reduced by designing an efficient gaseous emissions treatment in the composting facilities (Al-Rumaihi et al., 2020). On the other hand, in Human Toxicity water and Ecotoxicity water chronic the composting process has a small impact, compared to the landfill scenario. This causes fossil-based systems to reach very high values in these categories.

The impacts achieved for the disposable sets in this study are however significantly different from the impacts calculated in several comparative studies concerning plates manufactured in different raw materials. In (Bevilacqua et al., s.d.), a compostable plate, made of Mater-bi, was compared to a Polypropylene plate. The impact of the compostable plate was found to be higher in most categories, in contrast with the results obtained in this study. A similar result was obtained in the comparison of items made entirely of PLA with fossil-based ones (Pro.mo/Unionplast, 2015). Also in the comparison of clamshell made of PLA with fossil-based alternatives (Madival et al., 2009), the trend observed differs from the one obtained in the present study. The composition of the compostable objects and the processing technology of the raw materials influence the results. Using a different production system for PLA can lead to diverse outcomes, as assessed for cups (Vercalsteren et al., 2010). The optimization of production process can lead to a reduction of the environmental impact from bioproducts (Uihlein et al., 2008).

A different comparison of PLA clamshell with PS, PP and PET alternatives (Detzel and Krueger, 2006) confirms the trend obtained in the present paper for most categories. The different PLA technology considered is one of the reasons of the spotted differences. In the present study, the PLA6 was used, which represents the production technology of NatureWorks (NatureWorks, s.d.) for year 2006. In the IFEU study, the PLA5 is considered, representative of the 2005 NatureWorks (NatureWorks, s.d.) technology. The performances of the two present various differences (Vink et al., 2007) (Detzel and Krueger, 2006).

The multi-use set shows the lowest impact in several categories, in particular Global Warming Potential, Ozone Depletion, Ozone Formation, Acidification, Aquatic Eutrophication. The benefits derived from the reusable system strongly depend on the considered conditions of use as confirmed by the contrasting results of several previous studies. In the comparison between recyclable cardboard boxes and reusable plastic crates (Koskela et al., 2014), the reusable system has the greatest environmental burden. This is mainly due to the role played by transportation, which was not considered in this analysis. Reusable items have higher weight, so transportation gives greater contribution. On the other hand, if plastic single use crates are considered, the advantages of the reusable system are evident after only two uses (Tua et al., 2019). Comparisons between disposable cardboard boxes and reusable plastic boxes (Bala and Fullana, 2017) (Abejón, 2020) stated the convenience in adopting multi-use systems over single-use ones. The importance of the mass of reusable items was also highlighted for drinking bottles (Nessi et al., 2012) and for the aviation catering sector (Blanca-Alcubilla et al., 2020).

The study on the adoption of reusable plastic container in a food catering supply chain (Accorsi, 2014) confirms the reduction of the environmental burden due to the adoption of reusable plastic crates in terms of $CO_2$ emissions. The mentioned paper points out the influence of several parameters on the result of reusable systems. Uncertainty in data and parametric values can be found also in disposable systems (van der Harst et al., 2014). Therefore, a complete representation of all the real cases is challenging. For this reason, two sensitivity analysis are herein performed, in sections 3.2 and 3.3, in order to assess the susceptibility of the results to the number of uses and to the washing modality of the reusable system.

**Table 9**
Reference flow for the Sensitivity analysis on the number of uses.

| | PLA set | | PP set | | PS set | | Multi-use set |
|---|---|---|---|---|---|---|---|
| 1000 | Disposable plate made of PLA-PBS | 1000 | Disposable plate made of Polypropylene | 1000 | Disposable plate made of Polystyrene | 100 | Multi-use plate made of PLA-PBS |
| 1000 | Disposable cup made of PLA-PBS | 1000 | Disposable cup made of Polypropylene | 1000 | Disposable cup made of Polystyrene | 100 | Multi-use cup made of PLA-PBS |
| 1000 | Disposable cutlery made of PLA-PBS | 1000 | Disposable cutlery made of Polystyrene | 1000 | Disposable cutlery made of Polystyrene | 100 | Multi-use cutlery made of PLA-PBS |
| 1000 | Tray mat and napkin | 1000 | Tray mat and napkin | 1000 | Tray mat and napkin | 1000 | Tray mat and napkin |
| | | | | | | 1000 | Washing |

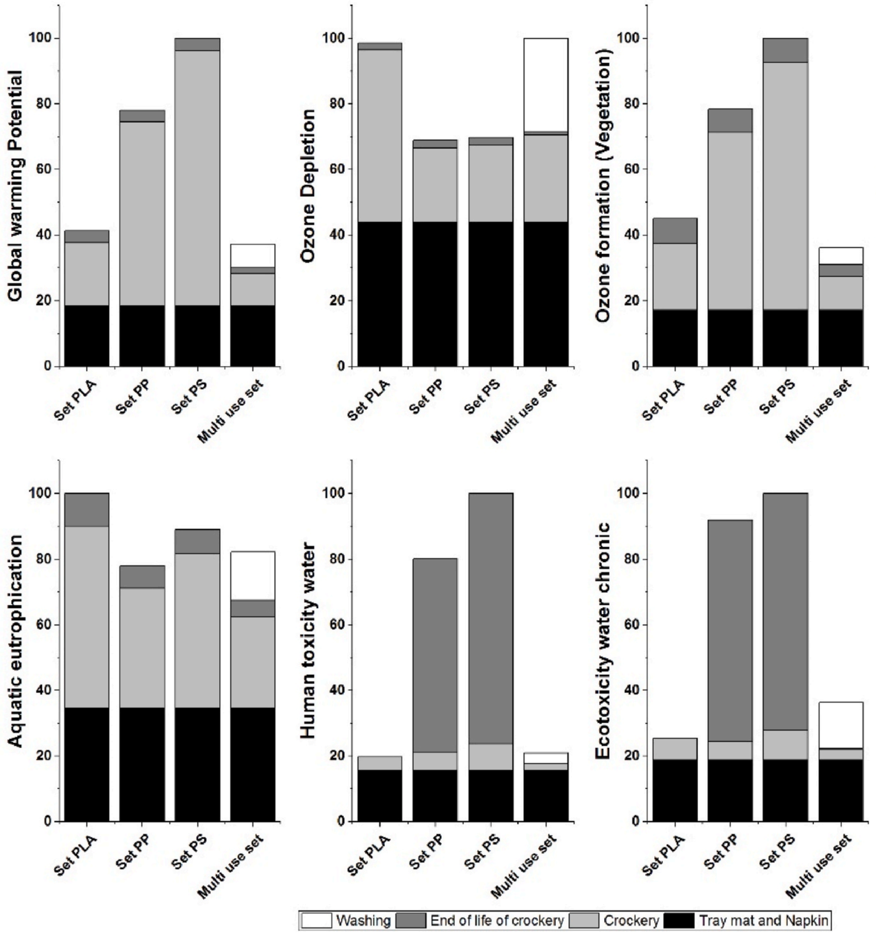

**Fig. 3.** Sensitivity analysis on the number of uses - Global Warming Potential, Ozone Depletion, Ozone Formation, Acidification, Aquatic eutrophication, Human Toxicity wate, Ecotoxicity water chronic.

### 3.2. *Number of uses*

It was assumed that only one reusable set was enough to fulfil the chosen functional unit. In reality, the items undergo wear and tear, they may break or chip during use or washing, so it is likely that they need to be replaced before being used 1000 times. A sensitivity analysis is made to assess the effect of the different number of uses on the total impact. By increasing the number of washings, the impact of raw material production decreases because it is divided between all the uses. It was shown for plastic clamshell that this reduction is relevant by increasing the number of uses from 1 to 10, less relevant from 10 to 20 and limited between from 20 to 50 (Levi et al., 2011). This means that no significant improvement can be achieved by increasing the number of uses over 50. A similar trend was also observed in the case of steel cutlery (Blanca-Alcubilla et al., 2020), where the asymptotic behaviour appears from 100 uses onwards.

In the present study, the sensitivity analysis is, therefore, carried out assuming that the reusable crockery is used 10 times as reported in (Blanca-Alcubilla et al., 2020), before being sent to a compost plant. This value is far below the asymptotic behaviour observed. The new reference flow of the analysed system is shown in Table 9. All the other parameters are unchanged.

The environmental impact of this sensitivity analysis is shown in Fig. 3. For greater usability, the results are presented in terms of percentage values. For each category, the most impactful system is given the value of 100 and all the other systems are represented proportionally. The impact of the reusable system is now increased and the difference with the PLA disposable set becomes very small, if any. This variation is particularly strong in the non-toxic categories, where the production of raw materials gives a great contribution to the total. In fact, in this analysis the raw material production and the end of life is no longer negligible for reusable systems. Despite the great variations

**Table 10**
Washing consumption per place setting - hand washing.

| Resource | Amount per place setting |
|---|---|
| Electricity | 0,090 kWh |
| Water | 3,543 l |
| Detergent | 0,0015 kg |

observed, the compostable sets, reusable or disposable, have still lower impact in most of the considered categories.

The influence of the number of uses on the results is also confirmed by the LCA of cups used in small and large events reported in (Vercalsteren et al., 2010). In fact, changing the number of uses had a clear effect on the ranking of the analysed cup types per impact category.

In all the considered categories, the difference in impact between the multi-use set and the PLA set is lower than 20%, in some it can be considered negligible. It can be assumed that the number of uses that makes the two systems equivalent is very close to 10. The same value was found for polypropylene cups (Garrido & Alvarez del Castillo, 2007). This breakeven number of uses is lower than the one found specifically for PLA cups (Cottafava, 2020), where also transportation to offsite washing is considered.

### 3.3. Washing modality

In baseline analysis, it was supposed that the washing process was made by a dishwasher with 2014 technology level. Since the washing process has a great influence on the multi-use set performance, a sensitivity analysis is performed by changing the washing mode.

It is assumed that the items are cleaned by handwashing, which is modelled by quantifying the amount of water, detergent and electricity needed (e.g., for heating water) (Paspaldzhiev et al., 2018). As previously done, it is considered a three-item place setting and the values used are presented in Table 10. All the other parameters are unchanged.

The environmental impact of this sensitivity analysis is shown in Fig. 4. For greater usability, the results are, once again, presented in terms of percentages. For each impact category, the most impactful system is given the value of 100 and all the other systems are represented proportionally.

The considered way of cleaning changes the ranking of the systems per category. In case of handwashing of the reusable systems, the impacts increase greatly for the Ozone Depletion, Acidification, Aquatic Eutrophication and Ecotoxicity category. With regard to the impact of the washing process, electricity gives the greatest contribution, as also assessed for the washing process of ceramic mugs (Martin et al., 2018). The use of an increased amount of water and detergent does not affect the results consistently.

Washing modality strongly influences the outcome of the reusable systems. As also demonstrated for coffee drinking systems (Ligthart and Ansems, 2007), cleaning stage is decisive for the total environmental burden. The user has plenty of freedom in the cleaning process, so the ultimate result is strongly user related. The way energy is produced is important too. In this study, the Italian Energy mix provided by Ecoinvent (Wernet et al., 2016) is used, but the adoption of certified ecopower can reduce the impact of the washing process (Pladerer et al., 2008).

Fig. 5 summarizes the achieved results. The radar plots allow a quick comparison among the different scenario investigated. The more the lines move away from the centre of the radar plot, the more the

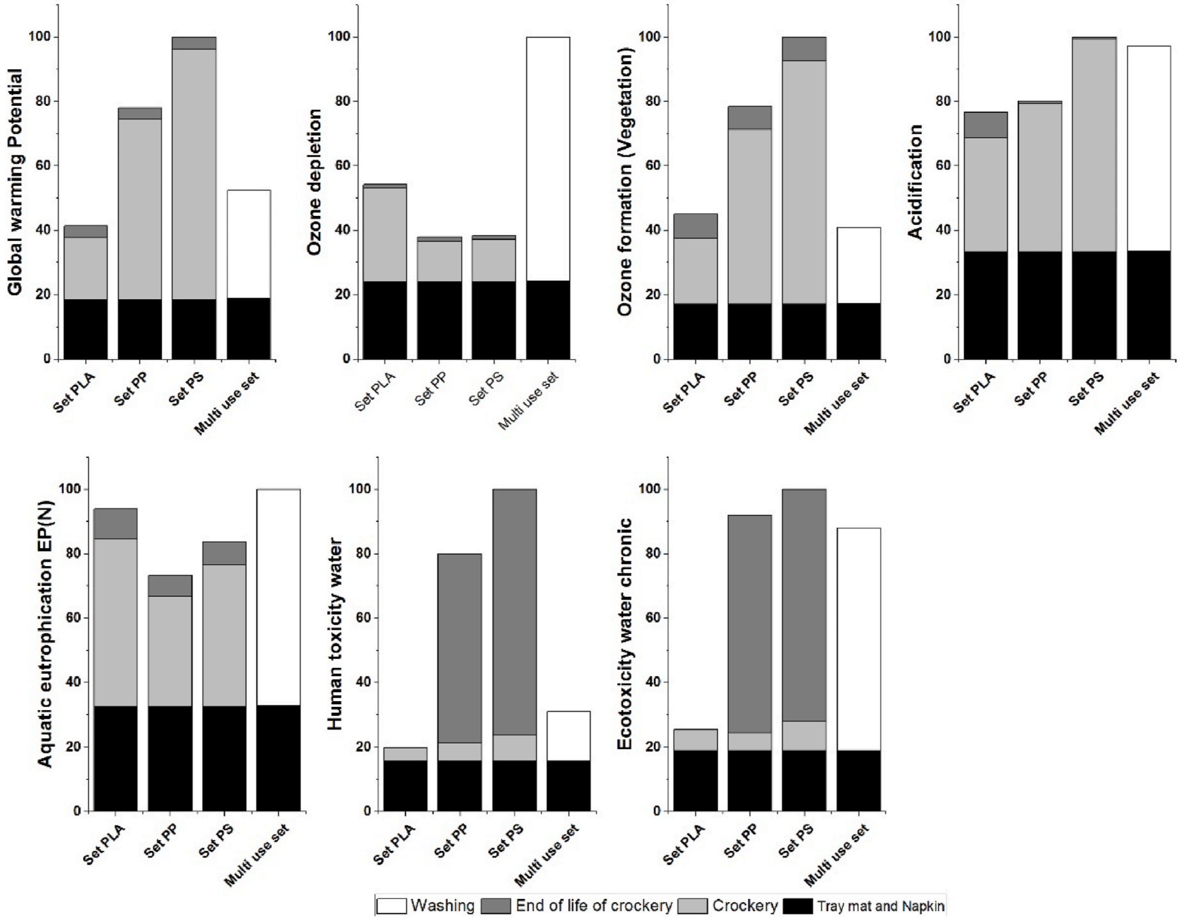

**Fig. 4.** Sensitivity analysis on washing modality - Global Warming Potential, Ozone Depletion, Ozone Formation, Acidification, Aquatic eutrophication, Human Toxicity wate, Ecotoxicity water chronic.

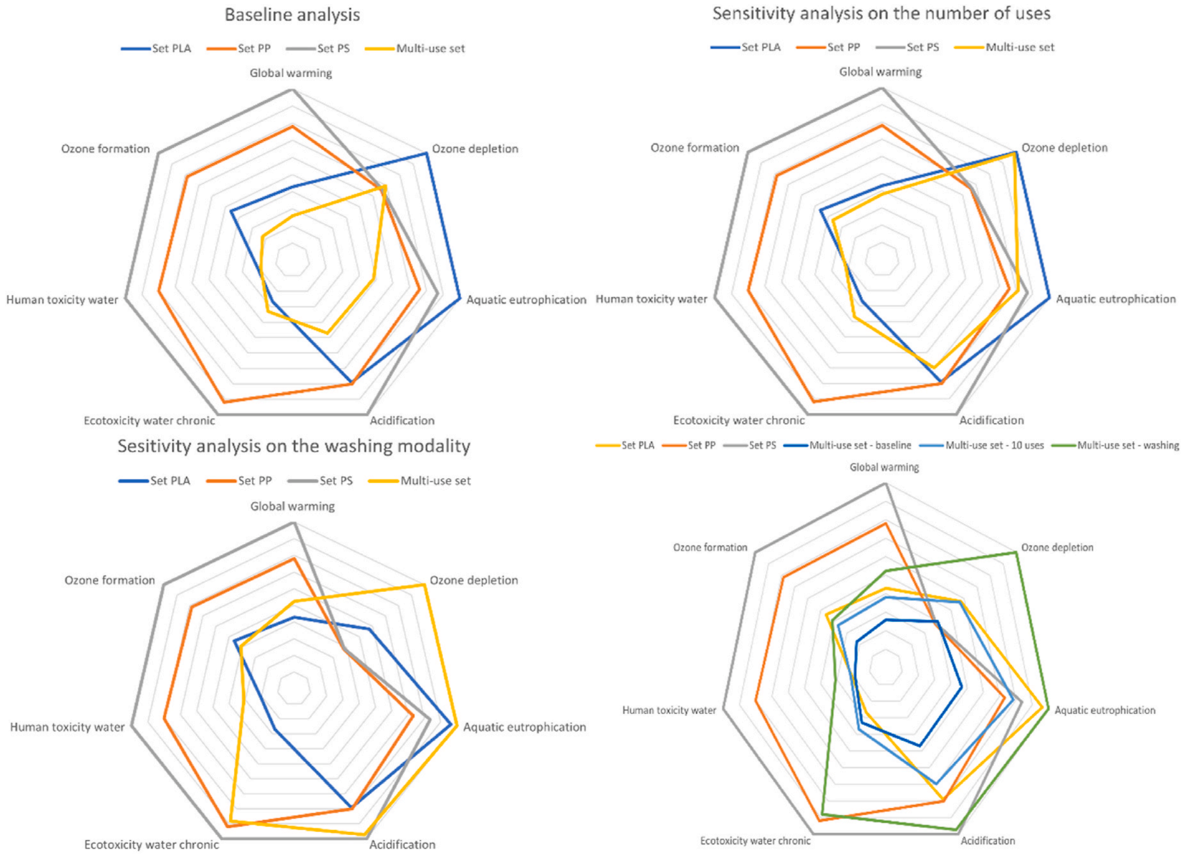

**Fig. 5.** Radar plot. Base and sensitivity analyses.

individual impact categories are relevant, resulting in a significant environmental footprint. From the developed analysis, it is possible to notice that using fossil-based raw materials for the manufacturing of the disposable tableware generate radar plots that are stretched towards the left hand side, where the impact categories are mostly related to the consumption and converting of the non-renewable raw materials. On the other hand, using bio-based plastics for the manufacturing of the disposable tableware generate radar plots that stretch towards the opposite side. They stretch towards the impact categories related to the consumptions of renewable resources and, in specific, related to the environmental impacts that are, indeed, necessary to grow the raw materials required for the manufacturing of the bioplastic (i.e., for sugar cane).

The overall comparison between the baseline scenario and the other scenarios under investigation (Fig. 5, bottom-right) shows how multi-use systems and sets based on bioplastic can boast similar trends of the radar plots. Biobased sets are able to produce effects on the environment that are somewhat similar to those caused by reusable items, but of smaller overall amount.

## 4. Conclusions

This study compared the environmental burden of different place settings used in mass catering. The focus was on the role of bioplastics and on the convenience of adopting reusable items to serve multiple meals. This paper wanted to assess the impact of multi-use bioplastic items and to evaluate the advantages and disadvantages compared to the disposable ones from an environmental point of view.

For the reusable system, the outcome strongly depends on the number of uses and on the washing modality it undergoes. In the baseline scenario, the reusable system appears to be the most favourable one, as its washing modality is efficient and the number of uses very high. Decreasing the number of uses to 10 makes the choice between the reusable set and the disposable PLA set practically indifferent. The washing scenario considered in the second sensitivity analysis (i.e., handwashing) makes the multi-use set the least convenient among the compostable ones. It is not possible to determine unequivocally the parameters the reusable set depends on, as they are all strongly user related. Also considering the sensitivity analysis, the results show that the compostable systems, both reusable and disposable, are the best solutions. Due to the uncertainty of the use conditions of the reusable systems, no absolute ranking can be identified between the two. The total impact of the fossil-based systems is strongly related to the landfill stage in the categories of Human Toxicity water and Ecotoxicity water chronic. Further improvements could be achieved in these categories by considering different end-of-life scenarios for these systems, such as energy recovery and recycling.

Lastly, reusable and PLA-based sets feature similar impacts for most categories. Bio-based place settings can produce effects on the environment that are comparable to those caused by reusable items, being them in most cases also of smaller overall amount.

## Declaration of competing interestCOI

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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