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Title: Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste

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Abstract: In Italy, most of the packaged food wasted during the distribution phase and at retail stores is disposed of in landfill, due to the absence of a sorting system able to separate food from packaging. A new experimental process, here presented, collects the packaged food waste from retailers, moves it to distribution centres, and then ships it to a sorting facility where the food is separated from its packaging. The sorted packaging materials are then sent to specific recycling or energy recovery centres, meaning that only a small amount of packaging material is disposed of in landfill.
In this study, the environmental performance of this innovative process is compared with the impacts generated by disposal in landfill using the Life Cycle Assessment (LCA) methodology. Data for the year 2015 in the Emilia Romagna region (Italy) was collated for this purpose; in this region, about 14,600 tons of food are wasted in the retail channel annually. The LCA is performed using the ReCiPe midpoint method; primary data was taken from the field, while secondary data came from literature and ecoinvent 3.3 databases. Three sensitivity analysis were carried out to evaluate the results when the distances covered during the transport phase, the composition of the packaging waste, or the EOL of the country where the analysis is performed varied.
Overall, the results show that the innovative scenario is more environmentally sound than the one currently in use. Taking into account the avoided impacts, the environmental impact turned out to be negative in all the categories, suggesting a beneficial effect on the environment.

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The Editor-in-Chief of Sustainable Production and Consumption
Prof. Adisa Azapagic
School of Chemical Eng. & Analytical Science
University of Manchester, Manchester, UK

Parma, ITALY, Tuesday, 23 January 2018

Dear Prof. Azapagic,

Please find enclosed the revised version of the manuscript entitled:

"Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste"

Authors: Gianluca Vitale, David Mosna, Eleonora Bottani, Roberto Montanari, Giuseppe Vignali

Please consider this article for a possible publication on a regular issue of "Sustainable Production and Consumption".
In this revised version, we tried to follow the comments and suggestions of all the three reviewers, trying to meet all the different requests. As requested by the journal guidelines each part of the modified text has been underlined in yellow.
We wish to take this opportunity to send to You our best regards.

Looking forward to hearing from You soon,

Yours sincerely
The authors

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Paper title: "Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste"

Ms. Ref. No.: SPC-D-17-00130

Comments to editors

Editors' comments	*Our notes*
Good work in general but some issues need to be at least dealt with and improved.	Thank you for your assessment. We tried to make the required changes to the article in order to satisfy your requests. As requested by the journal guidelines each part of the modified text has been underlined in yellow.
1. Better sorting process description with a graph incorporating the main functions, steps, end products.	Thank you for the request. In the revised version of the paper we have tried to better explain the rationale behind the sorting process and the classification of the PFW into different categories. Actually, the research has gone ahead in these months and as a consequence of the latest advancements, we have now inserted a new machine able to separate meat and fish from packaging, without damaging them, to produce high value pet food.
2. Final application of the recycling; do not mention a general product, each type of material has high potential in specific applications i.e. corrugated board are always new paper products while pet could be incorporated with virgin pet.	We do not fully understand your point of view, nor the specific point in the article where we cited a "final application of the recycling". The details about each specific recycling process are proposed in table 4. If you refer to the possible second life of the recycled materials, we added more explanation in the literature review on packaging material EOL valorisation.
3. If you follow Italian data, keep it until the end, you mention German EOL data.	The German EOL were used only for an evaluation of the environmental benefit achievable by a country which makes a higher use of the recycling process compared to Italy. This evaluation has been proposed in the sensitivity analysis (and not in the main analysis) as an example of the better performance the unpacking-sorting system could achieve if it was used in a country where the recycling is more adopted than in Italy
4. Major description/discussion of the results would be needed, not only general characterisation tables and diagrams.	We agree with you and therefore we have tried to explain the new obtained results in greater detail. Please see section 4.
5. If you print in white and black the graphs are not easily understood	We have tried use colours and crosshatching in the graph to make them clearer even is printing the article in white and black.

	Actually, with so many entries in the graph, it would be difficult to make them clearer than what we have done in the current version of the paper; therefore, we hope that they are acceptable in this form.
6. Sensitivity analysis could incorporate the different products addressed or the different EOL scenarios	We agreed with you and now we have added a third sensitivity analysis where different EOL scenarios are considered. Please see section 4.3.
7. Page 7; please describe each material end of life as it should be, i.e. paper is up to 98% oriented for recycling while plastics could have a great option in energy recovery.	Page 7 (of the original submission) provides an overview of the EOL of each packaging material, as obtained from the most recent literature. More details, again resulting from the literature, are proposed in Table 1. In our study, we adopted the allocation percentage values proposed in Table 3 (now Table 2); such values are specific to the Italian context and were derived from specific Italian sources. We have tried to explain this distinction in the paper.
8. Functional unit; you consider as reference the amount that is currently for charity purposes... but imagine that in the end these products do not have that objective... there are too many other final destination... i.e. they are thrown away... could you please have an alternative reference for measuring the functional unit in a more accurate manner??	Actually, the charity option was mentioned in the paper only because the data available in WRAP (2013) refer to the PFW intended to be donated for charity purpose. We used the same proportion (i.e. 13.8%) to determine the amount of packaging in the PFW wasted in the Emilia-Romagna region. However, this does not mean that we have analysed only the PFW that is diverted to charity associations, as our input data is different and represent the amount of PFW wasted at the retail stores in Emilia-Romagna region. We apologise if this was not clear in the original version of the paper. Nonetheless, to comply with your request of defining the functional unit in a more accurate way, we have now revised it, by excluding the amount of PFW originating from retail stores that is sold to charity purposes. This amount, in fact, would not be recovered in our proposed unpacking-sorting system. For all Italy, in 2017 there were 4,103 tons of food delivered to charity purposes; taking into account the population of the Emilia Romagna region, we estimated that a quote of 300 tons/year could have been delivered to charity in this region. This amount has been removed from the original functional unit of 14600 tons/years of wasted food.
9. If you include the trolleys as part of the study; does it really matter? wouldn´t it be more precise to focus on the sorting	Actually, the trolleys are strictly required in the new unpacking-sorting process. Indeed, to convey the PFW to the sorting facility,

stage? At least justify why you incorporate it.	smart trolleys will be provided to the medium and large retails stores (i.e. supermarkets and hypermarkets) in order to preliminary group the PFW, with the help of a specific software able to recognize and categorize the PFW in family groups. This is why we took into account this equipment in the evaluation; we have tried to explain this point better in the revised paper. Moreover, as can be seen in the last paragraph of section 4.2, the impact of the trolleys is significant in 4 impact categories.
10. There are two sorting facilities; one per dry and wet food and the other one for liquids.... please incorporate proper information on each one of them, a graph, etc.	As can be seen in section 3.2.2, the description of the food waste treated in the sorting plant has been enriched by adding six clusters of products processed. Moreover, as already recalled in replying to your point 1, the research activities have gone ahead and consequently three separation equipment have now been hypothesised instead of the original two machines. The related description is reported in the paragraphs immediately before figure 2. The graphical representation of the system (Figure 2) has been updated accordingly. We hope the this satisfies your request.
11. You mention there is a ViPR technology... that does not appear in the figure. Couldn´t it be interesting to incorporate the efficiency of this technology in the sensitivity analysis?	The ViPR specification has been now added to the graph. Thank you for bringing it to our attention. As far as the efficiency of this technology is concerned, the barcode scanner system is a highly tested instrument with an efficiency close to 99.5%, thanks to its capability to recognize the product's shape and to read nearly all kinds of bar code. Because of this high efficiency, testing different values in a sensitivity analysis is not required (in our opinion).
12. Method Re.CI.PE.; why did you choose this method? could you please compare it with others that could be applied?	The choice of the Re.CI.PE. method has been justified by adding a comparison and explanation of the different impact methods. Please see the first paragraphs of section 3.4. The comparison of the results provided by the Re.CI.PE. method with other methods that could be applied in the case under examination is not required for LCA studies..
13. Are you really incorporating in the analysis the EOL valorisation of pakaging materials? I did not see how.	We understand from your comment that our intended meaning with "valorisation" is actually not clear to the reader. What we meant is that the packaging has been valorised because it was not landfilled with the wasted food, but it has been separated from it and recycled/recovered in a

	traditional way. At the last part of the introduction we have specified our intended meaning by valorisation, and supported our statement by a similar definition provided by the European Commission.
14. In general you should include a proper description of the processes included in the analysis and main characteristics, outputs, etc. Thus would help comprehension	Following your suggestion, as well the recommendation of the reaming reviewers, the description of the sorting processes and the outputs have been enriched. We have paid particular attention to the description of the main processes included. Please see section 3.2.
15. Conclusions should be improved.	Conclusions and discussions have been improved by adding further considerations.

In the hope that our amendments satisfy your requests, we sincerely wish to thank you for your time and care in reviewing the paper.

Paper title: “Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste” **Ms. Ref. No.:** SPC-D-17-00130	
Comments to reviewer #2	
Reviewer’s comments	***Our notes***
The paper deals with an innovative and interesting topic. Indeed, some points need to be better explained before publication. See my detailed comments reported below.	Thank you for your positive assessment. We have tried to modified the article in order to satisfy your requests. As requested by the journal guidelines each part of the modified text has been underlined in yellow
1. Abstract: the first sentence should be completed by adding the geographical context where it is valid. In fact, I don't think it is valid in general and everywhere.	The geographical context has been added in the first sentence of the abstract. Thank you for bringing this lack to our attention.
2. Line 26: what are the consolidation centres? Throughout the rest of the paper this term is not used.	The text has been revised. In particular, we now refer to distribution centres only. Thank you for this suggestion.
3. Line 31: please change "method" with "methodology"	The word “method” has been changed with “methodology” as suggested.
4. Line 34: "primary data was taken from the field": this is obvious, as it is the definition of primary data Line 35: please change "Ecoinvent" with "ecoinvent" and "databases" with "database" or "datasets"	The word “Ecoinvent” has been changed with “ecoinvent”; similarly, “databases” has been replaced by “database” as suggested.
5. Line 90: please add a reference for the SORT project. Moreover, what is the meaning of "SORT"?	The reference has been added in the paper. SORT is the Italian acronym for the project title, i.e. “Technologies and models to unpack, manage inventory and track wasted food” (“Tecnologie e modelli per lo Spacchettamento, l'ORganizzazione delle scorte e il Tracciamento dei prodotti alimentari sprecati”).
6. Line 101: how did you find and selected these papers?	The papers reviewed in this section where found with using the Scopus database of Elsevier (www.scopus.com) and represent the main works, available online, concerning the EOL valorisation option of different packaging materials and published between 2008 and 2018.
7. Lines 112-113: delete the term "potential". The term "potential" after the name of the impact category indicates the characterisation factors.	The term “potential” has been removed according to your request.
8. Lines 111-115: is this valid for plastics in general or for a specific polymer?	The description in lines 111-115 is valid for plastics in general. We added a specification to identify the different kinds of plastic materials we are referring to.

9. Line 125 and line 140: why do you talk just about global warming?	As mentioned in the cited articles, global warming has first priority when it comes to Danish as well as European environmental policy. It is also reported by the authors cited that, as far as the uncertainties are concerned, the results regarding the impact categories result more precise if we look at global warming impact category. Nonetheless, we understand your warning and consequently, we have now avoided to mention expressively GHG in the description of the literature. We hope that this satisfies your request.
10. Line 152: how can the reader be sure that the current practice is landfill (and not, for example, incineration)? Is there a document that reports this information?	The actual lack of a system able to sort the packaged food waste (PFW) and to unpack it is the key point of the SORT research project, previously mentioned. Indeed, the main problem associated to PFW consists in the impossibility to recover its packaging material, by separating it from the wasted food. Because of this issue, neither the wasted food nor the packaging material of PFW can be recovered, and this is why all the PFW collected at retail stores is sent to landfilling or incinerated (Garcia-Garcia, 2015). We have added this explanation and the related reference in the text (at the end of the introduction section) to substantiate the rationale behind our study. There are no documents that report this information except from Garcia-Garcia 2015, 2017.. At the moment, if we consider the packaged food waste from retail stores, this is the most commonly known type of waste management.
11. Lines 169-170: which kind of data did the consortia provide? The text "according to the data provided by the Italian consortia" should be expanded and a more precise description about the way the waste composition was defined should be added.	We have modified the way the data provided by the different consortia are presented in the text. Please see section 3.2.1.
12. Line 171: please indicate here the author of the document and the year of access and put the link in the bibliography	Actually, as mentioned in our reply to your previous comment, we have modified the way the data provided by the different sources have been presented in section 3.2.1. In particular, the reference you mention has now been removed from the maintext and from the reference section.
13. Line 186: what do you mean with "considering the capability"? please explain better how you prepared Table 3	With this sentence we meant that the study and the table reported were referred to the amount managed by the Italian systems in the 2014-2015. We apologise for the improper use of English. We have now reworded this

	sentence and we hope that it is now clearer. The consideration made for now Table 2 has been better explained.
14. Line 202: reading the description of the whole scenario, it is not clear the usefulness of this preliminary classification Line 207: five boxes, one for each product family?	The preliminary classification is needed either to ensure that different storage conditions (e.g. refrigerated or at ambient temperature) are correctly applied to the different PFW, and that products with similar characteristics (e.g. fragile vs. non-fragile) are grouped together. This explanation has been added in the text (section 3.2.2). In Line 207, a specification about the boxes has been added in the text, as you suggested.
15. Lines 218-221: does this mean that there are 9 (3x3) groups?	In this article the analysis focuses only on packaging, for which there are 3 possible EOL options (i.e. recycling, energy recovery and landfill).
16. Line 222: the PFW all together or the PFW of each group?	The text has been revised. The PFW refer to each group.
17. Line 248: is this production of energy related to the incineration of packaging waste? Does the incinerator produce only electricity or also heat? How much are the electric and thermal efficiencies?	The energy production is related to the incineration of the packaging waste. The study evaluates only the electricity produced by incineration, while heat production is excluded because of the lack of specific data. In other words, it has been assumed that heat is not produced from waste recovery. The text has been revised and the efficiencies has been added.
18. Lines 253-254, point vi: this point should include not only the consumption of resources but also the emissions, and not only for recycling but also for incineration and landfill.	The text has been revised according to your suggestion.
19. Line 285: please add a reference or explain how you calculated the value of 0.5 kg.	The average weight of the PFW has been estimated starting from the data reported in section 3.2.1 and related to the composition of packaged food waste in Emilia Romagna region in 2016. We have added this specification in the same section.
20. Line 289: do you refer to the electricity consumption or also to the avoided electricity?	The text has been revised, adding that the average Italian electricity mix is used in both the cases.
21. Lines 297-300: this is really questionable.	The statement in lines 297-300 was actually deduced from a previous publication, i.e. the paper by Gala et al. (2015). In their study, these authors state that "each time a material is reintroduced into the market (i.e. at each cycle), it does not displace the primary production of the virgin material but the average mix of technologies that provide an average unit of the material itself" (p.648).

	We also found that this approach has been largely used in LCA studies since the publication of the paper by Gala et al. (2015). In line with this logic, in our study we have assumed that the packaging material separated from PFW and recovered (i.e. the secondary packaging material) will allow "*to partially replace a mix of primary materials (i.e. those obtained from virgin raw materials) and secondary materials (the recycled ones) in a finished product (Gala et al., 2015, Vitale et al., 2017)*". We have reworded this sentence and we hope that this is now clearer to the reader. Please see p.16.
22. Lines 319-321: this is not very clear: where is the voice "incineration"?	The term incineration refers to the process of "energy recovery" previously detailed in the paper. We have expressed this more clearly in the paper.
23. Table 4: what is the meaning of column REC/VIR? This is not explained in the text. If these values are the so-called substitution ratios or quality factors, this is in contrast with the piece of text of line 300. Moreover, the value for iron is really low.	"REC/VIR" is the same nomenclature used by Gala et al. (2016). An explanation has been added in a note to the table; these values represent the ratio between the environmental impact of the recycling process and that of the production process of virgin material. The numerical values were retrieved from different sources, which are all quoted in the Table.
24. Table 5: are you sure of the calorific value (LHV or HHV?) for aluminium? And what about iron and steel?	The calorific values (LHV) reported in table 5 were derived from SEIeditrice (2012), which is quoted in the paper. Iron and Steel have been now added to table 5. As far as glass is concerned, its calorific value is not reported, as the amount of material sent to energy recovery is null.
25. Table 6: values for functional unit should also be reported.	The values has been added in the Table.
26. Line 349: please improve the caption. The figure represents the contribution analysis.	The caption has been revised as suggested.
27. Lines 372-374: this concept is not very clear.	You are right that this concept was not so clear. We have read the paper once again and think that this statement is not strictly necessary; therefore, we have remove it in the revision. We hope that the text is more fluent now. ?
28. Line 376: do you mean the added impacts minus the avoided ones or just the avoided impacts? To calculate the	The reported results of the new process represent a comparative analysis between the new process and the current scenario as the

reported results, did you subtract the impacts of the current scenario?	analysis consider as avoided impact the transportation and landfilling of all the packaging that are considered in the current scenario. This has been highlighted in the title of the section and in almost all the figure and table captions.
29. Line 379: some values in the table are positive in sign, so I would change the caption (for example, I would substitute "benefits" with "impact", that is neutral)	The caption of the Table has been revised as suggested.
30. Line 381: please improve the caption (here we do not have absolute values but percentage values).	The caption has been revised.
31. Figure 4: how did you calculate the contributions reported in the figure? It seems that the negative part of the column is 100% for all the impact categories whereas the positive one is different. This is an uncommon representation: please explain how you realised it.	The representation for LCA analyses having environmental benefits are usually reported as in Figure 4 (Manfredi and Vignali 2015; Bertolini et al, 2016; mosna et al., 2016). The representation in Figure 4 aims at comparing different impact categories characterized by different measurement units. Because of the different scale, such comparison cannot be made with the absolute values of the impacts; therefore, the results were elaborated with Microsoft Excel™ and computed as relative (percentage) values. With this computation, the highest contribution, regardless if negative or positive, always scores 100%.
32. Line 382: better compared to what?	What we meant with this sentence is that the new scenario generate better results compared to the current scenario (as the analysis is comparative). Indeed, the results of the new scenario, as they are presented in Figure 4 and Table 7, already provide a comparison between the current scenario and the new one. Therefore, from their analysis it can be deduced that the new scenario generate better environmental results if compared to the current one. The text has been now revised adding a more specific explanation
33. Line 387: the term "positive" creates confusion. Line 388: please explain better this part: what do you mean with impact reduction? Which impact? And a reduction compared to what?	As explained in our response to your previous point, the results of the new scenario, as they are presented in Figure 4 and Table 7, already provide a comparison between the current scenario and the new one. Therefore, in Figure 4 all the negative terms represent positive contribution to the environment. (i.e. avoided impacts of the new process).In the LCA terminology, impact generated are typically referred to as “positive”, while impacts avoided as “negative”.

	We have now revised the sentence in line 387-388 to clarify what we meant and avoid further misunderstanding
34. Lines 399-401: this is really strange. Which sub-process and which substance is responsible for this?	The Ecoinvent dataset of the glass recycling process has been revised. The results now show negative impacts in line with other studies.
35. Line 405: what are these by-products?	The by-products we are referring to are the combustion by-products generated by the incineration process of the materials allocated to energy recovery. Examples of this by-products considered in the SimaPRO software package are carbon monoxide, dinitrogen monoxide, sulphur dioxide, ammonia, hydrogen chloride, etc. This has been mentioned in the paper.
36. Lines 426-428: this sentence is not clear. Please rephrased it.	The sentence has been revised as suggested, better describing the variations in the total impact due to the variations in the transport distance.
37. Line 433 and line 436: please differentiate the two captions.	The caption has been changed.
38. Lines 448-449: the new efficiency percentages should be reported explicitly in the text.	The new efficiency has been added to the text in a comprehensive Table.
39. Line 453 and line 463: please differentiate the two captions.	The caption has been changed.
40. Line 484: GWP represents the characterisation factors (and not the impact category).	The text has been revised

In the hope that our amendments satisfy your requests, we sincerely wish to thank you for your time and care in reviewing the paper.

Paper title: "Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste" **Ms. Ref. No.:** SPC-D-17-00130	
Comments to reviewer #3	
Reviewer's comments	***Our notes***
Even though the reported quantitative analysis based on the comparison between different strategies for the management of the Food packaging waste is undoubtedly of interest, the paper lacks of some structural parts that justify its publication.	Thank you for your assessment. We have tried to modified the article in order to satisfy your requests. As requested by the journal guidelines each part of the modified text has been underlined in yellow
1. Most of the efforts should be devoted to improve the rationale of the paper, the introduction and the review of the literature. ".	The introduction and the review of the literature have been revised. In particular, the introduction section has been restructured in the attempt to better convey the discourse toward the focus of our study (i.e. the valorisation of the packaging fraction of PFW). The rationale for studying this topic has been highlighted in the third paragraph of the Introduction. The literature review section has been enriched, according to a suggestion made by the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. We hope that this satisfies your request.
2. The link between these parts, the research goals, and the LCA carried out should be strengthened. A narrower and more focused literature review is necessary.	As reported in our reply to your previous comment, the literature review section has been enriched, according to a suggestion made by the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. We hope that this satisfies your request. On the basis of this new literature review, other parts of the paper have been rearranged. Particular attention was paid to the description of the research goals and to the gaps in the literature that we try to fill. Please see the end of the introduction section and section 2.
3. The economic aspect of the new process should be considered and assessed as well.	We have mentioned in the paper that our work focuses only on the valorisation of the primary packaging that can be obtained if unpacking and sorting the PFW. Similarly, we have mentioned that other (interrelated) topics (e.g. the valorisation options of the separated FW) are under evaluation or have

	been evaluated in other studies and are not dealt with here (see p.12). Similar considerations hold true for the evaluation of the economic aspects of the new process. For sure, we will carry out future papers where we will address the economic aspect of the problem. Therefore, this has been mentioned as a possible future research direction.
4. The discussion section is missing, but is necessary in my personal opinion. There, the authors should comment the findings in the view of what stated by the other studies in the topic.	The results of the analysis have been revised, making them more complete but not including a discussion section, because it could be too distant from the figures which explain the result.
5. Introduction is too generic and lacks to lead the reader through the rationale of the paper.	As reported in our reply to your comment #1, the introduction and the review of the literature have been revised. In particular, the introduction section has been restructured in the attempt to better convey the discourse toward the focus of our study (i.e. the valorisation of the packaging fraction of PFW). The rationale for studying this topic has been highlighted in the third paragraph of the Introduction. The literature review section has been enriched, according to a suggestion made by the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. We hope that this satisfies your request.
6. I would suggest to provide a systematic literature review based on keywords search in order to better argue what is stated by the authors at lines 77-81.	The literature review has been revised, by including more articles that were obtained using a more rigorous process. This has been explained in section 2.
7. Whether the paper focuses on a specific technology for FW sorting, the authors should better clarify how and when the obtained results and related findings could be generalizable.	We agree with you. This point is partially addresses by the second and the (new) third sensitivity analysis. These analyses show the benefits the proposed system if applied in countries which makes greater use of recycling (compared to Italy) or to countries where the composition of the packaging materials is different. The third sensitivity analysis has been introduced during the revision of the paper to gain further insights about the potentials of the proposed system in different context. We hope that this satisfies your request.
8. Is the illustrated technology (i.e. the sorter) really innovative, rather than it is used for an original application? This aspect should be seriously handled to	Actually, the development of the proposed unpacking-sorting process is the key object of a research project, funded by the Italian Ministry for University and Research under a specific research grant type Smart Cities and

justify the scientific content of this paper.	Communities. The project is called SORT (Italian acronym for “technologies and models to unpack, manage inventory and track wasted food”). The related details have been included in the paper and in the acknowledgments. As any research project funded by a National institute, the SORT project has undergone a rigorous evaluation process and turned out to be one of the 32 projects funded (out of 106 projects presented). We hope that this overview is sufficient to justify the scientific novelty of the research.
9. Literature Review: Whereas at the end of the Introduction Section the authors seemed to focus on Food Waste Treatment, I would expect a narrower literature review describing the state-of-art of the management options for the food package waste at the retailer.	As reported in our reply to your comment #1, the literature review section has been enriched, according to a suggestion made by you and the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. We hope that this satisfies your request.
10. In my opinion the conducted literature review seems suitable for a generic review on package materials EOL. Such a comprehensive perspective sounds poorly aligned with the field of comparison of this paper, and does not allow its benchmarking.	As reported in our reply to your comment #1, the literature review section has been enriched, according to a suggestion made by you and the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. We hope that this satisfies your request.
11. Furthermore, the articles surveyed in Table 1 are classified according to small panel of properties but are not described in the manuscript Some short sentences to describe each should be provided, at least for the main relevant studies.	Table 1 is intended to provide an overview of the EOL options of the different packaging materials, according to the literature published from 2008 to 2017. In order not to jeopardise the total length of the paper, describing all these studies in detail is not feasible. Therefore, we have focused the description in the maintext on the most recent studies or to those that turned out to be more relevant for our application. This is obviously a compromise solution between the paper length and the need for providing the reader with an overview of the EOL options of the different packaging materials, and we hope that this satisfies your request.
12. I would suggest to revise how the common practices for the EOL of different packaging materials are reported from line 107-144.	In order to not to weight down the article we preferred to keep the reporting of the article in a discursive way instead of using a Table.
13. A hierarchical block diagram would clearly illustrate how different strategies and processes are shared among different	In our opinion the most important information are reported in Table 3 and a hierarchical block diagram would not added

materials.	relevant information to the article
14. Materials and Methods The collection and manipulation of the dataset required to address the paper's goals is challenging.	Throughout section 3, we have tried to describe more clearly the set of sources and datasets used in the analysis made in the paper.
15. I personally appreciate what the authors did on linking and connecting different primary and secondary data sources. However I have some concerns about how the different sources are aligned in time (different periods) and space (different areas).	At the moment the data concerning the PFW are sparse. As the in field analysis of the retail stores was carried out in 2016, we tried to select the most data that were consistent with this timespan. As far as the geographic location is concerned, the punctual data always refer to Italy or are specific to the Emilia Romagna region. We have specified this in the paper to avoid further misunderstanding.
16. Could the authors find some papers that previously build their instance in such a way?	As reported in our reply to your comment #1, the literature review section has been enriched, according to a suggestion made by you and the remaining reviewers. We have now reviewed two main streams of literature, i.e. the EOL valorisation of packaging materials and the PFW valorisation. On the basis of the new literature review, we found 5 papers that appear to be related to our topic; however, none of these works directly addresses the valorisation of the packaging fraction of PFW and none of them describes the unpacking-sorting process of PFW. This has been more clearly stated in the paper.
17. A comparison with at least an example in the same field of research would be of help?	As reported in our reply to your previous comment, when carrying out the new literature review we found no studies that directly address the valorisation of the packaging fraction of PFW or describe the unpacking-sorting process of PFW. Having said that, we are not convinced that the results of our paper can be compared to other studies available in literature. Nonetheless, if you are aware of previous studies on a similar topic, that could be used as a benchmark for our study, please let us know and we will be pleased to add such comparison in our paper.
18. The way the input data and the different sources are integrated should be explained and discussed by the use of a schematic Figure explaining what the authors did, and enabling to replicate the analysis.	In the life cycle inventory analysis, we have tried to be as specific as possible in describing the data used as input in the SimaPRO software package. This should be sufficient to allow the analysis to be replicated using this software.
19. By quantifying different environmental mid-point metrics, the authors realize a	Actually, we tried to elaborate a graphical representation on multi-dimensional

differential analysis between the as-is and the to-be scenarios. I would suggest to synthesize the comparison by using cake graphs and multi-dimensions histograms to better highlight the obtained savings.	histograms (as it has been done in one of my previous study DOI: 10.1016/j.jclepro.2016.11.025), but due to the presence of positive and negative impacts and to the wide number of entries, such representation is almost impossible to understand. Therefore, we would prefer to leave the 2D histograms to synthesise the outcomes of our analysis. In doing so, we have used colours and crosshatching in a way that the graph should be readable even if figures are printed in black and white. We hope that this satisfies your request.
20. The sensitivity analysis is fair but the environmental break-even of the new process should be discussed in the view of mutual economic savings or costs.	As mentioned in our reply to your comment #3, our work focuses only on the valorisation of the primary packaging that can be obtained if unpacking and sorting the PFW. Similarly, we have mentioned that other (interrelated) topics (e.g. the valorisation options of the separated FW) are under evaluation or have been evaluated in other studies and are not dealt with here (see p.12). Similar considerations hold true for the evaluation of the economic aspects of the new process. For sure, we will carry out future papers where we will address the economic aspect of the problem. Therefore, this has been mentioned as a possible future research direction.
21. Discussion A discussion section is completely missing and this is unusual in the common LCA analyses proposed in the literature.	The results of the analysis have been revised, making them more complete including a discussion. However a specific discussion section has been not created not to have the figures with the main results far from the discussion.
22. Manuscript shape: The shape of contents, tables and Figures is of poor quality. Why tables and figures are not at least edited according to the same style?	We apologise for this inaccuracy. The figure and tables have now been edited using the same style for all of them. We hope that you will find them more satisfactory.
23. The revision of the English style by a native speaker is mandatory, because many parts of the paper are less fluent and hard to read.	

In the hope that our amendments satisfy your requests, we sincerely wish to thank you for your time and care in reviewing the paper.

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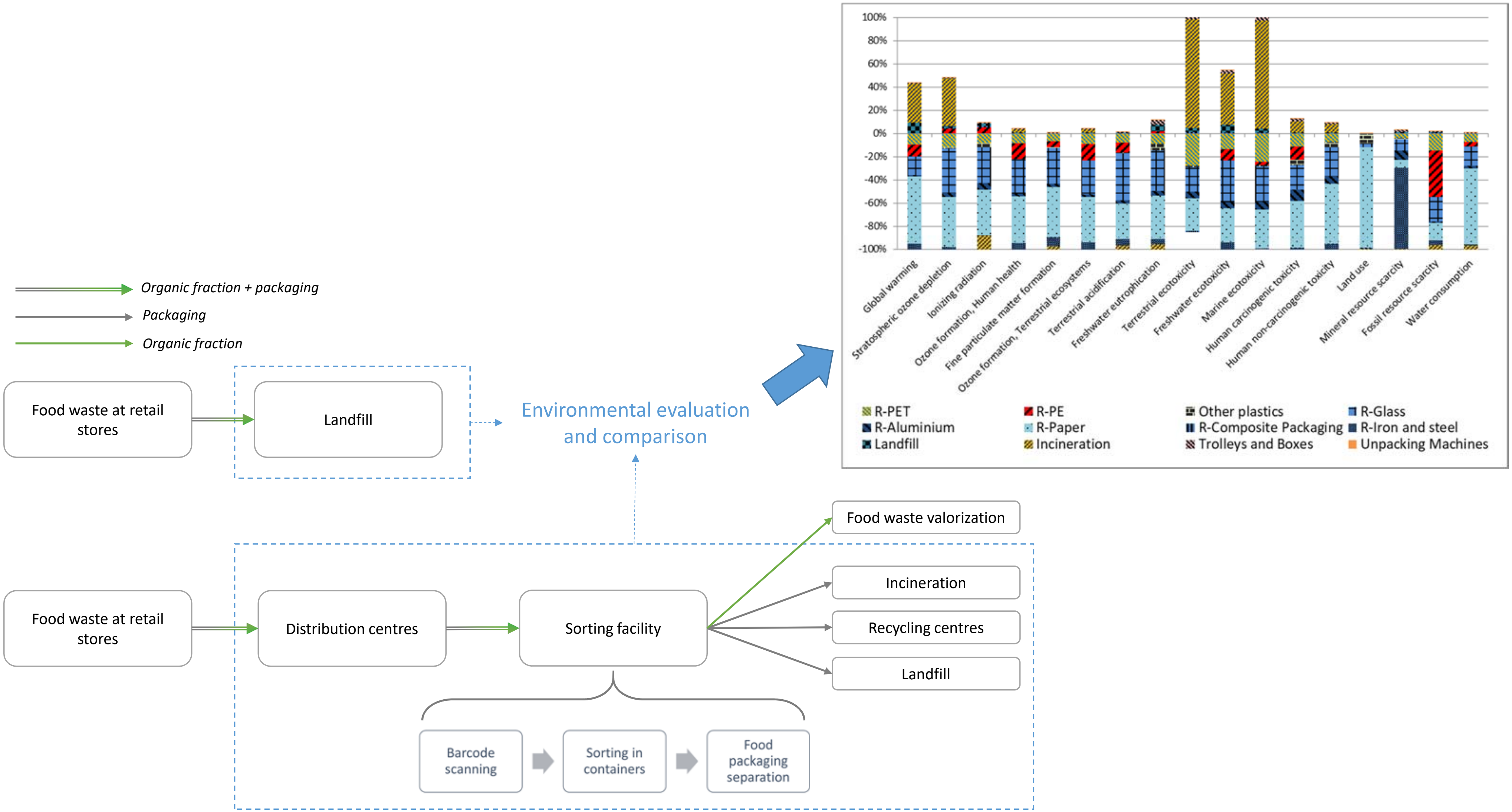

Highlights

We analyse and compare the environmental performance of two end-of-life scenarios of packaging materials derived from food waste.

The ReCiPe Method (2016) is used for the Life Cycle Assessment.

This work compares a current scenario of landfilling with a new process of sorting, separation and valorisation of packaging materials derived from food waste.

The results show that the new process is more environmental sound then the current one.

Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste

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Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste

Abstract

In Italy, most of the packaged food wasted during the distribution phase and at retail stores is disposed of in landfill, due to the absence of a sorting system able to separate food from packaging.
A new experimental process, here presented, collects the packaged food waste from retailers, moves it to distribution centres, and then ships it to a sorting facility where the food is separated from its packaging. The sorted packaging materials are then sent to specific recycling or energy recovery centres, meaning that only a small amount of packaging material is disposed of in landfill.
In this study, the environmental performance of this innovative process is compared with the impacts generated by disposal in landfill using the Life Cycle Assessment (LCA) methodology. Data for the year 2015 in the Emilia Romagna region (Italy) was collated for this purpose; in this region, about 14,600 tons of food are wasted in the retail channel annually. The LCA is performed using the ReCiPe midpoint method; primary data was taken from the field, while secondary data came from literature and ecoinvent 3.3 databases. Three sensitivity analysis were carried out to evaluate the results when the distances covered during the transport phase, the composition of the packaging waste, or the EOL of the country where the analysis is performed varied.
Overall, the results show that the innovative scenario is more environmentally sound than the one currently in use. Taking into account the avoided impacts, the environmental impact turned out to be negative in all the categories, suggesting a beneficial effect on the environment.

Keywords: Packaging material; Food waste; Recycling; End of Life; Unpacking; Life Cycle Assessment.

1 Introduction

Food waste (FW) generated across the Food Value Chain (FVC) turns out to be one of the major problems relating to food production. In 2011, the United Nations Food and Agriculture Organization (FAO) estimated that more than one third of food produced (about 1.3 billion tons) is lost (Gustavsson et al. 2011; FAO, 2013a; FAO, 2013b). Food can be wasted throughout the FVC, from primary production to the use phase (WRAP, 2007a; WRAP, 2007b; Fredriksen et al. 2010 and European Commission, 2015).

Packaging is a main part of any food, as it is fundamental to ensure that its organoleptic and hygienic properties are preserved; also, it ensures protection and conservation of the food quality and can contribute to reducing FW (Bertoluci et al. 2014). The global volume of packaging materials manufactured and disposed every day has led many researchers to deal with the issue of environmental impact, especially in the food sector (Vermeulen et al. 2012). Several studies have been carried out since 1990 with the aim of demonstrating the impact of packaging materials in the food sector and the best end-of-life (EOL) valorisation option for different types of them. Lately, Manfredi and Vignali (2014) found that glass packaging is the main cause of environmental impact generated by the production of tomato puree, while Bertolini et al. (2016) and Manfredi and Vignali (2015) analysed the impacts of several packaging materials respectively used for milk and beverages. In recent years, several studies have demonstrated extending food's shelf life by means of an improved packaging solution could reduce the environmental impact of the whole packaged food, acting mainly on the reduction of the FW associated to it (Williams and Wilkstrom, 2011; Grönman et al. 2013, Wikström et al. 2014; Manfredi et al. 2015).

The environmental impact of FW treatment has been studied extensively using the Life Cycle Assessment (LCA) method. In this study, however, we focus on the specific issue of valorising the packaging fraction of packaged food waste (PFW), i.e. the packaged food discarded at retail stores. "Valorisation" means any option where the packaging material is not disposed of in landfill, according to European Commission (2008) guidelines. The main problem associated to PFW consists in the impossibility to recover its packaging material, by separating it from the wasted food. In turn, this is primarily due to the lack of system able to mechanically separate the FW from its packaging. Consequently, at present all the PFW collected during the retail and distribution phases is then sent to landfilling or incinerated (Garcia-Garcia, 2015).

Based on these premises, this study aims to explore different valorisation options for primary packaging deriving from packaged food wasted at retail stores. In particular, it will show how an innovative process, consisting of an appropriate collection and sorting system for PFW, could be an effective valorisation option from an environmental point of view. The objective of this study, which is supported by the LCA methodology, is to evaluate the environmental performance of this new process for the sorted packaging materials compared to the current one (i.e. disposal in landfill). As it targets packaging materials, the analysis excludes the environmental impact of the FW disposed of in landfill.

This work is a part of the SORT project[2], Italian acronym for “Technologies and models to unpack, manage inventory and track wasted food”. The aim of the project is to valorise the packaged food waste collected from retail stores, in order to recover the product and its packaging.

The paper is organized as follows. After a literature review on EOL valorisation of PFW and packaging materials (section 2), the LCA methodology is applied taking into account the phases described in ISO 14044 (section 3). Environmental impact assessment is then performed considering the current scenario and comparing it with the new one. A sensitivity analysis is then carried out to show how different contexts could affect results (section 4). Finally, the conclusion section summarizes the main findings from this work and underlines activities for future research.

2 Literature review on packaged food waste and packaging material EOL valorisation

A literature review on EOL valorisation of PFW and packaging materials has been done in order to underline the research activities in the fields of PFW valorisation and possible EOL of the packaging materials associated to food waste. Both the systematic have been carried out using the Scopus database, provided by Elsevier.

2.1 Packaged food waste

The collected articles concerning the PFW cover a timespan from 2008 to 2018. They have been obtained by carrying out a query with the following set of keywords: “food waste”, “valorisation” and “packaging”. This query returned 112 articles, but only five of them are strictly related to the EOL management of PFW, which is the focus of this study. In particular, the articles excluded from

[2] Tecnologie e modelli per lo Spacchettamento, l'ORganizzazione delle scorte e il Tracciamento dei prodotti alimentari sprecati .

the analysis analysed either unpacked FW or general issues of FW management, or carried out surveys on FW in household.

Looking at the pertinent studies, the main EOL valorisation options of PFW are:

- Animal feed, anaerobic digestion and composting (Garcia-Garcia et al. 2015, 2017; Salemdeeb et al. 2017);
- Animal feed, anaerobic digestion, incineration (Vandermeersch et al. 2014);
- Animal feed, anaerobic digestion, incineration, landfill, compost and donation (Eriksson et al. 2015).

As reported in Garcia-Garcia et al. (2017, figure 3), the less preferred options of EOL valorisation of PFW are landfilling and thermal treatment with energy recovery. As far as the incineration and landfill are concerned, the unpacking phase is not strictly necessary (Garcia-Garcia et al., 2017). Conversely, to reduce the environmental impacts of the wasted food separated from the packaging, different waste management alternatives are suggested, such as composting and anaerobic digestion, for which the food needs to be unpacked before its treatment. Moreover, according to the European guidelines, the FW should preferentially be used as animal feed (Salemdeeb et al. 2017). To this end, the PFW has to be unpacked, with technologies that provide a minimum damage to the food and do not adulterate its matrix. In addition, each type of PFW must be treated individually, to avoid possible cross-contaminations (Garcia-Garcia et al., 2017).

Although the studies reviewed above focuses on PFW, none of them have analyses the techniques to recover packaging from PFW after a sorting phase. Consequently, the description of the unpacking and sorting processes are not dealt with in these papers. PFW consisting of expired or wasted products from retailers and. The present paper tries to bridge this gap of knowledge by proposing an innovative system of sorting, unpacking, inventory management and track of PFW and evaluating its environmental impact.

2.2 EOL valorisation of packaging

As the LCA analysis focuses on the valorisation of packaging materials separated from FW, this section reviews the studies relating to the EOL valorisation options of different packaging materials. Table 1 summarises some of the main works concerning the valorisation of packaging materials, again on a timespan from 2008 to 2018; later on we will refer to the most recent and detailed works, related to the valorisation of the different types of packaging materials. The articles have been retrived by carrying out a query with the following set of keywords: “packaging”, and “end-of-life”.

This query returned 169 articles, and 31 of them are strictly related to the EOL management of packaging materials.

		Packaging material analysed						
Reference	**Region**	**Paper**	**Plastic**	**Composite packaging**	**Glass**	**Aluminium**	**Iron and steel**	**EOL scenario**
Al-Maaded et al. (2012)	Qatar		x					recycling
Almeida et al. (2017)	Brazil		x		x	x		recycling, reuse
Arena et al. (2017)	UK						x	recycling
Damgaard et al. (2009)	Denmark					x	x	recycling
Detzel and Mönckert, (2009)	Germany					x		recycling
Fallah et al. (2009)	Iran	x	x		x	x	x	combination of landfill, recycling, incineration and composting
Ferrão et al. (2013)	Portugal	x	x	x	x	x	x	recycling; composting; energy recovery; landfill
Ferreira et al. (2014)	Portugal	x	x		x	x	x	recycling; incineration; landfilling
Gatti et al. (2008)	Brazil					x		recycling
Ghinea et al. (2014)	Romania	x						recycling
Giugliano et al. (2011)	Italy	x	x		x		x	recycling; composting; energy recovery
Gu et al. (2017)	China		x					recycling
Hopewell et al. (2009)	UK/UE (review)		x					landfilling; incineration; down-gauging; reuse; recycling
James, (2012)	UK	x						recycling
Kulczycka et al. (2015)	Poland	x	x		x	x	x	recycling; landfilling; energy recovery
Larsen et al. (2009)	Denmark				x			recycling
Laurent et al. (2014)	Review	x	x	x	x	x	x	recycling; reuse; use on land; landfilling
Malik et al. (2017)	India (review)		x					recycling
Merrild et al. (2008)	Europe	x		x				recycling; incineration
Meylan et al. (2015)	Switzerland				x			recycling
Mourad et al. (2008)	Brazil			x				recycling
Niero et al. (2016)	Denmark					x		recycling
Park and Gupta, (2015)	Hawaii		x					recycling; incineration
Pasqualino et al. (2011)	Spain		x	x	x	x		recycling; incineration; landfilling
Rigamonti et al. (2009)	Italy	x	x		x	x	x	recycling; incineration
Rigamonti et al. (2014)	Italy		x					recycling
Rochat et al. (2013)	Colombia		x					recycling
Romero-Hernández et al. (2009)	Mexico		x					recycling; landfilling
Schmidt et al. (2007)	Denmark	x						recycling; incineration; landfilling
Toniolo et al. (2013)	Italy		x	x				recycling (for PET); incineration and landfilling (for multilayer plastic film)
Villanueva and Wenzel, (2007)	Europe (review)	x						recycling; incineration; landfilling

Xie et al. (2013)	China			x				landfilling; incineration; paper recycling; separation of polyethylene from aluminium
Xie et al. (2016)	China			x				recycling

Table 1: List of LCA studies on packaging EOL valorisation.

According to Licciardello (2017), food packaging sustainability can be achieved at three levels: 1) at raw material level, by using recycled materials and renewable resources; 2) at production level, using more energy efficient processes; 3) at waste management level, by reusing, recycling and biodegradation. This paper then focuses on points 1 and 3, analysing the following materials:

Plastic: Recycling is the preferred solution for plastic waste management (Polyethylene (PE), Polyethylene terephthalate (PET), Polypropylene (PP), etc.), because it has a lower environmental impact in several impact categories ranging from global warming to human toxicity indicators (Al-Maaded et al. 2012). The main benefits arise from the avoided production of virgin plastic, as confirmed by most recent articles in this field (Gu et al., 2017; Malik et al., 2017).

Paper: According to the literature reviewed, the worst option for paper and cardboard waste management is landfilling, in particular when considering the impact on climate change potential and energy demand. The comparison between recycling and incineration is more complex. If we only consider energy demand and water consumption, recycling is preferable to incineration, but they are comparable if we consider climate change. Compared to landfill, the main advantage of incineration is the substitution of fossil fuels, whereas incinerators provide heat and electricity. For recycling, the advantage is the wood resources saved, which can be used for producing paper or generating energy, i.e. from renewable fuel, which does not contribute to global warming (Merrild et al. 2008).

Glass: the literature regarding the treatment of glass waste is limited. A possible reason is that the energy required to process glass waste is relatively low and then glass recycling almost always proves to be a better option than landfill with respect to the environmental impact. Reuse after cleaning could be an option for this material in case of bottles or containers; however, such scenario could be profitable only in presence of a reverse logistics system for glass recovery and in case appropriate cleaning agents are used, so as to ensure a safe reuse (Almeida et al. 2017). Energy recovery from glass is also not possible, and therefore recycling is the preferred treatment method (Larsen et al. 2009).

Aluminium, Iron and Steel: the literature concerning waste metal treatment shows that recycling systems reduce all the environmental impacts considerably, compared to incineration and disposal in landfill. The main reason for metal recycling (ferrous and nonferrous alike) is that the production of virgin metal is extremely energy intensive. Scrap metal recycling is significantly less energy demanding; for example, aluminium recycling only uses 5% of the energy used to produce virgin material (Damgaard et al. 2009).

Composite packaging (PE, Aluminum and Paperboard): the literature about the treatment of composite packaging waste is limited; nevertheless, the available findings confirm that composite packaging waste treatments impacting most on the environment are, in order: landfill disposal, incineration and recycling. Furthermore, the latter two techniques show overall beneficial effects on the environment. Recycling is the best option for saving energy, while incineration is the best option for emission reduction (Xie et al. 2016).

3 Materials and methods

3.1 Methodological approach

The LCA methodology was applied according to the principles and requirements provided by standards (ISO 14044). The *SimaPro* release 8.3 *LCA software* was used to support the assessment.

3.2 Goal and scope definition

The purpose of this work is to compare the environmental impacts of an EOL process which uses a new sorting system for packaging materials derived from PFW with those of a traditional disposal system for PFW (where the packaged food products are disposed of in landfill), using the LCA technique. The two scenarios considered refer to the food waste data collected in 2015 in the Emilia Romagna region (northern Italy).

3.2.1 Functional unit

The functional unit provides a reference unit for which the inventory data is normalized (ISO 14040, 2006). The data relating to the amount of packaged food discarded was derived by means of direct contacts with 63 retail stores of varying sizes (6 hypermarkets, 26 supermarkets and 31 minimarkets) distributed across the Emilia Romagna region. The retail stores involved in the SORT project were interviewed between June and July 2016. Based on the interviews, it was appraised that retailers of the region wasted about 14,600 tons of packaged food in 2015. A quota of 300 tons/year was removed from this amount, as it corresponds to the amount of wasted food donated to charity purposes in the Emilia Romagna region. This amount has been estimated starting from a national value of 4,103 tons/year (Avvenire, 2017). Based on the data collected, the food wasted at retail stores can be categorized in the following groups: bakery (14.69%), coffee (0.09%), drinks (0.25%), fish (0.68%), frozen foods (0.13%), meat (27.63%), milk and dairy products (29.35%), pasta (3.05%), ready-made food (3.39%), salami (2.34%), sauces (0.56%), fruits and vegetables

(9.38%), other (8.46%). Again on the basis of the data collected, the average weight of the PFW was estimated to account for ca. 0.5 kg.

According to the in-field study carried out in the UK by WRAP (2013), primary packaging accounts for 13.8% in weight (on average) of the packaged food product donated to charity for human consumption in 2011; WRAP estimated in fact that out of 5,800 tons of the donated packaged food about 800 tons is packaging. Applying the same ratio, we estimated that the 13.8% of 14,300 tons of PFW, i.e. 1,973 tons, consist of packaging material wasted together with the expired food products. Therefore, the functional unit of all the scenario analysed is 1,973 tons of packaging waste, which according to the data provided by FISE UNIRE & Fondazione per lo sviluppo sostenibile (2016) can be estimated to consists of:

- Plastic materials, which account for 29.82% of the total amount of waste and include:
    - PE (13.92%);
    - PET (7.14%);
    - Other plastic materials such as PP, polystyrene (PS) and polyvinyl chloride (PVC) (8.76%);
- Paper-based materials which account for 29.79% of the overall amount of waste;
- Glass (26.24%)
- Aluminum (1.35%)
- Iron and steel (9.65%);
- Composite packaging (3.10%).

For the new scenario, several EOL treatments for the different packaging materials were evaluated by considering the real scenario of the Italian packaging end of life (recycling, recovering or landfilling systems) in the years 2014-2015. To this end, as defined in specific Italian consortia, the quantity of each packaging material separated from the food waste was divided into three different EOL destinations, as shown in Table 2:

Packaging material	Recycling [ton]	Energy recovery [ton]	Landfill [ton]	Total [ton]
PE (COREPLA, 2015)	112.9	118.4	44.0	275.4
PET (COREPLA, 2015)	57.8	60.6	22.5	140.9
Other plastic (COREPLA, 2015)	70.9	74.3	27.7	172.9
Paper (COMIECO, 2016)	470.2	52.9	64.7	587.8
Glass (COREVE, 2016)	367.6	0.0	150.2	517.8
Aluminium (CIAL, 2016)	18.7	1.5	6.5	26.7

Composite packaging (TetraPak, 2016)	14.4	28.7	18	61.1
Iron and steel (Consorzio Ricrea, 2016)	139.8	0.0	50.7	190.5

Table 2: Destination of the packaging fraction separated from the food waste in Emilia Romagna.

3.2.2 System boundaries and assumptions

The case study examined in this paper concerns packaged food products wasted in retail and distribution systems in Emilia Romagna. This study only targets the primary packaging that can be separated from the FW (Figure 1). The valorisation options of the separated FW is under evaluation or evaluated in other studies (e.g. Mosna et al. 2016) and is not dealt with here.

In the current scenario, the PFW is collected from the retail stores and during the distribution phase, transported and disposed of in landfill; this is the present EOL of packaged food wasted in retailing, as deduced from the analysis of the retail stores (Figure 1A).

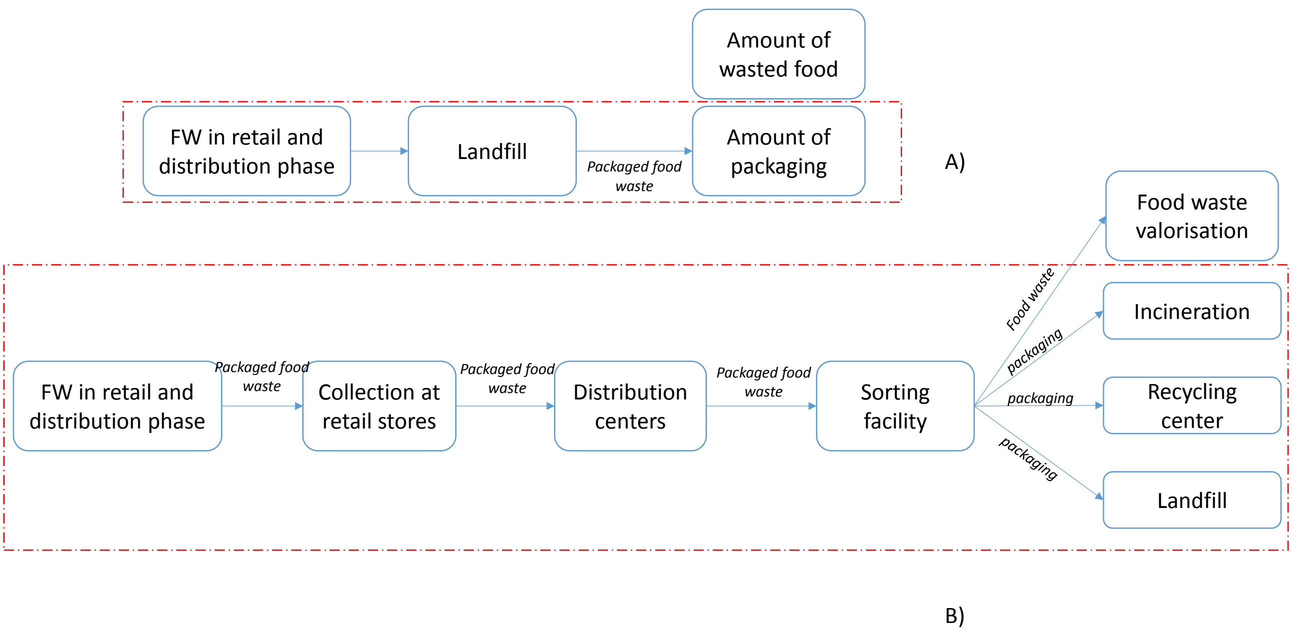

Figure 1: System boundaries of current scenario (A) and new process (B).

In the new process (Figure 1B), the PFW will be preliminary divided into five product families (i.e. fragile, not fragile, refrigerated, non-refrigerated and other), to ensure their safe transport. Product grouping will be carried out within the stores and supported by smart trolley, which provides assistance to the operators to separate the PFW. For this study, it was established that 930 out of 1557 retail stores of Emilia Romagna will be equipped with smart trolleys with five boxes (600*400*400 mm each), one for each product family, able to collect a maximum of 70 l of PFW per box. More precisely, the trolleys will be used only in hypermarkets and supermarkets, where the daily quantity of PFW is higher and can be separated in different boxes. Smaller retail stores will collect the whole amount of PFW in a unique box with the same capacity as those used in the trolley. All the boxes will be loaded on specific lorries, which will deliver them to the distribution centres every 4 days. The PFW will then be shipped every 4 days from the distribution centres to a centralized sorting facility, working in continuous, where the products, after a preliminary "chicane" that will align them in a single row (Figure 2), will be sorted into homogeneous groups and collected in different containers. Such sorting is supported by a portal scanner able to read bar codes and to identify items using integrated ViPR® (visual object recognition)[3] technology, with an average scanning capability of 100 products per minute and an efficiency close to 99.5% (Figure 2). The portal scanner is able to read the EAN13 code of each item, which uniquely identifies the packaged products. The EAN13 code of each food product is then used as the primary key to enter a database where all data regarding the food (e.g. ingredients, nutritional values and types of packaging materials) are stored. The sorting is carried out based on the packaging and product characteristics: more precisely, the PFW will be grouped as a function of the most suitable EOL valorisation, considering both the food waste option (reuse for pet food, for animal feed or for biogas production) and the packaging material option (recycling, energy recovery and landfill). On the basis of these criteria, 6 different product clusters have been identified:

1) meat and fish products, packaged in polymeric trays (pet food destination and packaging collection);
2) bread, pasta and dried biscuit (animal feed destination and packaging collection);
3) vegetable and fruits products (animal feed destination after drying and packaging collection);
4) water, spirits, drinks and beverages with screw cap packs (packaging collection only);
5) milk with screw cap packs (return to companies after drying and packaging collection);
6) other foodstuff (animal feed or biogas production and packaging collection).

The PFW of each group will subsequently be transferred to three food packaging separation machines able to separate the organic fraction from its packaging. For solid foodstuff (clusters 2, 3 and 6), unpacking technologies are currently available on the market (e.g. Atritor Turbo separator TS2096; Atritor, 2017) and make use of basic mechanical processes, such as compression, shredding and agitation screening to separate the content from its packaging (Mosna et al. 2016). A separation machine can be feed with one to five tonnes per hour of PFW and is able to separate both dry and wet FW with an estimated efficiency up to 99% in product recovery. In this case, the packaging materials are reduced to flakes, which could be valorised only through recycling or

[3] http://www.datalogic.com/eng/products/retail/in-counter-on-counter-scanners-scales/jade-x7-pd-615.html

energy recovery. Reuse will not be an option using this equipment, and, in any case, it would not be the best EOL valorisation for the materials treated. After separation, the food and packaging fractions might be slightly contaminated by one another; however, the contamination level is low and acceptable for the valorisation as animal feed or biomass of the food waste and for a non-food destination of the recycled packaging materials. After each treatment, the machine is completely cleaned by means of a Cleaning In Place (CIP) automatic system. For liquid food (clusters 4 and 5) a new separation machine has been designed; the machine will unscrew the cap, twist the bottle and empty it. The liquid food will be collected in containers, while the empty packaging in bins. For meat and fish products (cluster 1), a specific machine able to cut the packaging without damaging the food has been designed. The polymeric trays and the top film are cut on the short side of the packaging and then grasped on the opposite side by an anthropomorphic robot. By moving the tray, the robot will drop the food off inside a bin and put the packaging materials in a different container. It is essential that the food is kept intact for its valorisation in high value pet food, using only sliced selected foodstuffs.

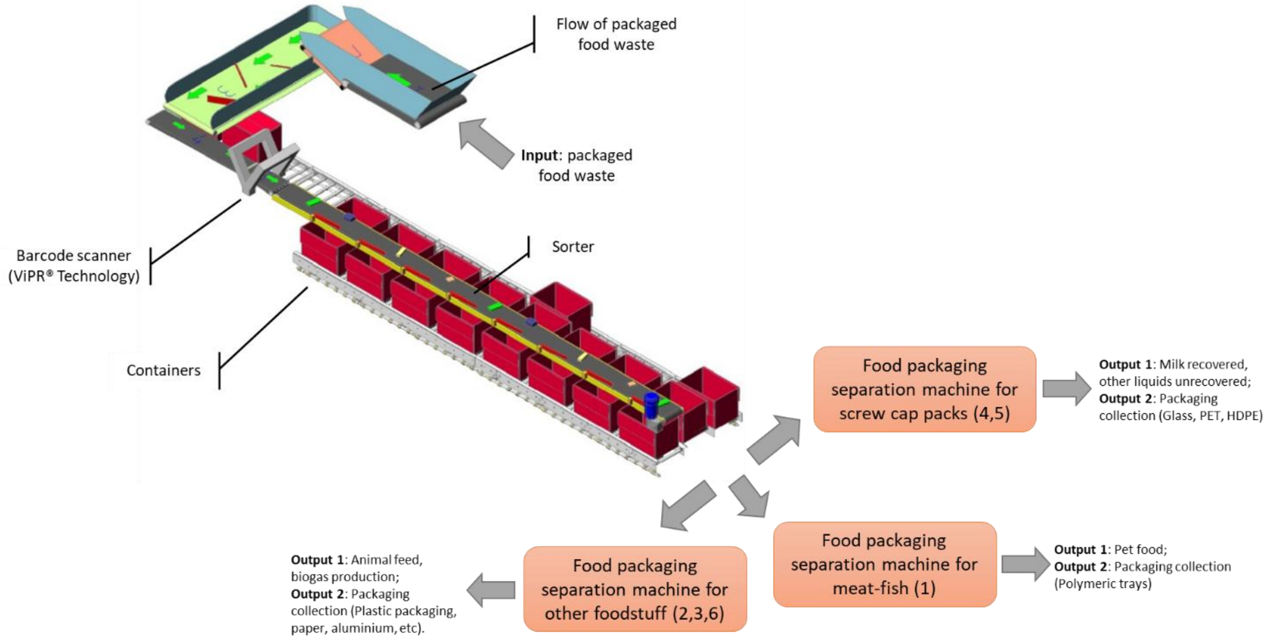

Figure 2: Sorting system.

All the separated packaging materials will then be sent to specific EOL destinations, such as incineration, recycling and landfill. To be consistent with the current scenario, the amount of recovered wasted food is again excluded from the analysis. The system boundaries for the valorisation of packaging materials in the new scenario can be seen in Figure 1B.

3.3 Life cycle inventory

In this step, we establish the phases, which have been either introduced or avoided in the new scenario. The avoided impacts are as follows: (i) transportation of the materials to the landfill sites; (ii) product disposal to landfills; (iii) the manufacturing of virgin and recycled material (taking into account the market mix and efficiency for the materials analysed, see Table 3); and (iv) the production of electricity, with an estimated efficiency of 25% (conversion factors for the materials analysed were extracted from literature, see Table 4). On the contrary, the impacts that have been introduced are: (i) grouping and collection of the PFW; (ii) transportation of boxes with PFW from the retail stores to the distribution centres; (iii) transportation of boxes with PFW from the distribution centres to the sorting facility; (iv) the industrial process for sorting, unpacking and splitting the food from the PFW; (v) the shipment of the separated packaging materials from the sorting facility to the EOL destinations; (vi) the use of water and other substances and the emissions relating to the sorting, separation and recycling, incineration and landfilling processes.

All primary data relating to the quantity of PFW during the distribution phase and at retail stores was gathered *via* questionnaires and personal interviews, and relates to the year 2015. Ecoinvent database v3.3 (Moreno Ruiz et al., 2016) and values from literature or Italian consortia were used as secondary data by considering the ones relating to the Italian or European situation. In particular, within the system boundary, the following assumptions and limitations have been made:

- The data relating to the transport activities was obtained considering the average distance covered by transport means in the Emilia Romagna region (related data was derived from logistics analyses carried out in the SORT project, bearing in mind that the sorting facility will be located close to the city of Bologna):
  - Current scenario: an average distance of 80 km per ton using a 3.5-7.5 metric ton EURO4 lorry for PFW transportation to landfill;
  - New scenario:
    - An average distance of 169.8 km per ton for PFW collection and transportation to the 19 distribution centres (the number of distribution centres to be included in the system was again derived from logistics analyses carried out in the SORT project);
    - An average distance of 58.58 km per ton for PFW transportation from the distribution centres to the sorting facility;

    - An average distance of 40 km per ton for separated packaging materials transportation from the sorting facility to recycling centre and incinerator, and of 10 km per ton for transportation to landfill.

  For the transportation from the distribution centres to the sorting facility a 16-32 metric ton, EURO4 lorry was used; for all the other transportation a 3.5-7.5 metric ton, EURO4 lorry was used;

- Mass-based allocation was used in order to account the share between organic mass and packaging into the PFW, as well as to account the share between the electric consumption of the sorting machine;
- The trolley used for grouping and collection of the PFW consists of a main chassis of stainless steel (30 kg), 4 wheels (1 kg of stainless steel plus 1 kg of synthetic rubber), 5 boxes of polypropylene (7.5 kg) and 1 central control panel (modelled as a laptop). A life span of 10 years has been assumed for each trolley;
- In the sorting and unpacking process, the specific values described in Table 5 were considered. In particular, taking into account the average product weight of 0.5 kg and the sorting speed of about 100 packages per minute, the resulting energy consumption and the weights of manufacturing materials for the sorting equipment are shown in Table 5, considering the life of the entire machinery to be 20 years;
- The average Italian electricity mix is used in the study both for the consumption and for the avoided quantities. (Moreno Ruiz et al., 2016);
- The ecoinvent database release 3.3 was used as a secondary data source by considering data relating to the Italian situation when possible (Moreno Ruiz et al., 2016);
- The secondary materials obtained from the packaging waste recycling process will be assumed to partially replace a mix of primary materials (i.e. those obtained from virgin raw materials) and secondary materials (the recycled ones) in a finished product (Gala et al., 2015, Vitale et al., 2017). The percentage of replacement changes according to the type of material. The savings in energy made and the reduction in emissions generated and raw materials used due to the avoided production of the mix of primary and secondary materials were taken into account in the recycling process. For instance, the production of one kg of PET bottle grade results in the emission of 2.15 kg of CO_2 eq. (Plastics Europe, 2011); such amount is reduced to about one third if a kilogram of recycled PET (r-PET) is considered (COREPLA, 2015). The details about the market mix (i.e. amount of virgin and

recycled material) for the materials analysed, as well as the performance of the recycling process, are shown in Table 3. These data were used in the computation of the impact according to the approach suggested by ISO/TR 14049 (2012) and Gala et al. (2015);

- For "Other plastics", it was assumed that all the recycled polymers will be used in the manufacturing of products traditionally made from plywood, for example outdoor furniture (fences, benches or facilities for children's playgrounds) (FISE UNIRE & Fondazione per lo sviluppo sostenibile, 2016);
- In the recycling processes, the efficiency values described in Table 3 and the landfill of residual rejected waste were also taken into account;
- The energy produced by the recovery process, in particular incineration of the separated packaging, will be assumed to replace the production of energy from the national network. The calorific values (LHV) based of packaging materials are shown in Table 4 according to the data provided by SEIeditrice (2012). The voice "incineration" includes the energy valorisation of the quantity of all the packaging materials that will be incinerated (corresponding to the quota labelled as "Energy recovery" in Table 2).

Packaging material	Recycling process				Market composition			Impact	
	Recycled product	**Efficiency**	**Data source**	**Avoided product**	**Amount of recycled material (%)**	**Amount of virgin material (%)**	**Data source**	**REC/VIR[4]**	**Data source**
Paper	Corrugated board, from recycling fibres	0.860	Ferreira et al. (2014)	Sulfate pulp	29%	71%	Gala et al. (2015), calculated from CEPI (2010)	0.9	Gala et al. (2015)
Composite packaging	Recycled paper and unseparated Al/PE	0.600	Xie et al. (2013)	Sulfate pulp	43%	57%	Gala et al. (2015), calculated from CEPI (2010)	0.806	Mungcharoen et al. (2010)
PET	PET granulate	0.755	Rigamonti et al. (2014)	PET granulate	13%	87%	Recycling Today (2017)	0.33	Malik et al. (2017)
PE	PE granulate	0.900	Rigamonti et al. (2014)	PE granulate	50%	50%	Gu et al. (2017)	0.90	Mungcharoen et al. (2010)
Other plastic materials	PP, PS, PVC, etc.	0.614	Rigamonti et al. (2014)	Outdoor furniture (plywood)	2.5%	97.5%	Plastic Europe (2015)	1	Rigamonti et al. (2009)
Glass	Glass from cullet	0.901	Rigamonti et al. (2009)	Glass from virgin materials (41.9% green, 30.3% white, 27.8% brown)	45%	55%	Roldán and Pino (2012) *apud* Gala et al. (2015)	0.428	Mungcharoen et al. (2010)
Aluminium	Aluminium from old scrap	0.883	Rigamonti et al. (2009)	Aluminium	75%	25%	Gala et al. (2015)	0.1	Gala et al. (2015)
Steel	Steel scrap	0.840	Ferreira et al. (2014); Arena et al. (2017)	Pig iron	50%	50%	Eurofer (2014); Gala et al. (2015)	0.297	Classen et al. (2009); Gala et al. (2015)
Iron	Ferrous scrap	0.840	Ferreira et al. (2014); Arena et al. (2017)	Pig iron	70%	30%	Cerdan et al. (2009)	0.089	Mungcharoen et al. (2010)

Table 3: Recycling process of packaging materials and related efficiency.

[4] Ratio between the environmental impact of recycling process (REC) and that of the production process of the virgin material (VIR).

Packaging material	Calorific value (LHV) [MJ/kg]
PE	46
PET	33
Other plastics	28
Paper	17
Glass	/
Aluminium	38.88
Iron and Steel	/
Composite packaging	20

Table 4: Calorific values of packaging materials (SEIeditrice, 2012).

Input	Unit	Conveyor belts	Atritor TS 2096	Unscrewing machine	Trays cutting machine
Electricity	kW	3.5	22	3.44	4.5
Compressed air	kW	-	0.75	0.5	0.5
Total consumption for functional unit	kWh	16681	36142	6259	7943
Equipment materials (20 years of life)	kg (PE)	4	/	1	/
	kg (stainless steel)	6	35	50	25

Table 5 Specific values for the sorting and unpacking process.

3.4 Methods of impact assessment

The software SimaPro release 8.4 contains a number of impact assessment methods that can be used to calculate the impact assessment results. These methods are divided into subgroups, namely European, North American, Single issue, Water footprint and Superseded. Taking into account the European methods, eight methods can be used to calculate the impact assessment results; in particular, the three most used methods are EPD, ILCD and ReCiPe, and include seven, eleven and seventeen impact categories, respectively. Of these three methods, the Re.Ci.Pe. method (Huijbregts et al. 2016) was selected as it is the most used in the context of waste management and can give a complete overview of various impact categories; in addition, the uncertainty of the results at this point is relatively low. The hierarchic perspective was selected for the analysis, as it is considered the most balanced of the three proposed by the method (Egalitarian, Individualist and Hierarchist). Impact values were calculated at midpoint level for 17 impact categories, i.e. (i) Global warming, (ii) Stratospheric ozone depletion, (iii) Ionizing radiation, (iv) Ozone formation, Human health, (v) Fine particulate matter formation, (vi) Ozone formation, Terrestrial ecosystems, (vii) Terrestrial acidification, (viii) Freshwater eutrophication, (ix) Terrestrial ecotoxicity, (x) Freshwater ecotoxicity, (xi) Marine ecotoxicity, (xii) Human carcinogenic toxicity, (xiii) Human non-carcinogenic toxicity, (xiv) Land use, (xv) Mineral resource scarcity, (xvi) Fossil resource scarcity, (xvii) Water consumption.

4 Life Cycle Impact Assessment

4.1 Current scenario: disposal in landfill

The results for the current scenario are reported in Table 6, while Figure 3 shows the relative contribution of each processing input.

Impact category	Measurement unit	Total	Transport	Disposal of in landfill						
				PE	PET	Other plastics	Paper	Aluminium	Glass	Iron and steel
Global warming	kg CO_2 eq.	1.34E+06	8.06E+04	4.19E+04	1.44E+04	1.99E+04	1.18E+06	1.23E+03	6.48E+03	3.00E+03
Stratospheric ozone depletion	kg CFC11 eq.	8.23E-02	3.32E-02	2.14E-03	1.56E-03	1.88E-03	4.21E-02	4.72E-04	6.69E-04	2.90E-04
Ionizing radiation	kBq Co-60 eq.	1.08E+03	6.53E+02	3.80E+01	1.98E+01	2.43E+01	2.02E+02	9.20E+00	9.94E+01	3.52E+01
Ozone formation, Human health	kg NOx eq.	4.39E+02	3.14E+02	2.31E+01	1.16E+01	1.42E+01	7.02E+01	4.73E+00	7.13E-01	2.21E-01
Fine particulate matter formation	kg PM2.5 eq.	1.21E+02	6.44E+01	5.63E+00	2.79E+00	3.50E+00	3.57E+01	2.45E+00	5.84E+00	8.94E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq.	4.48E+02	3.20E+02	2.35E+01	1.18E+01	1.45E+01	7.13E+01	4.81E+00	1.15E+00	3.56E-01
Terrestrial acidification	kg SO_2 eq.	4.27E+02	2.38E+02	1.67E+01	8.38E+00	1.06E+01	1.08E+02	5.80E+00	3.28E+01	7.06E+00
Freshwater eutrophication	kg P eq.	1.30E+01	1.73E+00	8.03E-02	4.37E-02	5.33E-02	6.04E-01	5.00E-02	1.05E+01	1.30E-03
Terrestrial ecotoxicity	kg 1,4-DCB eq.	2.29E+02	1.81E+02	1.97E+00	9.85E-01	1.23E+00	7.51E+00	4.44E-01	4.08E-01	3.48E+01
Freshwater ecotoxicity	kg 1,4-DCB eq.	2.88E+02	1.28E+02	6.59E+01	1.87E+01	9.08E+00	5.60E+01	1.86E+00	5.17E-01	8.70E+00
Marine ecotoxicity	kg 1,4-DCB eq.	7.69E+02	5.14E+02	9.84E+01	2.90E+01	1.59E+01	9.45E+01	3.64E+00	3.60E+00	9.63E+00
Human carcinogenic toxicity	kg 1,4-DCB eq.	8.03E+02	5.57E+02	2.66E+01	1.29E+01	1.85E+01	1.74E+02	8.34E+00	6.18E-01	4.65E+00
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	4.84E+05	3.53E+05	1.81E+04	5.52E+03	9.01E+03	8.50E+04	3.67E+03	1.00E+03	8.22E+03
Land use	m^2a crop eq.	6.52E+03	2.41E+03	8.84E+02	4.36E+02	5.34E+02	2.15E+03	1.15E+02	0.00E+00	0.00E+00
Mineral resource scarcity	kg Cu eq.	4.99E+02	2.30E+02	1.02E+01	5.06E+00	6.21E+00	3.02E+01	2.03E+00	1.98E+02	1.76E+01
Fossil resource scarcity	kg oil eq.	3.81E+04	2.71E+04	1.67E+03	8.30E+02	1.02E+03	4.76E+03	3.68E+02	1.77E+03	5.78E+02
Water consumption	m^3	7.01E+02	2.63E+02	8.19E+01	4.08E+01	5.01E+01	2.42E+02	1.36E+01	7.78E+00	2.29E+00

Table 6: Characterization results of the overall impact of the disposal in landfill scenario.

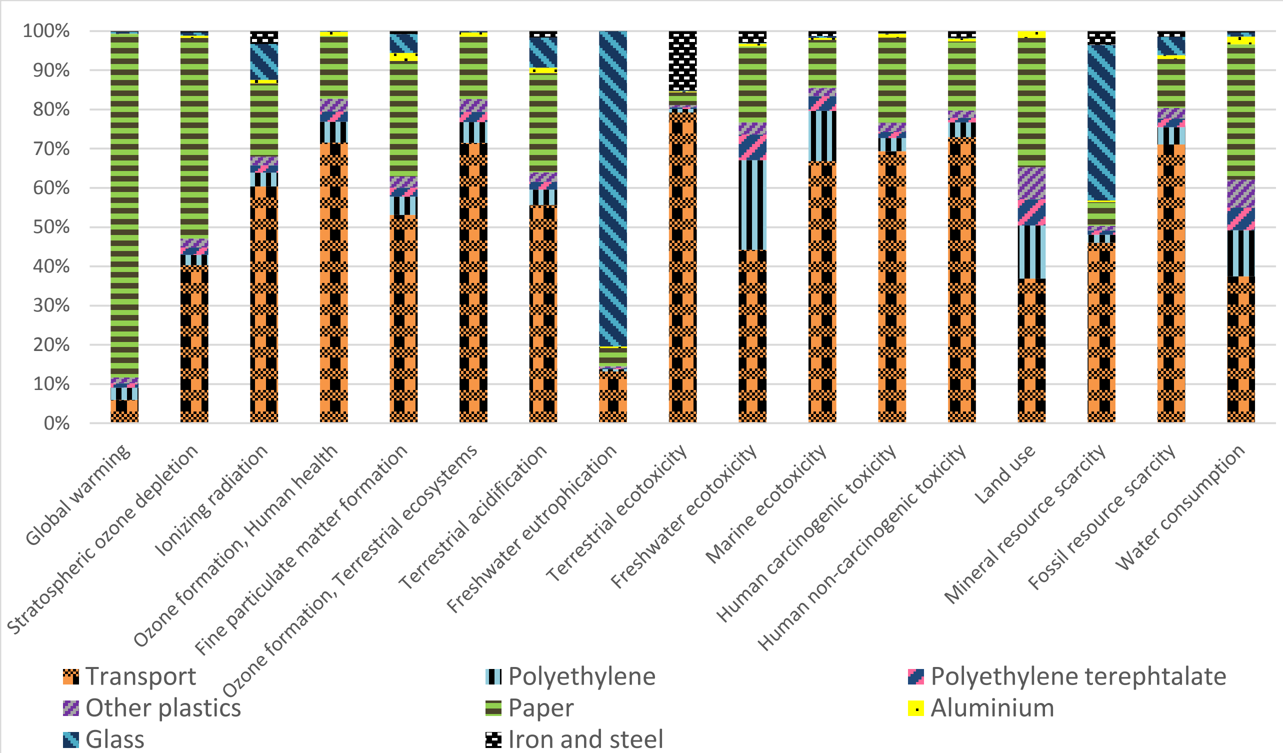

Figure 3: Contribution analysis of the environmental impact of current scenario.

As can be seen from the environmental impacts divided according to stages (Table 6 and Figure 3), disposal of the packaging materials in landfill represents a major contribution for 7 impact categories, namely Global warming, Stratospheric ozone depletion, Freshwater eutrophication, Freshwater ecotoxicity, Land use, Mineral resource scarcity and Water consumption. Conversely, transport to the landfill contributes the most in 8 categories; in particular, this phase impacts mainly in Human carcinogenic and non-carcinogenic toxicity, Ionizing radiation, Fossil resource scarcity and in the two Ozone formation human health and terrestrial ecotoxicity impact categories. These results are strictly connected to the well-known emissions and fossil fuel consumption typical of the transport process. For the two remaining categories, landfilling and transportation contribute almost to the same extent to the total impact.

Looking at the Global warming impact category, the first main contribution in terms of impact generated is landfilling of paper that accounts approximately for +88% of the total impact due to the high volume handled and to its rapid decay. Conversely, landfilling of glass contributes mainly to the Freshwater eutrophication and Mineral resource scarcity indicators, for which it accounts for +80% and +40% of the total impact, respectively. The contribution of the other materials is generally low for most of the impact categories, as they are almost inert products.

To summarize, the analysis of the current scenario highlights two contributions (i.e. paper landfilling and transport) that contribute mainly to the total impact generated.

4.2 Benefits from the new process: comparative analysis

The environmental impacts avoided thanks to the new process, compared to the current scenario, have been reported in Table 7 and Figure 4, by using the same 17 midpoint indicators as before. It is worth mentioning that negative values in Figure 4 and Table 7 denote a benefit for the environment, whereas positive values indicate an environmental burden. The representation in Figure 4 aims at comparing different impact categories characterized by different measurement units. Because of the different scale, such comparison cannot be made with the absolute values of the impacts; therefore, the results were elaborated and computed as relative (percentage) values

Impact category	Measurement unit	Total	Trolleys and boxes	Unpacking machines	Recycled Materials								Landfill	Incineration
					PET	PE	Other plastics	Glass	Aluminium	Paper	Composite packaging	Iron and steel		
Global warming	kg CO2 eq.	-1.04E+06	3.29E+03	2.94E+01	-1.71E+05	-1.88E+05	4.46E+03	-2.97E+05	-2.26E+04	-1.07E+06	3.56E+03	-8.85E+04	1.62E+05	6.23E+05
Stratospheric ozone depletion	kg CFC11 eq.	-2.08E-01	1.32E-03	8.02E-06	-4.78E-02	1.71E-02	-2.71E-03	-1.55E-01	-1.40E-02	-1.72E-01	2.96E-03	-9.00E-03	7.29E-03	1.64E-01
Ionizing radiation	kBq Co-60 eq.	-4.12E+03	1.69E+01	1.11E-01	-3.67E+02	2.55E+02	-1.55E+02	-1.39E+03	-2.80E+02	-1.77E+03	4.94E+01	-3.09E+01	9.47E+01	-5.32E+02
Ozone formation, Human health	kg NOx eq.	-2.62E+03	8.56E+00	7.49E-02	-2.32E+02	-3.68E+02	-5.20E+00	-8.02E+02	-6.21E+01	-1.11E+03	-2.77E+00	-1.48E+02	2.57E+01	7.97E+01
Fine particulate matter formation	kg PM2.5 eq.	-2.14E+03	7.86E+00	6.73E-02	-1.47E+02	-1.00E+02	-2.26E+01	-6.59E+02	-6.53E+01	-9.41E+02	-6.37E+00	-1.56E+02	1.05E+01	-6.17E+01
Ozone formation, Terrestrial ecosystems	kg NOx eq.	-2.70E+03	9.14E+00	7.82E-02	-2.43E+02	-4.14E+02	4.58E+00	-8.12E+02	-6.30E+01	-1.12E+03	-2.71E+00	-1.64E+02	2.63E+01	7.85E+01
Terrestrial acidification	kg SO2 eq.	-4.72E+03	1.50E+01	1.12E-01	-3.59E+02	-4.21E+02	-1.37E+01	-1.94E+03	-1.44E+02	-1.48E+03	3.04E+00	-2.69E+02	3.77E+01	-1.43E+02
Freshwater eutrophication	kg P eq.	-4.61E+01	1.98E+00	6.92E-03	-4.54E+00	9.39E-01	-3.05E+00	-1.83E+01	-2.13E+00	-1.96E+01	-1.86E-03	-2.39E+00	3.20E+00	-2.27E+00
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	6.08E+00	4.66E-02	-1.20E+02	1.83E+00	-5.77E+00	-9.28E+01	-2.54E+01	-1.22E+02	4.34E+00	-4.69E+00	1.55E+01	4.08E+02
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	1.36E+01	8.42E-02	-5.82E+01	-4.25E+01	2.02E+00	-1.55E+02	-2.22E+01	-1.31E+02	2.18E+00	-2.52E+01	2.83E+01	1.92E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	4.14E+01	2.24E-01	-3.59E+02	-4.95E+01	-1.42E+01	-4.47E+02	-1.02E+02	-5.09E+02	9.99E+00	-1.83E+00	5.22E+01	1.39E+03
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	1.63E+02	5.48E+00	-9.04E+02	-9.49E+02	-3.51E+02	-1.70E+03	-8.15E+02	-3.30E+03	-3.40E+00	-9.18E+01	4.80E+01	8.21E+02
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	2.99E+04	2.18E+02	-2.16E+05	2.04E+03	-1.28E+05	-7.46E+05	-1.81E+05	-1.54E+06	-9.39E+03	-1.29E+05	2.78E+04	2.18E+05
Land use	m^2 a crop eq.	-6.73E+05	9.41E+01	6.13E-01	-2.15E+03	2.77E+01	-5.44E+04	-2.07E+04	-1.89E+03	-5.85E+05	-8.69E+03	-1.98E+02	6.54E+02	-1.19E+03
Mineral resource scarcity	kg Cu eq.	-5.87E+03	8.57E+01	1.45E+00	-2.37E+02	1.54E+01	-7.21E+01	-5.75E+02	-4.81E+02	-4.18E+02	7.93E+00	-4.24E+03	7.53E+01	-3.49E+01
Fossil resource scarcity	kg oil eq.	-3.52E+05	1.03E+03	7.05E+00	-5.29E+04	-1.42E+05	1.16E+03	-7.65E+04	-3.02E+03	-5.54E+04	1.42E+03	-1.48E+04	2.58E+03	-1.35E+04
Water consumption	m^3	-1.60E+04	2.52E+01	2.12E-01	-1.16E+03	-6.35E+02	-1.72E+01	-2.61E+03	-3.93E+02	-1.06E+04	-1.25E+00	-1.25E+02	7.06E+01	-5.22E+02

Table 7: Impact of the new process: comparative evaluation.

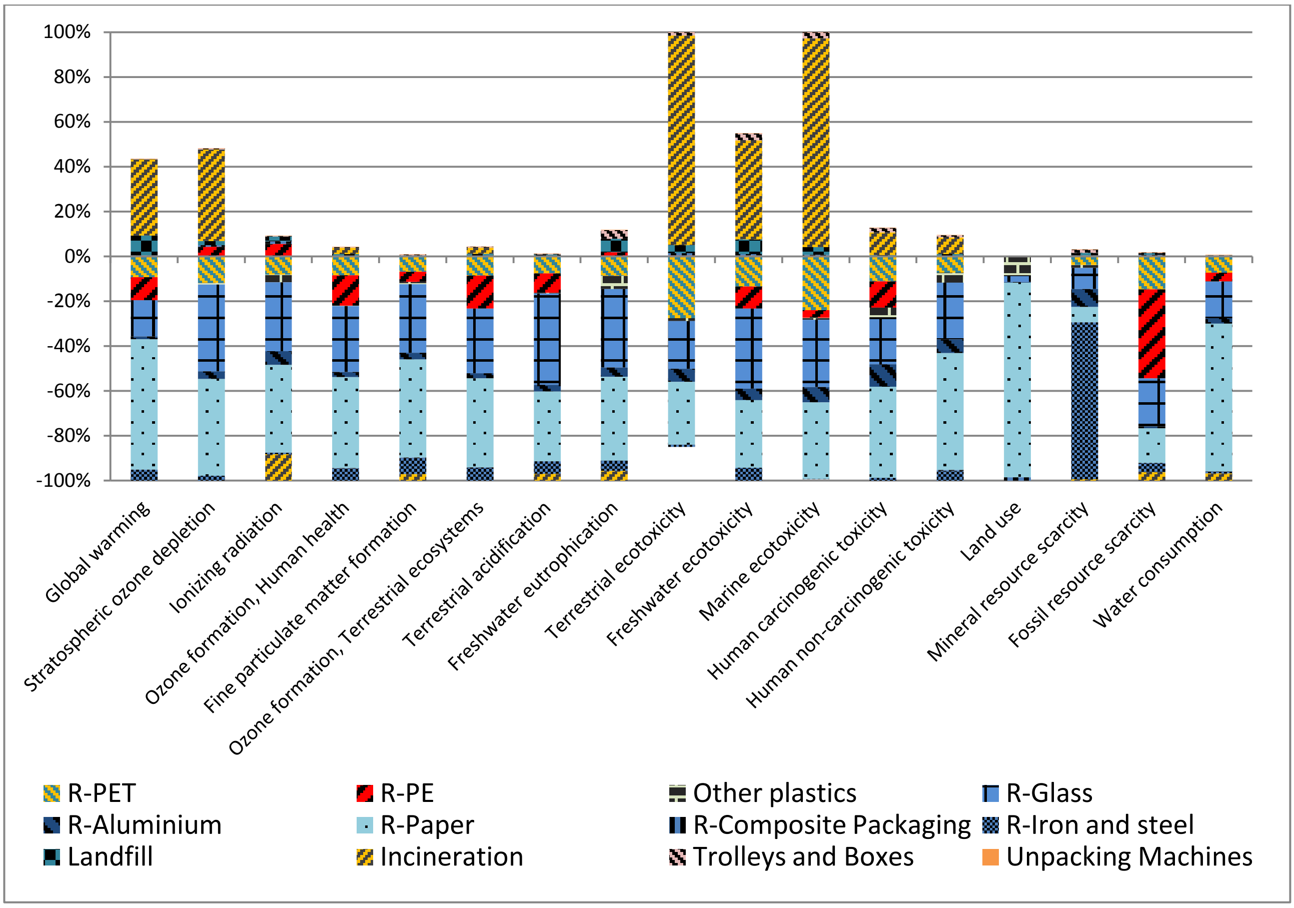

Figure 4: Percentage values of the environmental impacts of the new process: comparative evaluation.

Figure 4 shows that compared to the current scenario, the new process generates better results in almost all the impact categories analysed, resulting in negative impacts for 15 categories. Conversely, as far as the Terrestrial ecotoxicity is concerned, the current scenario appears to be more environmental friendly, probably due to the emissions connected to the incineration process of the new scenario. Incineration also nullifies the environmental benefit of the new process in Marine ecotoxicity impact category.

The environmental benefits of the new process are generated by the partial savings in raw materials (sulfate pulp, PE, PET, glass, pig iron, aluminium and plywood), and in energy and emissions from the materials recycling process respect to the virgin materials process (Gu et al. 2017; Malik et al. 2017). Similarly, the energy production is saved because it can be partially obtained thanks to the incineration process. Other waste management operations, such as grouping, PFW collection, sorting, unpacking and separation of food from PFW due to the electricity and fuels consumption entail environmental burdens which are however lower (by two or three order of magnitude) if compared to the benefit generated by the whole process.

The recycling of paper and glass represents the main contribution to these benefits: the impact reduction among the various categories accounts on average for -41% for paper and -25% glass. However, for all the considered categories, the main quota of avoided impact is due to paper recycling, because of the high volumes handled and the excellent efficiency of the recycling process.

Looking at the Global warming indicator, in addition to the aforementioned paper recycling (-58%), the avoided impact are mainly caused by glass recycling (-16%), PE recycling (-10%), PET recycling (-9%) and iron and steel recycling (-5%). On the other hand, incineration and landfill cause a positive impact on this indicator (+34% and +9% respectively). Even if the quantity of packaging materials treated in the incineration process are lower than that landfilled, its contribution to the global warming category is almost four times higher, due to the ease and fast combustion of plastics which emits CO_2 of fossil origin (Ferreira et al., 2014). The incineration process, which takes into account the amounts of all materials that will be incinerated, generates a positive impact mainly in the Ecotoxicity, Global warming (+34%) and Stratospheric ozone depletion (+41) impact categories; these results are due to the combustion by-products (e.g. carbon monoxide, dinitrogen monoxide, sulphur dioxide, ammonia…). Conversely, the highest avoided impact is observed in Ionizing radiation (-12%); for the remaining impact categories, the avoided impacts account for -4% on average, due to the energy produced by the incineration process.

PE recycling also generates significant positive impact in 3 categories (Stratospheric ozone depletion, Ionising radiation and Freshwater eutrophication), mainly due to the incoming transport activities and the recycling process.

Recycling of glass generates a negative impact in all the categories, with an average impact of -25%, due to the partial saving in virgin materials and in energy consumption during the production of new glass.

Looking at the Mineral resource scarcity, the major benefit (-70%) is due to the recycling of metal materials, unlike the other categories, where metal recycling involves very limited benefits to the environment.

Finally, the positive impacts of the trolleys turn out to be the main contribution to the Freshwater eutrophication (+4%), Freshwater ecotoxicity (+3%), Marine ecotoxicity (+3%) and Human carcinogenic toxicity (+2%), primarily due to the production of the electronic systems and of their steel structure.

4.3 Sensitivity analysis

In this study, three sensitivity analyses were carried out. Firstly, an evaluation was made to establish whether the total environmental performance is affected by a variation in the distance covered during the transport activity (i.e. the transportation of PFW to distribution centres, the transportation of PFW to the sorting facility and the transportation of packaging to the recycling centre). A second evaluation was then carried out to see how the new scenario would change in a different context, compliant with the European Union Directive 2008/98/EC, which sets out higher targets for the percentages of valorised packaging. In the third sensitivity analysis, the new process was applied considering the European scenario (EU28) of the packaging waste composition (Eurostat, 2017).

The first analysis is motivated by the fact that the distances between the retailers and the distribution centres could considerably increase if considering different regions of Italy or areas that are less populated than Emilia Romagna. We assume that no variations occur in the remaining processing phases when changing the transport distance. The proposed sensitivity analysis considers different transport distances, obtained by increasing the original values by 2, 4 and 6 times, to assess their influence on the process as a whole.

Impact category	**Measurement unit**	**Transport impact**	**Original total impact**	**New total impact**		
				Transport 2x	*Transport 4x*	*Transport 6x*
Global warming	kg CO2 eq.	2.24E+05	-1.04E+06	-8.14E+05	-7.02E+05	-5.90E+05
Stratospheric ozone depletion	kg CFC11 eq.	9.30E-02	-2.08E-01	-1.15E-01	-6.87E-02	-2.22E-02
Ionizing radiation	kBq Co-60 eq.	1.83E+03	-4.12E+03	-2.28E+03	-1.37E+03	-4.52E+02
Ozone formation, Human health	kg NOx eq.	8.86E+02	-2.62E+03	-1.73E+03	-1.29E+03	-8.43E+02
Fine particulate matter formation	kg PM2.5 eq.	1.79E+02	-2.14E+03	-1.96E+03	-1.87E+03	-1.78E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq.	9.03E+02	-2.70E+03	-1.80E+03	-1.34E+03	-8.93E+02
Terrestrial acidification	kg SO2 eq.	6.62E+02	-4.72E+03	-4.06E+03	-3.73E+03	-3.40E+03
Freshwater eutrophication	kg P eq.	4.66E+00	-4.61E+01	-4.15E+01	-3.91E+01	-3.68E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	5.29E+02	6.52E+01	5.94E+02	8.58E+02	1.12E+03
Freshwater ecotoxicity	kg 1,4-DCB eq.	3.69E+02	-1.96E+02	1.73E+02	3.57E+02	5.42E+02
Marine ecotoxicity	kg 1,4-DCB eq.	1.49E+03	9.67E+00	1.50E+03	2.24E+03	2.99E+03
Human carcinogenic toxicity	kg 1,4-DCB eq.	1.51E+03	-7.08E+03	-5.57E+03	-4.82E+03	-4.06E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	1.01E+06	-2.67E+06	-1.66E+06	-1.15E+06	-6.42E+05
Land use	m^2 a crop eq.	6.96E+03	-6.73E+05	-6.66E+05	-6.63E+05	-6.59E+05
Mineral resource scarcity	kg Cu eq.	6.21E+02	-5.87E+03	-5.25E+03	-4.94E+03	-4.63E+03
Fossil resource scarcity	kg oil eq.	7.56E+04	-3.52E+05	-2.76E+05	-2.38E+05	-2.01E+05
Water consumption	m^3	7.30E+02	-1.60E+04	-1.53E+04	-1.49E+04	-1.45E+04

Table 8: Results of the sensitivity analysis with variation in the transport phase.

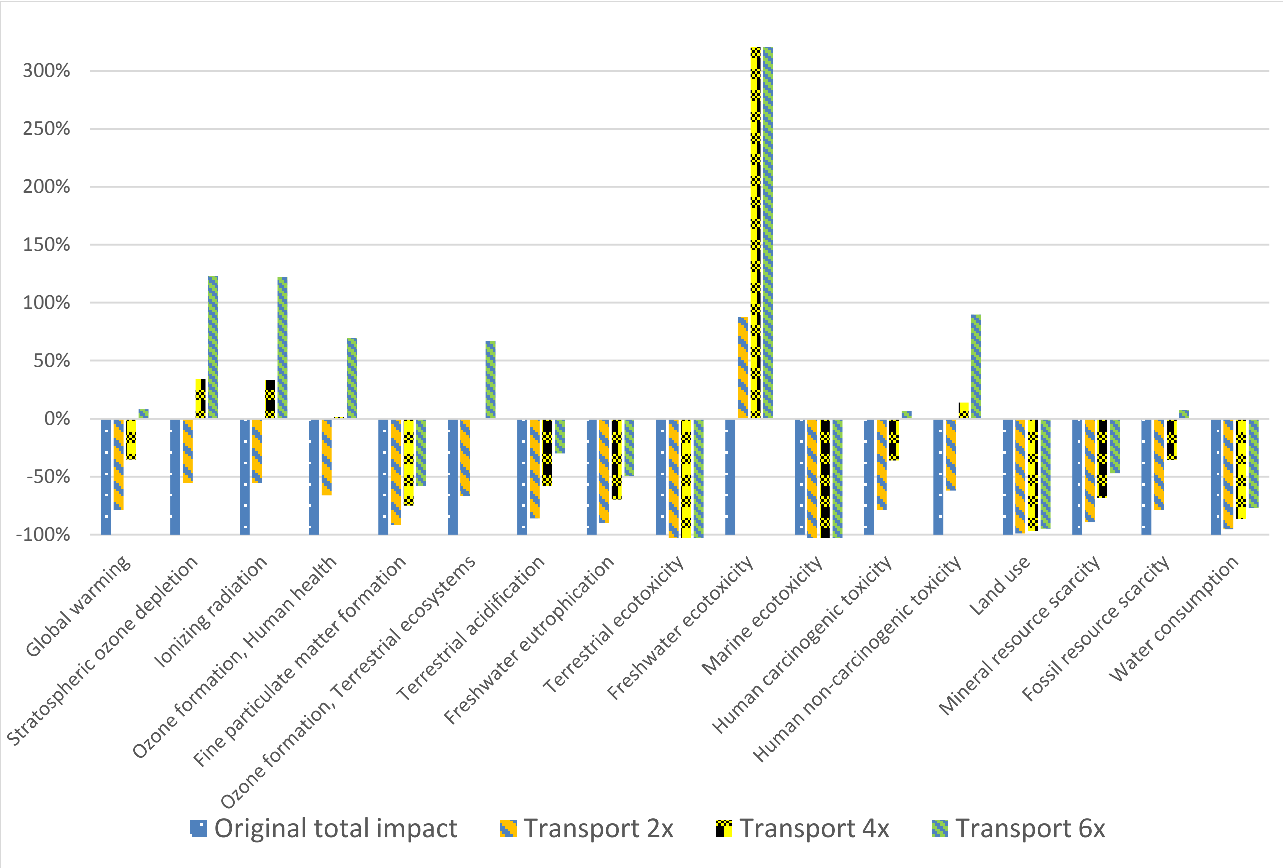

Figure 5: Percentage values of the environmental impacts with variation in the transport phase.

The results of this analysis (Figure 5 and Table 8) show that a change in the transport distance slightly influences the environmental impacts. When the transport distance is doubled, the total impact remains negative in most of the impact categories. Conversely, when the transport phase is multiplied by 4 or 6 meaningful variations can be noted, resulting in a total impact that for some categories turn out to be positive. More precisely, in the "*Transport 6x*" scenario the benefits in the Global warming category are nullified if compared with the current scenario, increasing from -1.04E+6 kg CO_2 eq. to 5.90E+5 kg CO_2 eq.

The second sensitivity analysis was carried out on the basis of European Union Directive 2008/98/EC, which sets out the basic concepts and definitions relating to waste management, such as definitions of waste, recycling and recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products.

The Directive introduces two new recycling and recovery targets to be achieved by 2020:

- 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households; and

- 70% preparing for re-use, recycling and other recovery of construction and demolition waste.

One of the member states that has already achieved and overtaken these targets is Germany (Umweltbundesamt, 2016). Hence, the example of Germany is taken to evaluate the performance the new process could achieve if it was used in a country where the recycling is more adopted than in Italy. To this end, the German EOL efficiency percentages (Table 9) were introduced in the analysis and applied to the same quantity of PFW in Emilia Romagna. This is expected to show what the Emilia Romagna scenario would be like if German recycling efficiencies were achieved.

GERMANY				
	Distribution %	% Recycling	% Energy Recovery	% Landfill
Iron and steel	9.65%	93	0	7
Alluminium	1.35%	88.1	3.7	8.2
Paper	29.79%	87.3	12.4	0.3
PE	13.92%	50.2	49.3	0.5
PET	7.14%	93.6	5.9	0.5
PLASMIX	8.76%	41	43	16
Glass	26.24%	89	0	11
Composite packaging	3.10%	23.6	47	29.4

Table 9: German EOL distribution percentage.

Impact category	**Unit**	**Italian scenario**	**German EOL efficiency percentages**
Global warming	kg CO2 eq.	-1.04E+06	-1.70E+06
Stratospheric ozone depletion	kg CFC11 eq.	-2.08E-01	-3.83E-01
Ionizing radiation	kBq Co-60 eq.	-4.12E+03	-5.55E+03
Ozone formation, Human health	kg NOx eq.	-2.62E+03	-3.36E+03
Fine particulate matter formation	kg PM2.5 eq.	-2.14E+03	-2.63E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq.	-2.70E+03	-3.47E+03
Terrestrial acidification	kg SO2 eq.	-4.72E+03	-5.92E+03
Freshwater eutrophication	kg P eq.	-4.61E+01	-6.97E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	-1.71E+02
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	-3.78E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	-7.84E+02
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	-9.46E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	-3.41E+06
Land use	m^2 a crop eq.	-6.73E+05	-7.37E+05
Mineral resource scarcity	kg Cu eq.	-5.87E+03	-7.68E+03
Fossil resource scarcity	kg oil eq.	-3.52E+05	-4.85E+05
Water consumption	m^3	-1.60E+04	-1.90E+04

Table 10: Results of the sensitivity analysis with variation in EOL product percentage.

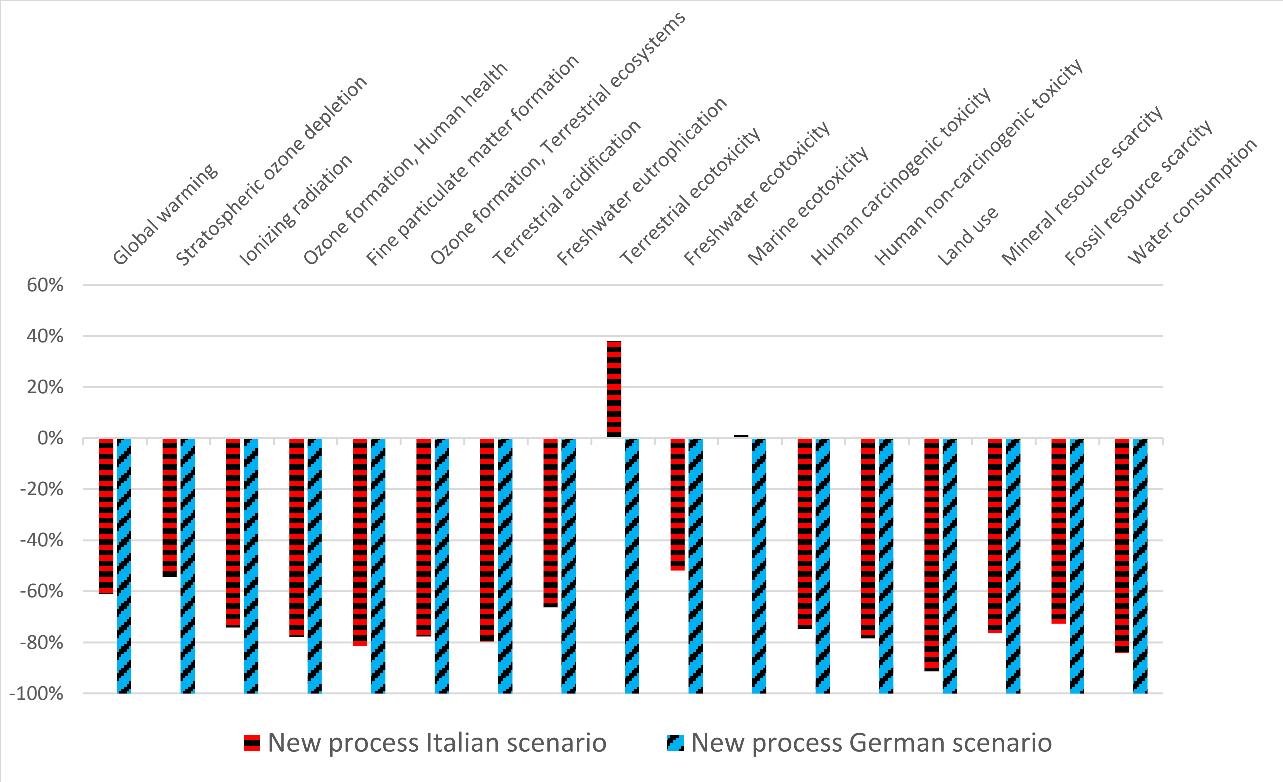

Figure 6 Environmental impacts analysis with variation in EOL product percentage.

The results of the second sensitivity analysis show that a change in the EOL percentage (Figure 6 and Table 10) has a significant influence on theenvironmental impact. Globally, it was proved that the “German scenario” generates more benefits for the environment than the “Italian scenario”, especially regarding the Terrestrial and Marine ecotoxicity impact categories, where an environmental benefit is now achieved. The impact that is avoided based on the German EOL percentage appears higher in all the categories, with an average absolute improvement of 38%.

Besides the categories mentioned above, the highest improvements are observed for Freshwater ecotoxicity (48%), Stratosferic ozone depletion (46%), Global warming (39%), Freshwater euthrophication (45%). This result is due to the higher percentage of materials destined for recycling and the lower landfill volumes.

Overall, the “German scenario” is more environmental friendly mainly due to the lower packaging percentage handled and allocated to the landfill and incineration, particularly for the impacts connected to the plastic materials.

Similar to the results reported in Rigamonti et al. (2009) and Ferreira et al. (2014), the recycling system involves a clear benefit for the environment for all the impact categories considered. Looking at the Global warming category, the German scenario avoids the emissions of 6.6E+05 of CO2 eq. compared to the new process applied to the Italian scenario.

The third sensitivity analysis was carried out setting as input the composition of the packaging waste of the European context (Eurostat, 2017) and keeping the EOL unchanged.

Impact category	Unit	New process Italian scenario	EU28
Global warming	kg CO2 eq	-1.04E+06	-1.46E+06
Stratospheric ozone depletion	kg CFC11 eq	-2.08E-01	-2.72E-01
Ionizing radiation	kBq Co-60 eq	-4.12E+03	-4.51E+03
Ozone formation, Human health	kg NOx eq	-2.62E+03	-2.84E+03
Fine particulate matter formation	kg PM2.5 eq	-2.14E+03	-2.37E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq	-2.70E+03	-2.92E+03
Terrestrial acidification	kg SO2 eq	-4.72E+03	-4.87E+03
Freshwater eutrophication	kg P eq	-4.61E+01	-5.04E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	-2.98E+01
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	-2.45E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	-3.36E+02
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	-7.84E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	-3.18E+06
Land use	m2a crop eq	-6.73E+05	-9.13E+05
Mineral resource scarcity	kg Cu eq	-5.87E+03	-5.46E+03
Fossil resource scarcity	kg oil eq	-3.52E+05	-3.17E+05
Water consumption	m3	-1.60E+04	-1.97E+04

Table 11: Results of the sensitivity analysis with variation of the composition of packaging waste (EU28).

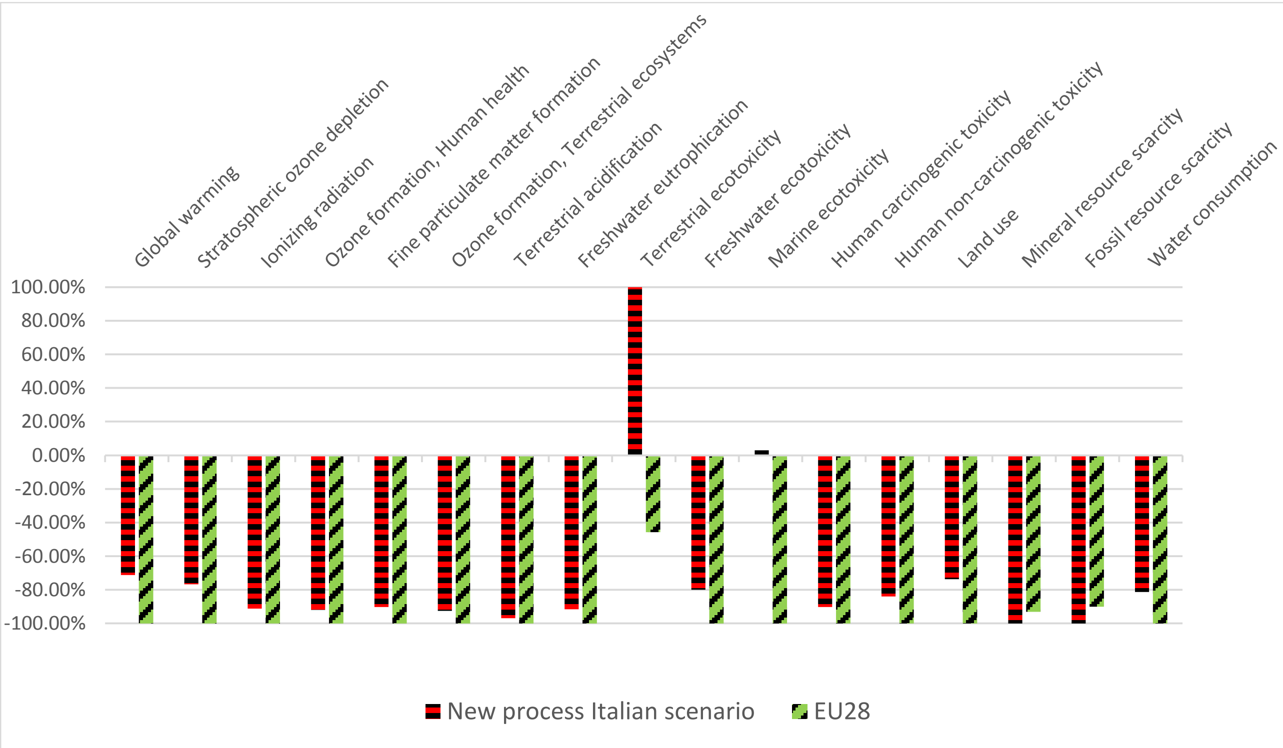

Figure 7: Environmental impacts analysis with variation in the composition of the packaging waste (EU28).

The results of the third sensitivity analysis (Figure 7 and Table 11) show that a change in the composition of packaging waste has a quite significant benefit on environmental impact, which improves by 15% on average. In addition, for Terrestrial ecotoxicity the result changes significantly, moving from a burden to a benefit for the environment. This is due to the high volumes of paper handled, which involves a corresponding amount of avoided sulfate pulp that generates a benefit to the environment.

5 Conclusions

Throughout this paper, the environmental impact of a new EOL process of food packaging materials has been analysed and compared to the current destination. Every year in the Emilia Romagna Region (a northern Italian region) 14,300 tons of packaged food collected from retail stores and during the distribution phase are wasted and sent to landfill sites. Among this quantity, approximately 13.8% (i.e. 1,973 tons/year) consists of packaging material that, at present, is neither sorted nor recycled. One way to solve this problem is to introduce a complex system of collection and sorting able to separate the PFW thrown away by retail outlets into organic fraction and packaging. Based on these premises, the study carries out an environmental evaluation of a system able to collect the PFW from distribution facilities and retail outlets and send it to a sorting facility, where the packaging materials will be divided and sent to the best EOL option.

This paper deals in particular with the EOL of packaging materials, for which it considers different processes (recycling, energy recovery and landfill) and takes into account the most recent performances in terms of efficiency.

The newly designed process ensures a reduction in the environmental impact in almost all the categories considered compared to the current scenario (disposal in landfill). Only for two impact categories does the current scenario perform better than the new process. To be more precise, the LCA analysis shows that the most relevant environmental benefits can be achieved when recycling paper and glass packaging materials. The results show also that the energy recovery process provides benefits in almost all the categories, due to avoided production of energy thanks to incineration (apart from Global warming, Stratospheric ozone depletion and the Ecotoxicity impact categories). Overall, this study proves that the proposed process, which includes the sorting and an EOL valorisation of packaging materials deriving from PFW, can give environmental benefits respect to the current scenario where the packaging materials of PFW are disposed of in landfill.

Regarding the sensitivity analysis carried out concerning all the packaging waste managed by the sorting system, the results show that if the percentage of “recycling” is enhanced, such as the German one, more benefits for the environment have been reached.

Further studies could investigate the environmental performance of other packaging treatment scenarios, such as pyrolysis with energy recovery, and include the impact of the recovery of organic food waste achieved with the sorting process. Moreover, this work focused only on the specific issue of valorising packaging material from PFW; other interrelated topics were not dealt with in this paper. The evaluation of the economic aspects of the new process is one of these topics. In this respect, as the process described in this paper is currently being implemented on the field, a final evaluation could be made when the system will be fully operating, to evaluate its sustainability from an environmental, economic and social point of view.

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Environmental impact of a new industrial process for the recovery and valorisation of packaging materials derived from packaged food waste

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Abstract

In Italy, most of the packaged food wasted during the distribution phase and at retail stores is disposed of in landfill, due to the absence of a sorting system able to separate food from packaging.
A new experimental process, here presented, collects the packaged food waste from retailers, moves it to distribution centres, and then ships it to a sorting facility where the food is separated from its packaging. The sorted packaging materials are then sent to specific recycling or energy recovery centres, meaning that only a small amount of packaging material is disposed of in landfill.
In this study, the environmental performance of this innovative process is compared with the impacts generated by disposal in landfill using the Life Cycle Assessment (LCA) methodology. Data for the year 2015 in the Emilia Romagna region (Italy) was collated for this purpose; in this region, about 14,600 tons of food are wasted in the retail channel annually. The LCA is performed using the ReCiPe midpoint method; primary data was taken from the field, while secondary data came from literature and ecoinvent 3.3 databases. Three sensitivity analysis were carried out to evaluate the results when the distances covered during the transport phase, the composition of the packaging waste, or the EOL of the country where the analysis is performed varied.
Overall, the results show that the innovative scenario is more environmentally sound than the one currently in use. Taking into account the avoided impacts, the environmental impact turned out to be negative in all the categories, suggesting a beneficial effect on the environment.

Keywords: Packaging material; Food waste; Recycling; Energy recovery; Unpacking; Life Cycle Assessment.

1 Introduction

Food waste (FW) generated across the Food Value Chain (FVC) turns out to be one of the major problems relating to food production. In 2011, the United Nations Food and Agriculture Organization (FAO) estimated that more than one third of food produced (about 1.3 billion tons) is lost (Gustavsson et al. 2011; FAO, 2013a; FAO, 2013b). Food can be wasted throughout the FVC, from primary production to the use phase (WRAP, 2007a; WRAP, 2007b; Fredriksen et al. 2010 and European Commission, 2015).

Packaging is a main part of any food, as it is fundamental to ensure that its organoleptic and hygienic properties are preserved; also, it ensures protection and conservation of the food quality and can contribute to reducing FW (Bertoluci et al. 2014). The global volume of packaging materials manufactured and disposed every day has led many researchers to deal with the issue of environmental impact, especially in the food sector (Vermeulen et al. 2012). Several studies have been carried out since 1990 with the aim of demonstrating the impact of packaging materials in the food sector and the best end-of-life (EOL) valorisation option for different types of them. Lately, Manfredi and Vignali (2014) found that glass packaging is the main cause of environmental impact generated by the production of tomato puree, while Bertolini et al. (2016) and Manfredi and Vignali (2015) analysed the impacts of several packaging materials respectively used for milk and beverages. In recent years, several studies have demonstrated extending food's shelf life by means of an improved packaging solution could reduce the environmental impact of the whole packaged food, acting mainly on the reduction of the FW associated to it (Williams and Wilkstrom, 2011; Grönman et al. 2013, Wikström et al. 2014; Manfredi et al. 2015).

The environmental impact of FW treatment has been studied extensively using the Life Cycle Assessment (LCA) method. In this study, however, we focus on the specific issue of valorising the packaging fraction of packaged food waste (PFW), i.e. the packaged food discarded at retail stores. "Valorisation" means any option where the packaging material is not disposed of in landfill, according to European Commission (2008) guidelines. The main problem associated to PFW consists in the impossibility to recover its packaging material, by separating it from the wasted food. In turn, this is primarily due to the lack of system able to mechanically separate the FW from its packaging. Consequently, at present all the PFW collected during the retail and distribution phases is then sent to landfilling or incinerated (Garcia-Garcia, 2015).

Based on these premises, this study aims to explore different valorisation options for primary packaging deriving from packaged food wasted at retail stores. In particular, it will show how an innovative process, consisting of an appropriate collection and sorting system for PFW, could be an effective valorisation option from an environmental point of view. The objective of this study, which is supported by the LCA methodology, is to evaluate the environmental performance of this new process for the sorted packaging materials compared to the current one (i.e. disposal in landfill). As it targets packaging materials, the analysis excludes the environmental impact of the FW disposed of in landfill.

This work is a part of the SORT project[2], Italian acronym for "Technologies and models to unpack, manage inventory and track wasted food". The aim of the project is to valorise the packaged food waste collected from retail stores, in order to recover the product and its packaging.

The paper is organized as follows. After a literature review on EOL valorisation of PFW and packaging materials (section 2), the LCA methodology is applied taking into account the phases described in ISO 14044 (section 3). Environmental impact assessment is then performed considering the current scenario and comparing it with the new one. A sensitivity analysis is then carried out to show how different contexts could affect results (section 4). Finally, the conclusion section summarizes the main findings from this work and underlines activities for future research.

2 Literature review on packaged food waste and packaging material EOL valorisation

A literature review on EOL valorisation of PFW and packaging materials has been done in order to underline the research activities in the fields of PFW valorisation and possible EOL of the packaging materials associated to food waste. Both the systematic have been carried out using the Scopus database, provided by Elsevier.

2.1 Packaged food waste

The collected articles concerning the PFW cover a timespan from 2008 to 2018. They have been obtained by carrying out a query with the following set of keywords: "food waste", "valorisation" and "packaging". This query returned 112 articles, but only five of them are strictly related to the EOL management of PFW, which is the focus of this study. In particular, the articles excluded from

[2] Tecnologie e modelli per lo Spacchettamento, l'ORganizzazione delle scorte e il Tracciamento dei prodotti alimentari sprecati .

the analysis analysed either unpacked FW or general issues of FW management, or carried out surveys on FW in household.

Looking at the pertinent studies, the main EOL valorisation options of PFW are:

- Animal feed, anaerobic digestion and composting (Garcia-Garcia et al. 2015, 2017; Salemdeeb et al. 2017);
- Animal feed, anaerobic digestion, incineration (Vandermeersch et al. 2014);
- Animal feed, anaerobic digestion, incineration, landfill, compost and donation (Eriksson et al. 2015).

As reported in Garcia-Garcia et al. (2017, figure 3), the less preferred options of EOL valorisation of PFW are landfilling and thermal treatment with energy recovery. As far as the incineration and landfill are concerned, the unpacking phase is not strictly necessary (Garcia-Garcia et al., 2017). Conversely, to reduce the environmental impacts of the wasted food separated from the packaging, different waste management alternatives are suggested, such as composting and anaerobic digestion, for which the food needs to be unpacked before its treatment. Moreover, according to the European guidelines, the FW should preferentially be used as animal feed (Salemdeeb et al. 2017). To this end, the PFW has to be unpacked, with technologies that provide a minimum damage to the food and do not adulterate its matrix. In addition, each type of PFW must be treated individually, to avoid possible cross-contaminations (Garcia-Garcia et al., 2017).

Although the studies reviewed above focuses on PFW, none of them have analyses the techniques to recover packaging from PFW after a sorting phase. Consequently, the description of the unpacking and sorting processes are not dealt with in these papers. PFW consisting of expired or wasted products from retailers and. The present paper tries to bridge this gap of knowledge by proposing an innovative system of sorting, unpacking, inventory management and track of PFW and evaluating its environmental impact.

2.2 EOL valorisation of packaging

As the LCA analysis focuses on the valorisation of packaging materials separated from FW, this section reviews the studies relating to the EOL valorisation options of different packaging materials. Table 1 summarises some of the main works concerning the valorisation of packaging materials, again on a timespan from 2008 to 2018; later on we will refer to the most recent and detailed works, related to the valorisation of the different types of packaging materials. The articles have been retrived by carrying out a query with the following set of keywords: “packaging”, and “end-of-life”.

This query returned 169 articles, and 31 of them are strictly related to the EOL management of packaging materials.

		Packaging material analysed						
Reference	**Region**	**Paper**	**Plastic**	**Composite packaging**	**Glass**	**Aluminium**	**Iron and steel**	**EOL scenario**
Al-Maaded et al. (2012)	Qatar		x					recycling
Almeida et al. (2017)	Brazil		x		x	x		recycling, reuse
Arena et al. (2017)	UK						x	recycling
Damgaard et al. (2009)	Denmark					x	x	recycling
Detzel and Mönckert, (2009)	Germany					x		recycling
Fallah et al. (2009)	Iran	x	x		x	x	x	combination of landfill, recycling, incineration and composting
Ferrão et al. (2013)	Portugal	x	x	x	x	x	x	recycling; composting; energy recovery; landfill
Ferreira et al. (2014)	Portugal	x	x		x	x	x	recycling; incineration; landfilling
Gatti et al. (2008)	Brazil					x		recycling
Ghinea et al. (2014)	Romania	x						recycling
Giugliano et al. (2011)	Italy	x	x		x		x	recycling; composting; energy recovery
Gu et al. (2017)	China		x					recycling
Hopewell et al. (2009)	UK/UE (review)		x					landfilling; incineration; down-gauging; reuse; recycling
James, (2012)	UK	x						recycling
Kulczycka et al. (2015)	Poland	x	x		x	x	x	recycling; landfilling; energy recovery
Larsen et al. (2009)	Denmark				x			recycling
Laurent et al. (2014)	Review	x	x	x	x	x	x	recycling; reuse; use on land; landfilling
Malik et al. (2017)	India (review)		x					recycling
Merrild et al. (2008)	Europe	x		x				recycling; incineration
Meylan et al. (2015)	Switzerland				x			recycling
Mourad et al. (2008)	Brazil			x				recycling
Niero et al. (2016)	Denmark					x		recycling
Park and Gupta, (2015)	Hawaii		x					recycling; incineration
Pasqualino et al. (2011)	Spain		x	x	x	x		recycling; incineration; landfilling
Rigamonti et al. (2009)	Italy	x	x		x	x	x	recycling; incineration
Rigamonti et al. (2014)	Italy		x					recycling
Rochat et al. (2013)	Colombia		x					recycling
Romero-Hernández et al. (2009)	Mexico		x					recycling; landfilling
Schmidt et al. (2007)	Denmark	x						recycling; incineration; landfilling
Toniolo et al. (2013)	Italy		x	x				recycling (for PET); incineration and landfilling (for multilayer plastic film)
Villanueva and Wenzel, (2007)	Europe (review)	x						recycling; incineration; landfilling

Xie et al. (2013)	China			x				landfilling; incineration; paper recycling; separation of polyethylene from aluminium
Xie et al. (2016)	China			x				recycling

Table 1: List of LCA studies on packaging EOL valorisation.

According to Licciardello (2017), food packaging sustainability can be achieved at three levels: 1) at raw material level, by using recycled materials and renewable resources; 2) at production level, using more energy efficient processes; 3) at waste management level, by reusing, recycling and biodegradation. This paper then focuses on points 1 and 3, analysing the following materials:

Plastic: Recycling is the preferred solution for plastic waste management (Polyethylene (PE), Polyethylene terephthalate (PET), Polypropylene (PP), etc.), because it has a lower environmental impact in several impact categories ranging from global warming to human toxicity indicators (Al-Maaded et al. 2012). The main benefits arise from the avoided production of virgin plastic, as confirmed by most recent articles in this field (Gu et al., 2017; Malik et al., 2017).

Paper: According to the literature reviewed, the worst option for paper and cardboard waste management is landfilling, in particular when considering the impact on climate change potential and energy demand. The comparison between recycling and incineration is more complex. If we only consider energy demand and water consumption, recycling is preferable to incineration, but they are comparable if we consider climate change. Compared to landfill, the main advantage of incineration is the substitution of fossil fuels, whereas incinerators provide heat and electricity. For recycling, the advantage is the wood resources saved, which can be used for producing paper or generating energy, i.e. from renewable fuel, which does not contribute to global warming (Merrild et al. 2008).

Glass: the literature regarding the treatment of glass waste is limited. A possible reason is that the energy required to process glass waste is relatively low and then glass recycling almost always proves to be a better option than landfill with respect to the environmental impact. Reuse after cleaning could be an option for this material in case of bottles or containers; however, such scenario could be profitable only in presence of a reverse logistics system for glass recovery and in case appropriate cleaning agents are used, so as to ensure a safe reuse (Almeida et al. 2017). Energy recovery from glass is also not possible, and therefore recycling is the preferred treatment method (Larsen et al. 2009).

Aluminium, Iron and Steel: the literature concerning waste metal treatment shows that recycling systems reduce all the environmental impacts considerably, compared to incineration and disposal in landfill. The main reason for metal recycling (ferrous and nonferrous alike) is that the production of virgin metal is extremely energy intensive. Scrap metal recycling is significantly less energy demanding; for example, aluminium recycling only uses 5% of the energy used to produce virgin material (Damgaard et al. 2009).

Composite packaging (PE, Aluminum and Paperboard): the literature about the treatment of composite packaging waste is limited; nevertheless, the available findings confirm that composite packaging waste treatments impacting most on the environment are, in order: landfill disposal, incineration and recycling. Furthermore, the latter two techniques show overall beneficial effects on the environment. Recycling is the best option for saving energy, while incineration is the best option for emission reduction (Xie et al. 2016).

3 Materials and methods

3.1 Methodological approach

The LCA methodology was applied according to the principles and requirements provided by standards (ISO 14044). The *SimaPro* release 8.3 *LCA software* was used to support the assessment.

3.2 Goal and scope definition

The purpose of this work is to compare the environmental impacts of an EOL process which uses a new sorting system for packaging materials derived from PFW with those of a traditional disposal system for PFW (where the packaged food products are disposed of in landfill), using the LCA technique. The two scenarios considered refer to the food waste data collected in 2015 in the Emilia Romagna region (northern Italy).

3.2.1 Functional unit

The functional unit provides a reference unit for which the inventory data is normalized (ISO 14040, 2006). The data relating to the amount of packaged food discarded was derived by means of direct contacts with 63 retail stores of varying sizes (6 hypermarkets, 26 supermarkets and 31 minimarkets) distributed across the Emilia Romagna region. The retail stores involved in the SORT project were interviewed between June and July 2016. Based on the interviews, it was appraised that retailers of the region wasted about 14,600 tons of packaged food in 2015. A quota of 300 tons/year was removed from this amount, as it corresponds to the amount of wasted food donated to charity purposes in the Emilia Romagna region. This amount has been estimated starting from a national value of 4,103 tons/year (Avvenire, 2017). Based on the data collected, the food wasted at retail stores can be categorized in the following groups: bakery (14.69%), coffee (0.09%), drinks (0.25%), fish (0.68%), frozen foods (0.13%), meat (27.63%), milk and dairy products (29.35%), pasta (3.05%), ready-made food (3.39%), salami (2.34%), sauces (0.56%), fruits and vegetables

(9.38%), other (8.46%). Again on the basis of the data collected, the average weight of the PFW was estimated to account for ca. 0.5 kg.

According to the in-field study carried out in the UK by WRAP (2013), primary packaging accounts for 13.8% in weight (on average) of the packaged food product donated to charity for human consumption in 2011; WRAP estimated in fact that out of 5,800 tons of the donated packaged food about 800 tons is packaging. Applying the same ratio, we estimated that the 13.8% of 14,300 tons of PFW, i.e. 1,973 tons, consist of packaging material wasted together with the expired food products. Therefore, the functional unit of all the scenario analysed is 1,973 tons of packaging waste, which according to the data provided by FISE UNIRE & Fondazione per lo sviluppo sostenibile (2016) can be estimated to consists of:

- Plastic materials, which account for 29.82% of the total amount of waste and include:
    - PE (13.92%);
    - PET (7.14%);
    - Other plastic materials such as PP, polystyrene (PS) and polyvinyl chloride (PVC) (8.76%);
- Paper-based materials which account for 29.79% of the overall amount of waste;
- Glass (26.24%)
- Aluminum (1.35%)
- Iron and steel (9.65%);
- Composite packaging (3.10%).

For the new scenario, several EOL treatments for the different packaging materials were evaluated by considering the real scenario of the Italian packaging end of life (recycling, recovering or landfilling systems) in the years 2014-2015. To this end, as defined in specific Italian consortia, the quantity of each packaging material separated from the food waste was divided into three different EOL destinations, as shown in Table 2:

Packaging material	**Recycling [ton]**	**Energy recovery [ton]**	**Landfill [ton]**	**Total [ton]**
PE (COREPLA, 2015)	112.9	118.4	44.0	275.4
PET (COREPLA, 2015)	57.8	60.6	22.5	140.9
Other plastic (COREPLA, 2015)	70.9	74.3	27.7	172.9
Paper (COMIECO, 2016)	470.2	52.9	64.7	587.8
Glass (COREVE, 2016)	367.6	0.0	150.2	517.8
Aluminium (CIAL, 2016)	18.7	1.5	6.5	26.7

Composite packaging (TetraPak, 2016)	14.4	28.7	18	61.1
Iron and steel (Consorzio Ricrea, 2016)	139.8	0.0	50.7	190.5

Table 2: Destination of the packaging fraction separated from the food waste in Emilia Romagna.

3.2.2 System boundaries and assumptions

The case study examined in this paper concerns packaged food products wasted in retail and distribution systems in Emilia Romagna. This study only targets the primary packaging that can be separated from the FW (Figure 1). The valorisation options of the separated FW is under evaluation or evaluated in other studies (e.g. Mosna et al. 2016) and is not dealt with here.

In the current scenario, the PFW is collected from the retail stores and during the distribution phase, transported and disposed of in landfill; this is the present EOL of packaged food wasted in retailing, as deduced from the analysis of the retail stores (Figure 1A).

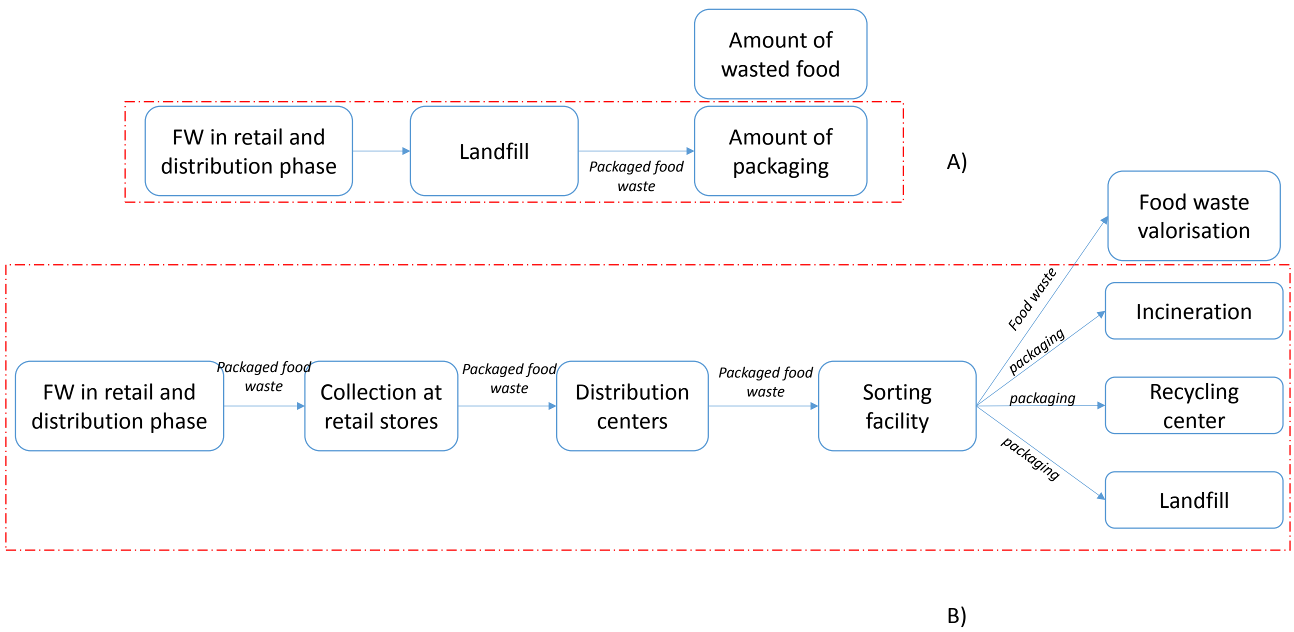

Figure 1: System boundaries of current scenario (A) and new process (B).

In the new process (Figure 1B), the PFW will be preliminary divided into five product families (i.e. fragile, not fragile, refrigerated, non-refrigerated and other), to ensure their safe transport. Product grouping will be carried out within the stores and supported by smart trolley, which provides assistance to the operators to separate the PFW. For this study, it was established that 930 out of 1557 retail stores of Emilia Romagna will be equipped with smart trolleys with five boxes (600*400*400 mm each), one for each product family, able to collect a maximum of 70 l of PFW per box. More precisely, the trolleys will be used only in hypermarkets and supermarkets, where the daily quantity of PFW is higher and can be separated in different boxes. Smaller retail stores will collect the whole amount of PFW in a unique box with the same capacity as those used in the trolley. All the boxes will be loaded on specific lorries, which will deliver them to the distribution centres every 4 days. The PFW will then be shipped every 4 days from the distribution centres to a centralized sorting facility, working in continuous, where the products, after a preliminary "chicane" that will align them in a single row (Figure 2), will be sorted into homogeneous groups and collected in different containers. Such sorting is supported by a portal scanner able to read bar codes and to identify items using integrated ViPR® (visual object recognition)[3] technology, with an average scanning capability of 100 products per minute and an efficiency close to 99.5% (Figure 2). The portal scanner is able to read the EAN13 code of each item, which uniquely identifies the packaged products. The EAN13 code of each food product is then used as the primary key to enter a database where all data regarding the food (e.g. ingredients, nutritional values and types of packaging materials) are stored. The sorting is carried out based on the packaging and product characteristics: more precisely, the PFW will be grouped as a function of the most suitable EOL valorisation, considering both the food waste option (reuse for pet food, for animal feed or for biogas production) and the packaging material option (recycling, energy recovery and landfill). On the basis of these criteria, 6 different product clusters have been identified:

1) meat and fish products, packaged in polymeric trays (pet food destination and packaging collection);
2) bread, pasta and dried biscuit (animal feed destination and packaging collection);
3) vegetable and fruits products (animal feed destination after drying and packaging collection);
4) water, spirits, drinks and beverages with screw cap packs (packaging collection only);
5) milk with screw cap packs (return to companies after drying and packaging collection);
6) other foodstuff (animal feed or biogas production and packaging collection).

The PFW of each group will subsequently be transferred to three food packaging separation machines able to separate the organic fraction from its packaging. For solid foodstuff (clusters 2, 3 and 6), unpacking technologies are currently available on the market (e.g. Atritor Turbo separator TS2096; Atritor, 2017) and make use of basic mechanical processes, such as compression, shredding and agitation screening to separate the content from its packaging (Mosna et al. 2016). A separation machine can be feed with one to five tonnes per hour of PFW and is able to separate both dry and wet FW with an estimated efficiency up to 99% in product recovery. In this case, the packaging materials are reduced to flakes, which could be valorised only through recycling or

[3] http://www.datalogic.com/eng/products/retail/in-counter-on-counter-scanners-scales/jade-x7-pd-615.html

energy recovery. Reuse will not be an option using this equipment, and, in any case, it would not be the best EOL valorisation for the materials treated. After separation, the food and packaging fractions might be slightly contaminated by one another; however, the contamination level is low and acceptable for the valorisation as animal feed or biomass of the food waste and for a non-food destination of the recycled packaging materials. After each treatment, the machine is completely cleaned by means of a Cleaning In Place (CIP) automatic system. For liquid food (clusters 4 and 5) a new separation machine has been designed; the machine will unscrew the cap, twist the bottle and empty it. The liquid food will be collected in containers, while the empty packaging in bins. For meat and fish products (cluster 1), a specific machine able to cut the packaging without damaging the food has been designed. The polymeric trays and the top film are cut on the short side of the packaging and then grasped on the opposite side by an anthropomorphic robot. By moving the tray, the robot will drop the food off inside a bin and put the packaging materials in a different container. It is essential that the food is kept intact for its valorisation in high value pet food, using only sliced selected foodstuffs.

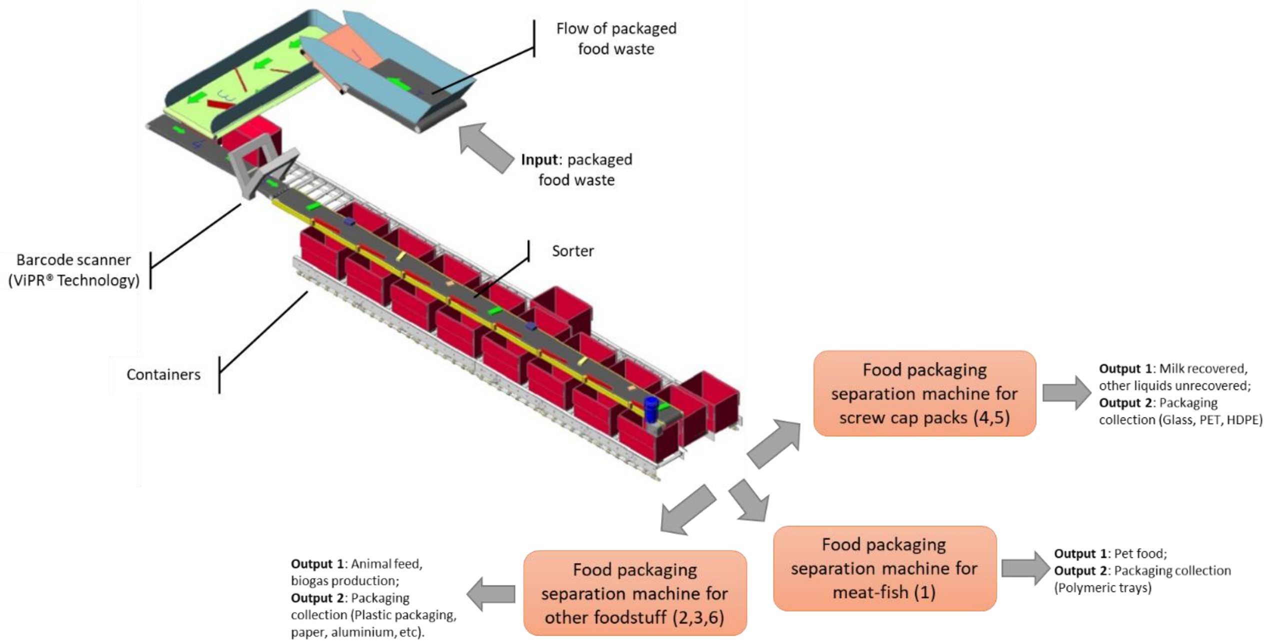

Figure 2: Sorting system.

All the separated packaging materials will then be sent to specific EOL destinations, such as incineration, recycling and landfill. To be consistent with the current scenario, the amount of recovered wasted food is again excluded from the analysis. The system boundaries for the valorisation of packaging materials in the new scenario can be seen in Figure 1B.

3.3 Life cycle inventory

In this step, we establish the phases, which have been either introduced or avoided in the new scenario. The avoided impacts are as follows: (i) transportation of the materials to the landfill sites; (ii) product disposal to landfills; (iii) the manufacturing of virgin and recycled material (taking into account the market mix and efficiency for the materials analysed, see Table 3); and (iv) the production of electricity, with an estimated efficiency of 25% (conversion factors for the materials analysed were extracted from literature, see Table 4). On the contrary, the impacts that have been introduced are: (i) grouping and collection of the PFW; (ii) transportation of boxes with PFW from the retail stores to the distribution centres; (iii) transportation of boxes with PFW from the distribution centres to the sorting facility; (iv) the industrial process for sorting, unpacking and splitting the food from the PFW; (v) the shipment of the separated packaging materials from the sorting facility to the EOL destinations; (vi) the use of water and other substances and the emissions relating to the sorting, separation and recycling, incineration and landfilling processes.

All primary data relating to the quantity of PFW during the distribution phase and at retail stores was gathered *via* questionnaires and personal interviews, and relates to the year 2015. Ecoinvent database v3.3 (Moreno Ruiz et al., 2016) and values from literature or Italian consortia were used as secondary data by considering the ones relating to the Italian or European situation. In particular, within the system boundary, the following assumptions and limitations have been made:

- The data relating to the transport activities was obtained considering the average distance covered by transport means in the Emilia Romagna region (related data was derived from logistics analyses carried out in the SORT project, bearing in mind that the sorting facility will be located close to the city of Bologna):
    - Current scenario: an average distance of 80 km per ton using a 3.5-7.5 metric ton EURO4 lorry for PFW transportation to landfill;
    - New scenario:
        - An average distance of 169.8 km per ton for PFW collection and transportation to the 19 distribution centres (the number of distribution centres to be included in the system was again derived from logistics analyses carried out in the SORT project);
        - An average distance of 58.58 km per ton for PFW transportation from the distribution centres to the sorting facility;

    - An average distance of 40 km per ton for separated packaging materials transportation from the sorting facility to recycling centre and incinerator, and of 10 km per ton for transportation to landfill.

  For the transportation from the distribution centres to the sorting facility a 16-32 metric ton, EURO4 lorry was used; for all the other transportation a 3.5-7.5 metric ton, EURO4 lorry was used;

- Mass-based allocation was used in order to account the share between organic mass and packaging into the PFW, as well as to account the share between the electric consumption of the sorting machine;
- The trolley used for grouping and collection of the PFW consists of a main chassis of stainless steel (30 kg), 4 wheels (1 kg of stainless steel plus 1 kg of synthetic rubber), 5 boxes of polypropylene (7.5 kg) and 1 central control panel (modelled as a laptop). A life span of 10 years has been assumed for each trolley;
- In the sorting and unpacking process, the specific values described in Table 5 were considered. In particular, taking into account the average product weight of 0.5 kg and the sorting speed of about 100 packages per minute, the resulting energy consumption and the weights of manufacturing materials for the sorting equipment are shown in Table 5, considering the life of the entire machinery to be 20 years;
- The average Italian electricity mix is used in the study both for the consumption and for the avoided quantities. (Moreno Ruiz et al., 2016);
- The ecoinvent database release 3.3 was used as a secondary data source by considering data relating to the Italian situation when possible (Moreno Ruiz et al., 2016);
- The secondary materials obtained from the packaging waste recycling process will be assumed to partially replace a mix of primary materials (i.e. those obtained from virgin raw materials) and secondary materials (the recycled ones) in a finished product (Gala et al., 2015, Vitale et al., 2017). The percentage of replacement changes according to the type of material. The savings in energy made and the reduction in emissions generated and raw materials used due to the avoided production of the mix of primary and secondary materials were taken into account in the recycling process. For instance, the production of one kg of PET bottle grade results in the emission of 2.15 kg of CO_2 eq. (Plastics Europe, 2011); such amount is reduced to about one third if a kilogram of recycled PET (r-PET) is considered (COREPLA, 2015). The details about the market mix (i.e. amount of virgin and

recycled material) for the materials analysed, as well as the performance of the recycling process, are shown in Table 3. These data were used in the computation of the impact according to the approach suggested by ISO/TR 14049 (2012) and Gala et al. (2015);

- For "Other plastics", it was assumed that all the recycled polymers will be used in the manufacturing of products traditionally made from plywood, for example outdoor furniture (fences, benches or facilities for children's playgrounds) (FISE UNIRE & Fondazione per lo sviluppo sostenibile, 2016);
- In the recycling processes, the efficiency values described in Table 3 and the landfill of residual rejected waste were also taken into account;
- The energy produced by the recovery process, in particular incineration of the separated packaging, will be assumed to replace the production of energy from the national network. The calorific values (LHV) based of packaging materials are shown in Table 4 according to the data provided by SEIeditrice (2012). The voice "incineration" includes the energy valorisation of the quantity of all the packaging materials that will be incinerated (corresponding to the quota labelled as "Energy recovery" in Table 2).

Packaging material	Recycling process				Market composition			Impact	
	Recycled product	Efficiency	Data source	Avoided product	Amount of recycled material (%)	Amount of virgin material (%)	Data source	REC/VIR[4]	Data source
Paper	Corrugated board, from recycling fibres	0.860	Ferreira et al. (2014)	Sulfate pulp	29%	71%	Gala et al. (2015), calculated from CEPI (2010)	0.9	Gala et al. (2015)
Composite packaging	Recycled paper and unseparated Al/PE	0.600	Xie et al. (2013)	Sulfate pulp	43%	57%	Gala et al. (2015), calculated from CEPI (2010)	0.806	Mungcharoen et al. (2010)
PET	PET granulate	0.755	Rigamonti et al. (2014)	PET granulate	13%	87%	Recycling Today (2017)	0.33	Malik et al. (2017)
PE	PE granulate	0.900	Rigamonti et al. (2014)	PE granulate	50%	50%	Gu et al. (2017)	0.90	Mungcharoen et al. (2010)
Other plastic materials	PP, PS, PVC, etc.	0.614	Rigamonti et al. (2014)	Outdoor furniture (plywood)	2.5%	97.5%	Plastic Europe (2015)	1	Rigamonti et al. (2009)
Glass	Glass from cullet	0.901	Rigamonti et al. (2009)	Glass from virgin materials (41.9% green, 30.3% white, 27.8% brown)	45%	55%	Roldán and Pino (2012) *apud* Gala et al. (2015)	0.428	Mungcharoen et al. (2010)
Aluminium	Aluminium from old scrap	0.883	Rigamonti et al. (2009)	Aluminium	75%	25%	Gala et al. (2015)	0.1	Gala et al. (2015)
Steel	Steel scrap	0.840	Ferreira et al. (2014); Arena et al. (2017)	Pig iron	50%	50%	Eurofer (2014); Gala et al. (2015)	0.297	Classen et al. (2009); Gala et al. (2015)
Iron	Ferrous scrap	0.840	Ferreira et al. (2014); Arena et al. (2017)	Pig iron	70%	30%	Cerdan et al. (2009)	0.089	Mungcharoen et al. (2010)

Table 3: Recycling process of packaging materials and related efficiency.

[4] Ratio between the environmental impact of recycling process (REC) and that of the production process of the virgin material (VIR).

Packaging material	Calorific value (LHV) [MJ/kg]
PE	46
PET	33
Other plastics	28
Paper	17
Glass	/
Aluminium	38.88
Iron and Steel	/
Composite packaging	20

Table 4: Calorific values of packaging materials (SEIeditrice, 2012).

Input	Unit	Conveyor belts	Atritor TS 2096	Unscrewing machine	Trays cutting machine
Electricity	kW	3.5	22	3.44	4.5
Compressed air	kW	-	0.75	0.5	0.5
Total consumption for functional unit	kWh	16681	36142	6259	7943
Equipment materials (20 years of life)	kg (PE)	4	/	1	/
	kg (stainless steel)	6	35	50	25

Table 5 Specific values for the sorting and unpacking process.

3.4 Methods of impact assessment

The software SimaPro release 8.4 contains a number of impact assessment methods that can be used to calculate the impact assessment results. These methods are divided into subgroups, namely European, North American, Single issue, Water footprint and Superseded. Taking into account the European methods, eight methods can be used to calculate the impact assessment results; in particular, the three most used methods are EPD, ILCD and ReCiPe, and include seven, eleven and seventeen impact categories, respectively. Of these three methods, the Re.Ci.Pe. method (Huijbregts et al. 2016) was selected as it is the most used in the context of waste management and can give a complete overview of various impact categories; in addition, the uncertainty of the results at this point is relatively low. The hierarchic perspective was selected for the analysis, as it is considered the most balanced of the three proposed by the method (Egalitarian, Individualist and Hierarchist). Impact values were calculated at midpoint level for 17 impact categories, i.e. (i) Global warming, (ii) Stratospheric ozone depletion, (iii) Ionizing radiation, (iv) Ozone formation, Human health, (v) Fine particulate matter formation, (vi) Ozone formation, Terrestrial ecosystems, (vii) Terrestrial acidification, (viii) Freshwater eutrophication, (ix) Terrestrial ecotoxicity, (x) Freshwater ecotoxicity, (xi) Marine ecotoxicity, (xii) Human carcinogenic toxicity, (xiii) Human non-carcinogenic toxicity, (xiv) Land use, (xv) Mineral resource scarcity, (xvi) Fossil resource scarcity, (xvii) Water consumption.

4 Life Cycle Impact Assessment

4.1 Current scenario: disposal in landfill

The results for the current scenario are reported in Table 6, while Figure 3 shows the relative contribution of each processing input.

Impact category	Measurement unit	Total	Transport	Disposal of in landfill						
				PE	PET	Other plastics	Paper	Aluminium	Glass	Iron and steel
Global warming	kg CO_2 eq.	1.34E+06	8.06E+04	4.19E+04	1.44E+04	1.99E+04	1.18E+06	1.23E+03	6.48E+03	3.00E+03
Stratospheric ozone depletion	kg CFC11 eq.	8.23E-02	3.32E-02	2.14E-03	1.56E-03	1.88E-03	4.21E-02	4.72E-04	6.69E-04	2.90E-04
Ionizing radiation	kBq Co-60 eq.	1.08E+03	6.53E+02	3.80E+01	1.98E+01	2.43E+01	2.02E+02	9.20E+00	9.94E+01	3.52E+01
Ozone formation, Human health	kg NOx eq.	4.39E+02	3.14E+02	2.31E+01	1.16E+01	1.42E+01	7.02E+01	4.73E+00	7.13E-01	2.21E-01
Fine particulate matter formation	kg PM2.5 eq.	1.21E+02	6.44E+01	5.63E+00	2.79E+00	3.50E+00	3.57E+01	2.45E+00	5.84E+00	8.94E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq.	4.48E+02	3.20E+02	2.35E+01	1.18E+01	1.45E+01	7.13E+01	4.81E+00	1.15E+00	3.56E-01
Terrestrial acidification	kg SO_2 eq.	4.27E+02	2.38E+02	1.67E+01	8.38E+00	1.06E+01	1.08E+02	5.80E+00	3.28E+01	7.06E+00
Freshwater eutrophication	kg P eq.	1.30E+01	1.73E+00	8.03E-02	4.37E-02	5.33E-02	6.04E-01	5.00E-02	1.05E+01	1.30E-03
Terrestrial ecotoxicity	kg 1,4-DCB eq.	2.29E+02	1.81E+02	1.97E+00	9.85E-01	1.23E+00	7.51E+00	4.44E-01	4.08E-01	3.48E+01
Freshwater ecotoxicity	kg 1,4-DCB eq.	2.88E+02	1.28E+02	6.59E+01	1.87E+01	9.08E+00	5.60E+01	1.86E+00	5.17E-01	8.70E+00
Marine ecotoxicity	kg 1,4-DCB eq.	7.69E+02	5.14E+02	9.84E+01	2.90E+01	1.59E+01	9.45E+01	3.64E+00	3.60E+00	9.63E+00
Human carcinogenic toxicity	kg 1,4-DCB eq.	8.03E+02	5.57E+02	2.66E+01	1.29E+01	1.85E+01	1.74E+02	8.34E+00	6.18E-01	4.65E+00
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	4.84E+05	3.53E+05	1.81E+04	5.52E+03	9.01E+03	8.50E+04	3.67E+03	1.00E+03	8.22E+03
Land use	m^2a crop eq.	6.52E+03	2.41E+03	8.84E+02	4.36E+02	5.34E+02	2.15E+03	1.15E+02	0.00E+00	0.00E+00
Mineral resource scarcity	kg Cu eq.	4.99E+02	2.30E+02	1.02E+01	5.06E+00	6.21E+00	3.02E+01	2.03E+00	1.98E+02	1.76E+01
Fossil resource scarcity	kg oil eq.	3.81E+04	2.71E+04	1.67E+03	8.30E+02	1.02E+03	4.76E+03	3.68E+02	1.77E+03	5.78E+02
Water consumption	m^3	7.01E+02	2.63E+02	8.19E+01	4.08E+01	5.01E+01	2.42E+02	1.36E+01	7.78E+00	2.29E+00

Table 6: Characterization results of the overall impact of the disposal in landfill scenario.

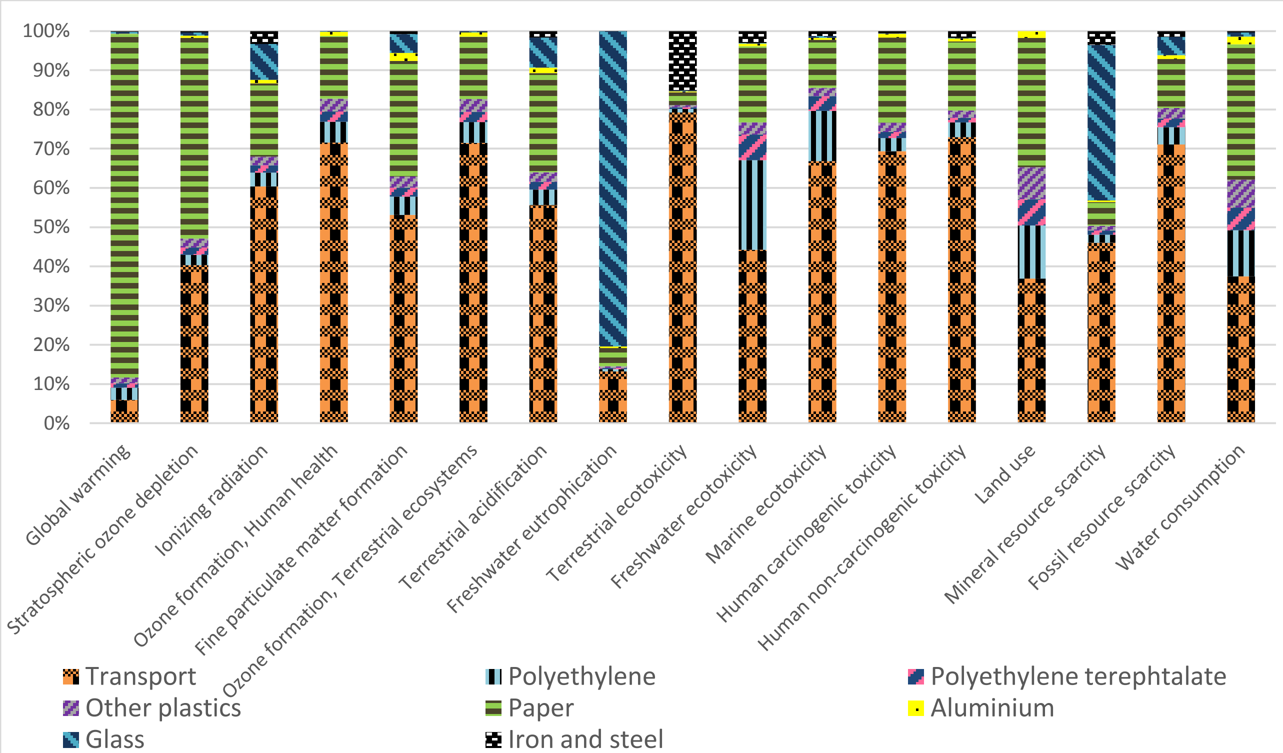

Figure 3: Contribution analysis of the environmental impact of current scenario.

As can be seen from the environmental impacts divided according to stages (Table 6 and Figure 3), disposal of the packaging materials in landfill represents a major contribution for 7 impact categories, namely Global warming, Stratospheric ozone depletion, Freshwater eutrophication, Freshwater ecotoxicity, Land use, Mineral resource scarcity and Water consumption. Conversely, transport to the landfill contributes the most in 8 categories; in particular, this phase impacts mainly in Human carcinogenic and non-carcinogenic toxicity, Ionizing radiation, Fossil resource scarcity and in the two Ozone formation human health and terrestrial ecotoxicity impact categories. These results are strictly connected to the well-known emissions and fossil fuel consumption typical of the transport process. For the two remaining categories, landfilling and transportation contribute almost to the same extent to the total impact.

Looking at the Global warming impact category, the first main contribution in terms of impact generated is landfilling of paper that accounts approximately for +88% of the total impact due to the high volume handled and to its rapid decay. Conversely, landfilling of glass contributes mainly to the Freshwater eutrophication and Mineral resource scarcity indicators, for which it accounts for +80% and +40% of the total impact, respectively. The contribution of the other materials is generally low for most of the impact categories, as they are almost inert products.

To summarize, the analysis of the current scenario highlights two contributions (i.e. paper landfilling and transport) that contribute mainly to the total impact generated.

4.2 Benefits from the new process: comparative analysis

The environmental impacts avoided thanks to the new process, compared to the current scenario, have been reported in Table 7 and Figure 4, by using the same 17 midpoint indicators as before. It is worth mentioning that negative values in Figure 4 and Table 7 denote a benefit for the environment, whereas positive values indicate an environmental burden. The representation in Figure 4 aims at comparing different impact categories characterized by different measurement units. Because of the different scale, such comparison cannot be made with the absolute values of the impacts; therefore, the results were elaborated and computed as relative (percentage) values

Impact category	Measurement unit	Total	Trolleys and boxes	Unpacking machines	Recycled Materials								Landfill	Incineration
					PET	PE	Other plastics	Glass	Aluminium	Paper	Composite packaging	Iron and steel		
Global warming	kg CO_2 eq.	-1.04E+06	3.29E+03	2.94E+01	-1.71E+05	-1.88E+05	4.46E+03	-2.97E+05	-2.26E+04	-1.07E+06	3.56E+03	-8.85E+04	1.62E+05	6.23E+05
Stratospheric ozone depletion	kg CFC11 eq.	-2.08E-01	1.32E-03	8.02E-06	-4.78E-02	1.71E-02	-2.71E-03	-1.55E-01	-1.40E-02	-1.72E-01	2.96E-03	-9.00E-03	7.29E-03	1.64E-01
Ionizing radiation	kBq Co-60 eq.	-4.12E+03	1.69E+01	1.11E-01	-3.67E+02	2.55E+02	-1.55E+02	-1.39E+03	-2.80E+02	-1.77E+03	4.94E+01	-3.09E+01	9.47E+01	-5.32E+02
Ozone formation, Human health	kg NOx eq.	-2.62E+03	8.56E+00	7.49E-02	-2.32E+02	-3.68E+02	-5.20E+00	-8.02E+02	-6.21E+01	-1.11E+03	-2.77E+00	-1.48E+02	2.57E+01	7.97E+01
Fine particulate matter formation	kg PM2.5 eq.	-2.14E+03	7.86E+00	6.73E-02	-1.47E+02	-1.00E+02	-2.26E+01	-6.59E+02	-6.53E+01	-9.41E+02	-6.37E+00	-1.56E+02	1.05E+01	-6.17E+01
Ozone formation, Terrestrial ecosystems	kg NOx eq.	-2.70E+03	9.14E+00	7.82E-02	-2.43E+02	-4.14E+02	4.58E+00	-8.12E+02	-6.30E+01	-1.12E+03	-2.71E+00	-1.64E+02	2.63E+01	7.85E+01
Terrestrial acidification	kg SO_2 eq.	-4.72E+03	1.50E+01	1.12E-01	-3.59E+02	-4.21E+02	-1.37E+01	-1.94E+03	-1.44E+02	-1.48E+03	3.04E+00	-2.69E+02	3.77E+01	-1.43E+02
Freshwater eutrophication	kg P eq.	-4.61E+01	1.98E+00	6.92E-03	-4.54E+00	9.39E-01	-3.05E+00	-1.83E+01	-2.13E+00	-1.96E+01	-1.86E-03	-2.39E+00	3.20E+00	-2.27E+00
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	6.08E+00	4.66E-02	-1.20E+02	1.83E+00	-5.77E+00	-9.28E+01	-2.54E+01	-1.22E+02	4.34E+00	-4.69E+00	1.55E+01	4.08E+02
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	1.36E+01	8.42E-02	-5.82E+01	-4.25E+01	2.02E+00	-1.55E+02	-2.22E+01	-1.31E+02	2.18E+00	-2.52E+01	2.83E+01	1.92E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	4.14E+01	2.24E-01	-3.59E+02	-4.95E+01	-1.42E+01	-4.47E+02	-1.02E+02	-5.09E+02	9.99E+00	-1.83E+00	5.22E+01	1.39E+03
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	1.63E+02	5.48E+00	-9.04E+02	-9.49E+02	-3.51E+02	-1.70E+03	-8.15E+02	-3.30E+03	-3.40E+00	-9.18E+01	4.80E+01	8.21E+02
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	2.99E+04	2.18E+02	-2.16E+05	2.04E+03	-1.28E+05	-7.46E+05	-1.81E+05	-1.54E+06	-9.39E+03	-1.29E+05	2.78E+04	2.18E+05
Land use	m^2 a crop eq.	-6.73E+05	9.41E+01	6.13E-01	-2.15E+03	2.77E+01	-5.44E+04	-2.07E+04	-1.89E+03	-5.85E+05	-8.69E+03	-1.98E+02	6.54E+02	-1.19E+03
Mineral resource scarcity	kg Cu eq.	-5.87E+03	8.57E+01	1.45E+00	-2.37E+02	1.54E+01	-7.21E+01	-5.75E+02	-4.81E+02	-4.18E+02	7.93E+00	-4.24E+03	7.53E+01	-3.49E+01
Fossil resource scarcity	kg oil eq.	-3.52E+05	1.03E+03	7.05E+00	-5.29E+04	-1.42E+05	1.16E+03	-7.65E+04	-3.02E+03	-5.54E+04	1.42E+03	-1.48E+04	2.58E+03	-1.35E+04
Water consumption	m^3	-1.60E+04	2.52E+01	2.12E-01	-1.16E+03	-6.35E+02	-1.72E+01	-2.61E+03	-3.93E+02	-1.06E+04	-1.25E+00	-1.25E+02	7.06E+01	-5.22E+02

Table 7: Impact of the new process: comparative evaluation.

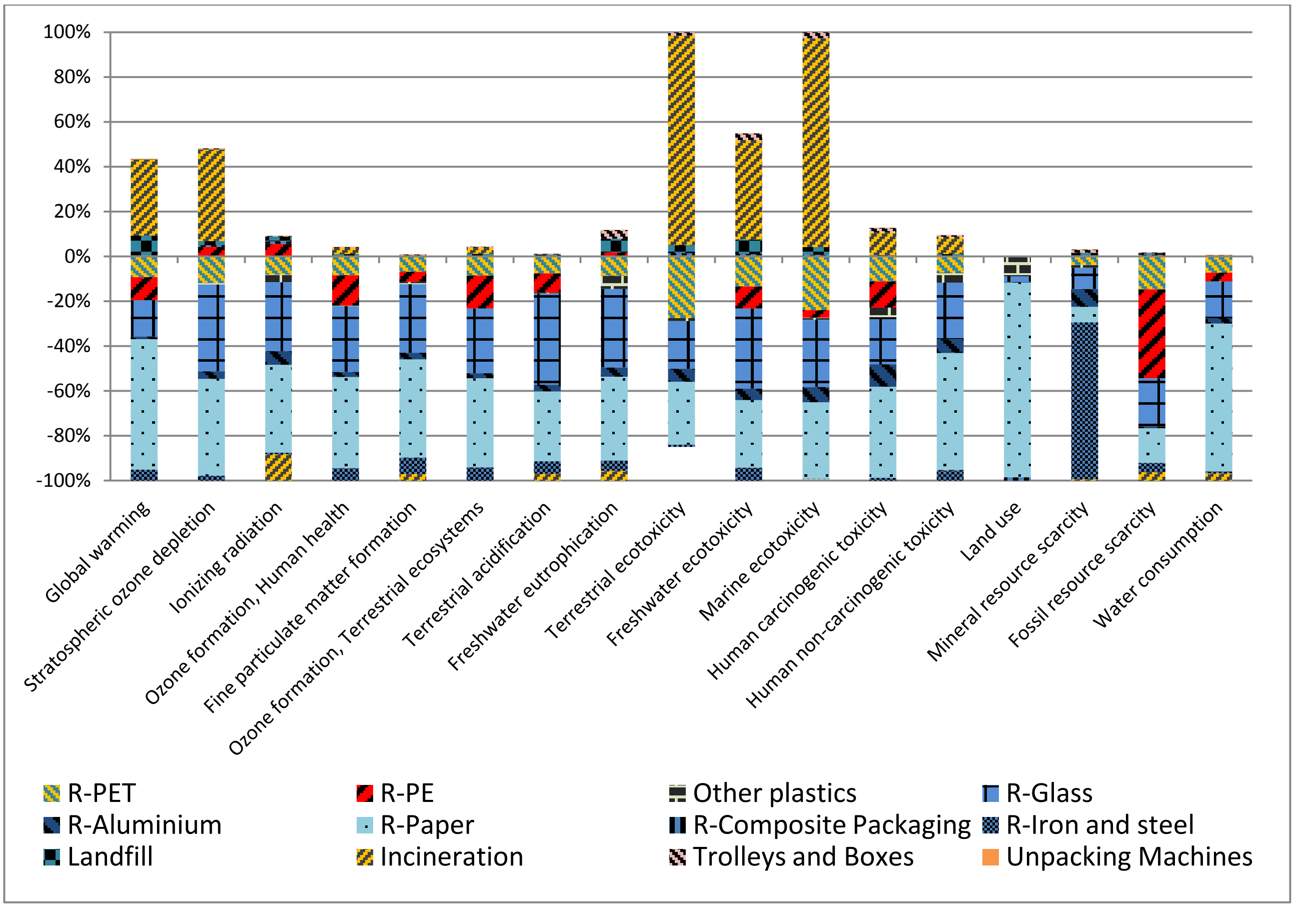

Figure 4: Percentage values of the environmental impacts of the new process: comparative evaluation.

Figure 4 shows that compared to the current scenario, the new process generates better results in almost all the impact categories analysed, resulting in negative impacts for 15 categories. Conversely, as far as the Terrestrial ecotoxicity is concerned, the current scenario appears to be more environmental friendly, probably due to the emissions connected to the incineration process of the new scenario. Incineration also nullifies the environmental benefit of the new process in Marine ecotoxicity impact category.

The environmental benefits of the new process are generated by the partial savings in raw materials (sulfate pulp, PE, PET, glass, pig iron, aluminium and plywood), and in energy and emissions from the materials recycling process respect to the virgin materials process (Gu et al. 2017; Malik et al. 2017). Similarly, the energy production is saved because it can be partially obtained thanks to the incineration process. Other waste management operations, such as grouping, PFW collection, sorting, unpacking and separation of food from PFW due to the electricity and fuels consumption entail environmental burdens which are however lower (by two or three order of magnitude) if compared to the benefit generated by the whole process.

The recycling of paper and glass represents the main contribution to these benefits: the impact reduction among the various categories accounts on average for -41% for paper and -25% glass. However, for all the considered categories, the main quota of avoided impact is due to paper recycling, because of the high volumes handled and the excellent efficiency of the recycling process.

Looking at the Global warming indicator, in addition to the aforementioned paper recycling (-58%), the avoided impact are mainly caused by glass recycling (-16%), PE recycling (-10%), PET recycling (-9%) and iron and steel recycling (-5%). On the other hand, incineration and landfill cause a positive impact on this indicator (+34% and +9% respectively). Even if the quantity of packaging materials treated in the incineration process are lower than that landfilled, its contribution to the global warming category is almost four times higher, due to the ease and fast combustion of plastics which emits CO_2 of fossil origin (Ferreira et al., 2014). The incineration process, which takes into account the amounts of all materials that will be incinerated, generates a positive impact mainly in the Ecotoxicity, Global warming (+34%) and Stratospheric ozone depletion (+41) impact categories; these results are due to the combustion by-products (e.g. carbon monoxide, dinitrogen monoxide, sulphur dioxide, ammonia…). Conversely, the highest avoided impact is observed in Ionizing radiation (-12%); for the remaining impact categories, the avoided impacts account for -4% on average, due to the energy produced by the incineration process.

PE recycling also generates significant positive impact in 3 categories (Stratospheric ozone depletion, Ionising radiation and Freshwater eutrophication), mainly due to the incoming transport activities and the recycling process.

Recycling of glass generates a negative impact in all the categories, with an average impact of -25%, due to the partial saving in virgin materials and in energy consumption during the production of new glass.

Looking at the Mineral resource scarcity, the major benefit (-70%) is due to the recycling of metal materials, unlike the other categories, where metal recycling involves very limited benefits to the environment.

Finally, the positive impacts of the trolleys turn out to be the main contribution to the Freshwater eutrophication (+4%), Freshwater ecotoxicity (+3%), Marine ecotoxicity (+3%) and Human carcinogenic toxicity (+2%), primarily due to the production of the electronic systems and of their steel structure.

4.3 Sensitivity analysis

In this study, three sensitivity analyses were carried out. Firstly, an evaluation was made to establish whether the total environmental performance is affected by a variation in the distance covered during the transport activity (i.e. the transportation of PFW to distribution centres, the transportation of PFW to the sorting facility and the transportation of packaging to the recycling centre). A second evaluation was then carried out to see how the new scenario would change in a different context, compliant with the European Union Directive 2008/98/EC, which sets out higher targets for the percentages of valorised packaging. In the third sensitivity analysis, the new process was applied considering the European scenario (EU28) of the packaging waste composition (Eurostat, 2017).

The first analysis is motivated by the fact that the distances between the retailers and the distribution centres could considerably increase if considering different regions of Italy or areas that are less populated than Emilia Romagna. We assume that no variations occur in the remaining processing phases when changing the transport distance. The proposed sensitivity analysis considers different transport distances, obtained by increasing the original values by 2, 4 and 6 times, to assess their influence on the process as a whole.

Impact category	**Measurement unit**	**Transport impact**	**Original total impact**	**New total impact**		
				Transport 2x	*Transport 4x*	*Transport 6x*
Global warming	kg CO_2 eq.	2.24E+05	-1.04E+06	-8.14E+05	-7.02E+05	-5.90E+05
Stratospheric ozone depletion	kg CFC11 eq.	9.30E-02	-2.08E-01	-1.15E-01	-6.87E-02	-2.22E-02
Ionizing radiation	kBq Co-60 eq.	1.83E+03	-4.12E+03	-2.28E+03	-1.37E+03	-4.52E+02
Ozone formation, Human health	kg NOx eq.	8.86E+02	-2.62E+03	-1.73E+03	-1.29E+03	-8.43E+02
Fine particulate matter formation	kg PM2.5 eq.	1.79E+02	-2.14E+03	-1.96E+03	-1.87E+03	-1.78E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq.	9.03E+02	-2.70E+03	-1.80E+03	-1.34E+03	-8.93E+02
Terrestrial acidification	kg SO_2 eq.	6.62E+02	-4.72E+03	-4.06E+03	-3.73E+03	-3.40E+03
Freshwater eutrophication	kg P eq.	4.66E+00	-4.61E+01	-4.15E+01	-3.91E+01	-3.68E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	5.29E+02	6.52E+01	5.94E+02	8.58E+02	1.12E+03
Freshwater ecotoxicity	kg 1,4-DCB eq.	3.69E+02	-1.96E+02	1.73E+02	3.57E+02	5.42E+02
Marine ecotoxicity	kg 1,4-DCB eq.	1.49E+03	9.67E+00	1.50E+03	2.24E+03	2.99E+03
Human carcinogenic toxicity	kg 1,4-DCB eq.	1.51E+03	-7.08E+03	-5.57E+03	-4.82E+03	-4.06E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	1.01E+06	-2.67E+06	-1.66E+06	-1.15E+06	-6.42E+05
Land use	m^2 a crop eq.	6.96E+03	-6.73E+05	-6.66E+05	-6.63E+05	-6.59E+05
Mineral resource scarcity	kg Cu eq.	6.21E+02	-5.87E+03	-5.25E+03	-4.94E+03	-4.63E+03
Fossil resource scarcity	kg oil eq.	7.56E+04	-3.52E+05	-2.76E+05	-2.38E+05	-2.01E+05
Water consumption	m^3	7.30E+02	-1.60E+04	-1.53E+04	-1.49E+04	-1.45E+04

Table 8: Results of the sensitivity analysis with variation in the transport phase.

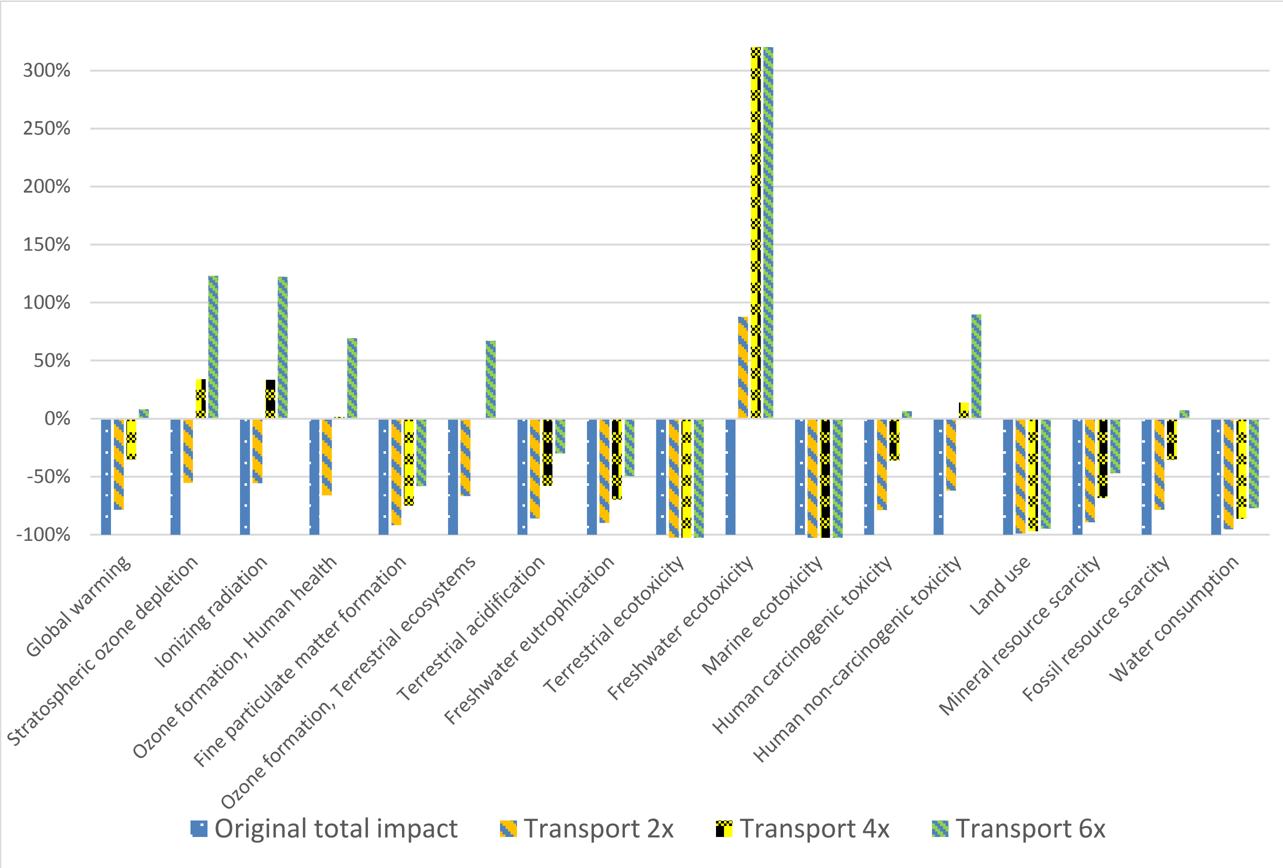

Figure 5: Percentage values of the environmental impacts with variation in the transport phase.

The results of this analysis (Figure 5 and Table 8) show that a change in the transport distance slightly influences the environmental impacts. When the transport distance is doubled, the impact remains negative in most of the impact categories, resulting in a total impact that is negative as well. Conversely, when the transport phase is multiplied by 4 or 6 meaningful variations can be noted. More precisely, in the "*Transport 6x*" scenario the benefits in the Global warming category are nullified if compared with the current scenario, increasing from -1.04E+6 kg CO_2 eq. to 5.90E+5 kg CO_2 eq.

The second sensitivity analysis was carried out on the basis of European Union Directive 2008/98/EC, which sets out the basic concepts and definitions relating to waste management, such as definitions of waste, recycling and recovery. It explains when waste ceases to be waste and becomes a secondary raw material (so called end-of-waste criteria), and how to distinguish between waste and by-products.

The Directive introduces two new recycling and recovery targets to be achieved by 2020:

- 50% preparing for re-use and recycling of certain waste materials from households and other origins similar to households; and

- 70% preparing for re-use, recycling and other recovery of construction and demolition waste.

One of the member states that has already achieved and overtaken these targets is Germany (Umweltbundesamt, 2016). Hence, the example of Germany is taken to evaluate the performance the new process could achieve if it was used in a country where the recycling is more adopted than in Italy. To this end, the German EOL efficiency percentages (Table 9) were introduced in the analysis and applied to the same quantity of PFW in Emilia Romagna. This is expected to show what the Emilia Romagna scenario would be like if German recycling efficiencies were achieved.

GERMANY				
	Distribution %	% Recycling	% Energy Recovery	% Landfill
Iron and steel	9.65%	93	0	7
Alluminium	1.35%	88.1	3.7	8.2
Paper	29.79%	87.3	12.4	0.3
PE	13.92%	50.2	49.3	0.5
PET	7.14%	93.6	5.9	0.5
PLASMIX	8.76%	41	43	16
Glass	26.24%	89	0	11
Composite packaging	3.10%	23.6	47	29.4

Table 9: German EOL distribution percentage.

Impact category	**Unit**	**Italian scenario**	**German EOL efficiency percentages**
Global warming	kg CO2 eq.	-1.04E+06	-1.70E+06
Stratospheric ozone depletion	kg CFC11 eq.	-2.08E-01	-3.83E-01
Ionizing radiation	kBq Co-60 eq.	-4.12E+03	-5.55E+03
Ozone formation, Human health	kg NOx eq.	-2.62E+03	-3.36E+03
Fine particulate matter formation	kg PM2.5 eq.	-2.14E+03	-2.63E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq.	-2.70E+03	-3.47E+03
Terrestrial acidification	kg SO2 eq.	-4.72E+03	-5.92E+03
Freshwater eutrophication	kg P eq.	-4.61E+01	-6.97E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	-1.71E+02
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	-3.78E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	-7.84E+02
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	-9.46E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	-3.41E+06
Land use	m^2 a crop eq.	-6.73E+05	-7.37E+05
Mineral resource scarcity	kg Cu eq.	-5.87E+03	-7.68E+03
Fossil resource scarcity	kg oil eq.	-3.52E+05	-4.85E+05
Water consumption	m^3	-1.60E+04	-1.90E+04

Table 10: Results of the sensitivity analysis with variation in EOL product percentage.

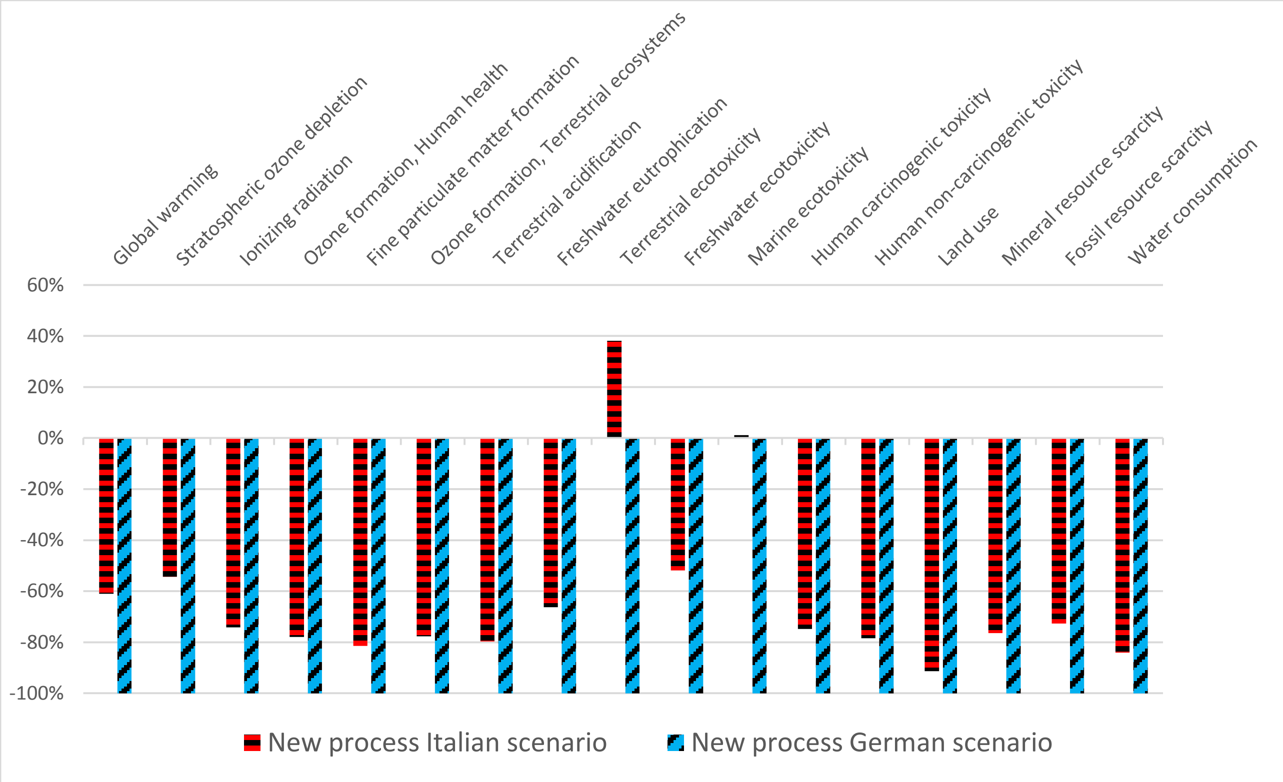

Figure 6 Environmental impacts analysis with variation in EOL product percentage.

The results of the second sensitivity analysis show that a change in the EOL percentage (Figure 6 and Table 10) has a significant influence on theenvironmental impact. Globally, it was proved that the “German scenario” generates more benefits for the environment than the “Italian scenario”, especially regarding the Terrestrial and Marine ecotoxicity impact categories, where an environmental benefit is now achieved. The impact that is avoided based on the German EOL percentage appears higher in all the categories, with an average absolute improvement of 38%.

Besides the categories mentioned above, the highest improvements are observed for Freshwater ecotoxicity (48%), Stratosferic ozone depletion (46%), Global warming (39%), Freshwater euthrophication (45%). This result is due to the higher percentage of materials destined for recycling and the lower landfill volumes.

Overall, the “German scenario” is more environmental friendly mainly due to the lower packaging percentage handled and allocated to the landfill and incineration, particularly for the impacts connected to the plastic materials.

Similar to the results reported in Rigamonti et al. (2009) and Ferreira et al. (2014), the recycling system involves a clear benefit for the environment for all the impact categories considered. Looking at the Global warming category, the German scenario avoids the emissions of 6.6E+05 of CO2 eq. compared to the new process applied to the Italian scenario.

The third sensitivity analysis was carried out setting as input the composition of the packaging waste of the European context (Eurostat, 2017) and keeping the EOL unchanged.

Impact category	Unit	New process Italian scenario	EU28
Global warming	kg CO2 eq	-1.04E+06	-1.46E+06
Stratospheric ozone depletion	kg CFC11 eq	-2.08E-01	-2.72E-01
Ionizing radiation	kBq Co-60 eq	-4.12E+03	-4.51E+03
Ozone formation, Human health	kg NOx eq	-2.62E+03	-2.84E+03
Fine particulate matter formation	kg PM2.5 eq	-2.14E+03	-2.37E+03
Ozone formation, Terrestrial ecosystems	kg NOx eq	-2.70E+03	-2.92E+03
Terrestrial acidification	kg SO2 eq	-4.72E+03	-4.87E+03
Freshwater eutrophication	kg P eq	-4.61E+01	-5.04E+01
Terrestrial ecotoxicity	kg 1,4-DCB eq.	6.52E+01	-2.98E+01
Freshwater ecotoxicity	kg 1,4-DCB eq.	-1.96E+02	-2.45E+02
Marine ecotoxicity	kg 1,4-DCB eq.	9.67E+00	-3.36E+02
Human carcinogenic toxicity	kg 1,4-DCB eq.	-7.08E+03	-7.84E+03
Human non-carcinogenic toxicity	kg 1,4-DCB eq.	-2.67E+06	-3.18E+06
Land use	m2a crop eq	-6.73E+05	-9.13E+05
Mineral resource scarcity	kg Cu eq	-5.87E+03	-5.46E+03
Fossil resource scarcity	kg oil eq	-3.52E+05	-3.17E+05
Water consumption	m3	-1.60E+04	-1.97E+04

Table 11: Results of the sensitivity analysis with variation of the composition of packaging waste (EU28).

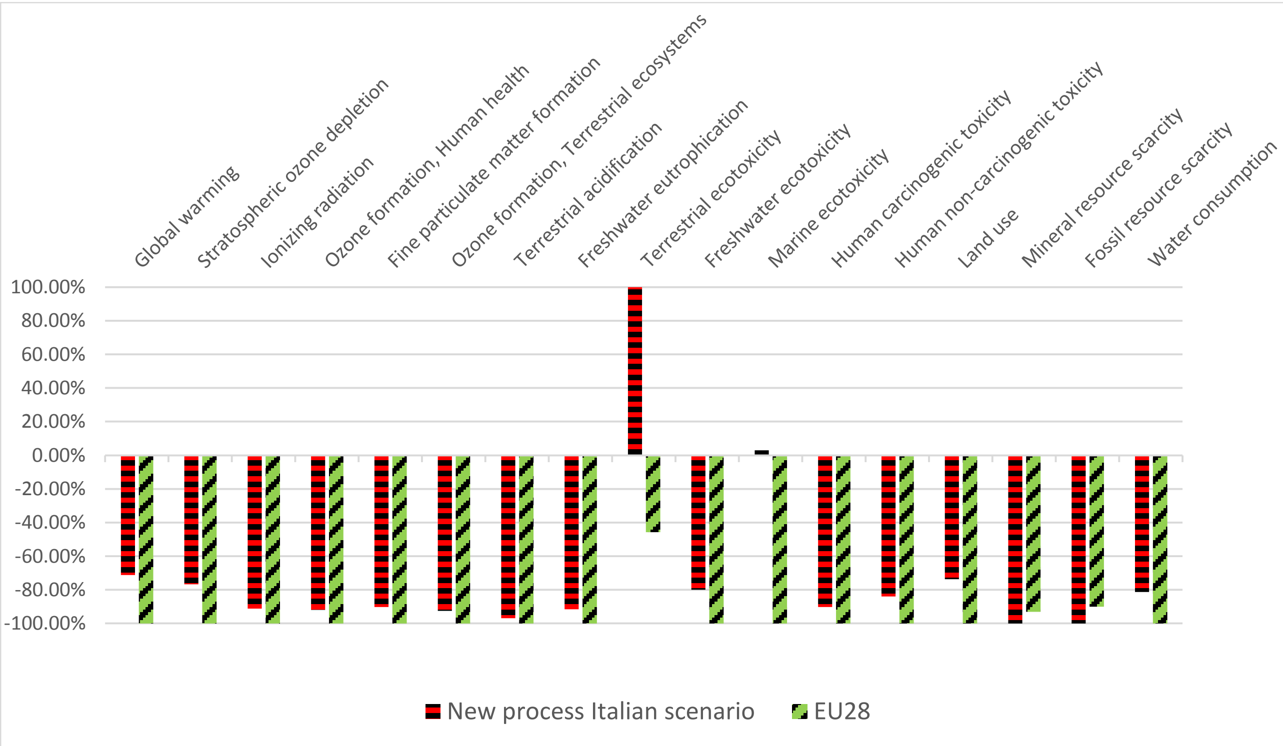

Figure 7: Environmental impacts analysis with variation in the composition of the packaging waste (EU28).

The results of the third sensitivity analysis (Figure 7 and Table 11) show that a change in the composition of packaging waste has a quite significant benefit on environmental impact, which improves by 15% on average. In addition, for Terrestrial ecotoxicity the result changes significantly, moving from a burden to a benefit for the environment. This is due to the high volumes of paper handled, which involves a corresponding amount of avoided sulfate pulp that generates a benefit to the environment.

5 Conclusions

Throughout this paper, the environmental impact of a new EOL process of food packaging materials has been analysed and compared to the current destination. Every year in the Emilia Romagna Region (a northern Italian region) 14,300 tons of packaged food collected from retail stores and during the distribution phase are wasted and sent to landfill sites. Among this quantity, approximately 13.8% (i.e. 1,973 tons/year) consists of packaging material that, at present, is neither sorted nor recycled. One way to solve this problem is to introduce a complex system of collection and sorting able to separate the PFW thrown away by retail outlets into organic fraction and packaging. Based on these premises, the study carries out an environmental evaluation of a system able to collect the PFW from distribution facilities and retail outlets and send it to a sorting facility, where the packaging materials will be divided and sent to the best EOL option.

This paper deals in particular with the EOL of packaging materials, for which it considers different processes (recycling, energy recovery and landfill) and takes into account the most recent performances in terms of efficiency.

The newly designed process ensures a reduction in the environmental impact in almost all the categories considered compared to the current scenario (disposal in landfill). Only for two impact categories does the current scenario perform better than the new process. To be more precise, the LCA analysis shows that the most relevant environmental benefits can be achieved when recycling paper and glass packaging materials. The results show also that the energy recovery process provides benefits in almost all the categories, due to avoided production of energy thanks to incineration (apart from Global warming, Stratospheric ozone depletion and the Ecotoxicity impact categories). Overall, this study proves that the proposed process, which includes the sorting and an EOL valorisation of packaging materials deriving from PFW, can give environmental benefits respect to the current scenario where the packaging materials of PFW are disposed of in landfill.

Regarding the sensitivity analysis carried out concerning all the packaging waste managed by the sorting system, the results show that if the percentage of "recycling" is enhanced, such as the German one, more benefits for the environment have been reached.

Further studies could investigate the environmental performance of other packaging treatment scenarios, such as pyrolysis with energy recovery, and include the impact of the recovery of organic food waste achieved with the sorting process. Moreover, this work focused only on the specific issue of valorising packaging material from PFW; other interrelated topics were not dealt with in this paper. The evaluation of the economic aspects of the new process is one of these topics. In this respect, as the process described in this paper is currently being implemented on the field, a final evaluation could be made when the system will be fully operating, to evaluate its sustainability from an environmental, economic and social point of view.

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