Design of a sustainable packaging in the food sector by applying LCA

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Received: 28 January 2013 / Accepted: 25 June 2013 / Published online: 10 July 2013

1 Introduction

The aim of the present study was to assess the sustainability of two packaging alternatives of a poultry product. Life cycle assessment (LCA) studies in the food sector, and livestock products in particular, are consistently increasing (Verge et al. 2009; Bengtsson and Seddon 2013; de Vries and de Boer 2010); the environmental impacts of food products, especially livestock products such as beef and poultry, are mainly related to the production of the food itself (de Vries and de Boer 2010); nevertheless, taking into consideration packaging alternatives of livestock and derived products is of primary interest when considering the overall sustainability of a food product (González-García et al. 2013). Usually, the choice of a packaging that best suites the requirements of fresh food is driven by issues such as cost, shelf life, safety, practicality, and in the past few years, environmental sustainability. This last topic is usually intended as sustainability of the packaging itself and end-of-life management (Meneses et al. 2012; Levi et al. 2011; Suwanmanee et al. 2013), so that packaging alternatives characterized by low impacts related to their production and waste management (such as biopolymers and biodegradable polymers) (Colwill et al. 2012) are usually felt as the most sustainable choices, especially when debates are held out of the scientific community.
One of the aims of the present paper is to show that LCA may be a useful tool in order to improve the environmental

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performances of a system when stages that are usually not considered as part of the system are included in the analysis. Indeed, the choice of a material, such as aluminum, that allows for its direct use in the cooking stage avoids the use of another container in the oven and, if properly designed according to the food contained, it can allow for further savings during the cooking itself.

In the present study, the sustainability of a polystyrene-based tray (PS in the manuscript) and an aluminum tray (AL in the manuscript) was assessed. The latter alternative was specifically designed to optimize the cooking stage. Indeed, the peculiar shape and thickness of the AL tray allowed for a reduction of the cooking time by 10 min (40 min instead of 50 min) in a traditional oven at a temperature of 200 °C, if compared to traditional cooking in a ceramic or aluminum (not specifically designed) tray. So, LCA performed according to ISO 14040-44, considered a "from-cradle-to-grave" perspective: the use phase was identified with the cooking stage of the product.

The quantification and the inclusion of the impacts coming from the cooking stage might be of primary interest when the most sustainable packaging alternative of food to be cooked before being consumed must be chosen, especially in those countries such as Italy or Germany where the production of electric energy has a high share of fossil fuels (Ecoinvent 2.0 Database -www.ecoinvent.ch) and, accordingly, the associated impacts (in terms of CO_2 eq) are significant. It is known that the production of primary aluminum is highly impacting (Tan and Khoo 2005), but these higher impacts may be compensated by the use of a certain amount of secondary material and from emission savings during the cooking stage.

Both polystyrene and aluminum are highly recyclable, so different scenarios for the management of end-of-life were hypothesized, according to ISO 14040-44 (2006) and PAS 2050 (2011). Impact assessment was performed using the Greenhouse Gas Protocol (GGP) (World Business Council for Sustainable Development (WBCSD) and World Resources Institute (WRI) 2009) and, since it was argued that the impact assessment performed using only CO_2 eq quantification may have some limitations (Laurent et al. 2012; Röös et al. 2013), the ILCD 2011 midpoint method (JRC 2012a) and Cumulative Energy Demand (CED) were also included in the study.

2 Materials and methods

2.1 Product description

The functional unit here adopted is one tray (i.e., one PS tray and one AL tray). The two trays have the same function (i.e., carrying one piece of poultry product) and they have just the same performance; indeed, they guarantee the same shelf life of the product contained. The two trays are commercially used by an Italian food industry which was the source of primary data reported in the following paragraphs.

The life cycle of all products is presented in a simplified view in Fig. 1. The PS tray was made of polystyrene and weighted 13.15 g, while the AL tray was made of primary aluminum (70 wt%) and secondary aluminum (30 wt%) and weighted 23.5 g. All the other components of the packaging, such as polyethylene labels, PVC films, and glue, which are similar for the two alternatives, were included in the LCA also considering their transport (modeled taking into consideration the amount of materials transported in a lorry and the distance from the supplier), packaging, and production (Table 1).

2.2 Inventory

Data for the production of raw materials (polystyrene, aluminum, polymers for labels and films…), production process of the two trays, transport of all materials to the poultry producer, use phase, and end-of-life were considered. In particular, the AL tray was made of an alloy of primary (70 wt%) and secondary (30 wt%) material. The fuel needed for transport and its emissions were considered. Raw material specifications and producers were supplied by the poultry producer, as well as any other useful information to construct the mass balance and the mass flow of all relevant input and output streams.

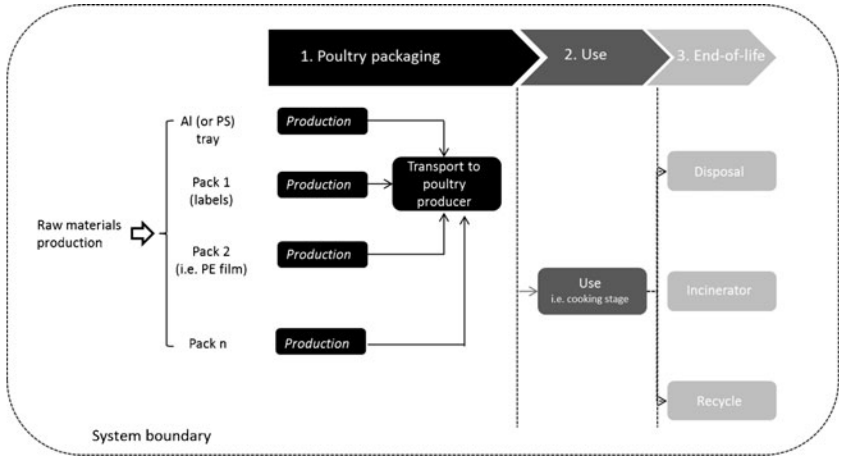
The emissions during the use phase (e.g., cooking) were calculated according to the Italian energy country mix, since the product under investigation is commercialized mainly in Italy. The only energy source input is grid electricity during the cooking stage, and the Italian energy mix was used. It was assumed that the Italian energy mix accounts for 0.605 kg CO_2 eq/kWh (EcoInvent 2010). Data reporting the estimation of the energy consumption of an oven and the inventory for the use phase are reported in Tables 2 and 3 (Leonardi et al. 2011). The tray dedicated to the cooking of the poultry product contained in the PS tray was taken into account. It was modeled as a ceramic tray (1.1 kg) whose expected life is 1,000 uses. The washing of the tray was modeled as hand washing, using 7 L water and 3 g of detergent.

The end-of-life management of the two trays (i.e., recycling, disposal, incineration) referred to the Italian waste management statistics of PS and aluminum products, and they are reported in Table 4 (COREPLA 2011; ISPRA 2009).

Data regarding the composition of the two trays, as well as energy consumption, cooking time, and temperature, were primary data obtained by an Italian company in the poultry sector, while data regarding raw materials production, i.e., polymeric granulated materials, as well as transport emissions and related environmental loads were taken from the EcoInvent database (EcoInvent 2010).

The end-of-life stage is dominated by recycling of the trays' materials: different alternatives can be considered to calculate the impacts related to recycling. In particular, approaches such

Fig. 1 Simplified flowchart of the system under investigation



as recycled content (PAS 2050 (2011)) or substitution (ISO 14040-44) can be used. The two end-of-life approaches are schematized in the flowcharts of Figs. 2 and 3.

1. Recycled content or cutoff: according to this scenario, the environmental impacts of recycling management were not attributed to the system under investigation because, once recycled, they start a new life in a second product/process. This approach is consistent with a *strong sustainability* concept (Frischknecht 2010) drawn to the preservation of natural capital.

   The recycled content approach in the present study leads to apply a cutoff rule for the impacts of recycling. Indeed, according to PAS 2050 (2011), the impacts (E) of a product containing a known amount of recycled material are equal to:

$$E = (1-R_1)E_v + R_1 E_R + (1-R_2)E_D \quad (1)$$

   where R_1 is the proportion of recycled material input, R_2 is the proportion of material in the product that is recycled at end-of-life, E_R is the emissions and removals arising from recycled material input per unit of material, E_v is the emission and removals arising from virgin material input per unit of material, and E_D is the emissions and removals arising from disposal of waste material per unit of material.

   So, by applying Eq. 1 to the present study, impacts of end-of-life management are the ones involving incineration and disposal of polystyrene and aluminum, while R_1 is equal to 30 % for the AL tray and 0 % for the PS tray.

2. Substitution or system expansion: the environmental impacts of recycling management were included in the system under investigation, both for PS and AL, and the methodology of *avoided burden* was applied to the amount of input primary material that is recycled at end-of-life (TR ISO 14049:2000). In Fig. 3, the parameters R_1, E_R, E_v, and E_D are the same as in Fig. 2, while R_3 is the amount of primary material recycled at end-of-life and $x_{AL/PS}$ is the amount of virgin material saved, by taking into consideration the efficiency of the recycling process. This approach is consistent with a *weak sustainability* perspective, as described in Frischknecht (2010).

Table 1 Components of the two packaging alternatives accounted for in the present study

	AL tray Weight [g]	PS tray Weight [g]
Tray	23.500	13.150
PVC film	4.030	4.030
Label 1	1.560	1.560
Label 2	0.290	0.290
Label 3	0.770	0.770
Label 4	0.890	0.890
Granulated glue	0.875	0.875
Corrugated board plateaux	67.500	67.500
PE film	1.250	1.250

No allocation procedures were needed during the analysis. The analysis was performed using the SimaPro 7.3.3 Software.

2.3 Impact assessment

Life cycle impact assessment (LCIA) was performed using three different methods.

(a) GGP—This method, developed by the WRI and the WBCSD, is an accounting standard of greenhouse gas (GHG) emissions, based on IPCC GWP_{100} data. The total GHG emissions for a product inventory are calculated as the sum of GHG emissions, in CO_2 eq, and it allows for a distinction among four different CO_2 eq sources:

- GHG emissions from fossil sources
- Biogenic carbon emissions

Table 2 Estimation of electric energy oven consumption (considering time, initial heating, and temperature)

Temperature [°C]	Specific consumption [kWh/min]	Initial heating [kWh]
180	0.0192	0.29
200	0.0217	0.29

- Carbon storage
- GHG emissions from land transformation

In this paper, the four sources will be also reported separately in order to identify those with the most impact. A sensitivity analysis was performed for GGP, in order to assess the significance of the differences calculated between the impacts of the two products.

(b) CED—This method allows the calculation of nonrenewable and renewable sources of energy demand.

(c) ILCD 2011 midpoint method—This method was released by the European Commission, Joint Research Centre in 2012. It supports the correct use of the characterization factors for impact assessment as recommended in the ILCD guidance document (JRC 2012a). This LCIA method includes 16 midpoint impact categories: climate change, ozone depletion, human toxicity cancer effects, human toxicity noncancer effects, particulate matter, ionizing radiation HH, ionizing radiation E, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, land use, water resource depletion, and resource depletion. Each category is classified as levels 1, 2, and 3 or interim according to their quality. Level 1 is the highest quality (recommended and satisfactory), and interim is the lowest (most promising among others, but still immature to be recommended) (JRC 2012b).

3 Results

3.1 Greenhouse Gas Protocol

The GHG emissions of the production of the two trays, expressed as kilograms of CO_2 eq, are reported in Table 5, thus excluding the use phase and end-of-life. The GHG emissions of the two packaging alternatives are reported in Fig. 4: the total amounts of CO_2 eq are reported separately for the different sources, according to the GGP method and ISO 14067 (2012) requirements. The fossil contribution is, as expected, the most relevant one. The total amount of CO_2 eq is equal to 0.136 kg for PS and 0.372 kg for AL. This result is consistent with the high impacts related to primary aluminum production. As it can be observed by comparing the results of Table 5 and Fig. 4, the impact of the two trays on the whole packaging is 77 and 36 % for the AL and PS alternative, respectively.

Table 3 Estimation of electric energy consumption during the cooking stage (the AL tray can be directly used for oven cooking, while the PS tray needs a second container for cooking)

Tray	Temperature [°C]	Cooking time [min]	Consumption [kWh]
AL tray	200	50	1.38
PS tray	200	60	1.59

Table 4 Italian scenario for end-of-life management of tray materials

Tray	End-of-life			
	Weight [g]	Recycling [%]	Incinerator [%]	Disposal [%]
AL tray	23.5	72	5	23
PS tray	13.15	61	35	4

Impacts of end-of-life were <0.01 kg CO_2 eq for both trays, when the cutoff rule at recycling was applied. According to this scenario, the sum of tray production and end-of-life stages would lead to the assessment that the PS tray holds lower impacts compared to the AL one.

On the contrary, when a substitution approach was applied to end-of-life management (starting from EcoInvent data for avoided burdens), benefits to AL and PS tray were equal to −0.181 and −0.0243 kg CO_2 eq, respectively. Thus, according to this scenario, the AL tray is still less sustainable when the sum of the production and end-of-life stages was considered. Indeed, AL tray emissions were 0.191 kg CO_2 eq, while PS tray emissions were 0.0107 kg CO_2 eq, taking into consideration the sum of the four CO_2 eq sources.

The use stage (i.e., cooking) had the most impact for both alternatives. Emissions associated to PS tray were equal to 0.92 kg CO_2 eq, while that of the AL tray were 0.80 kg CO_2

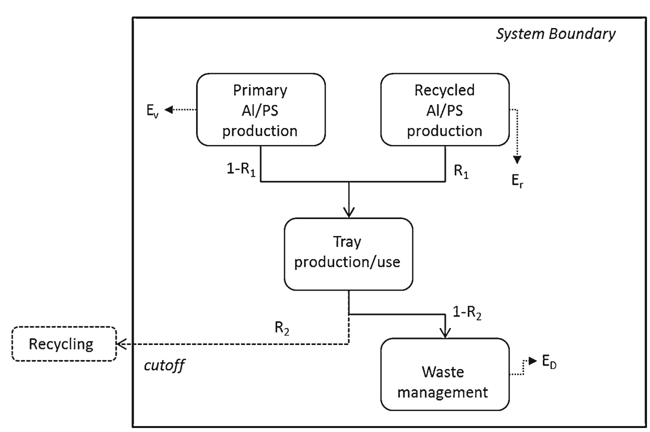
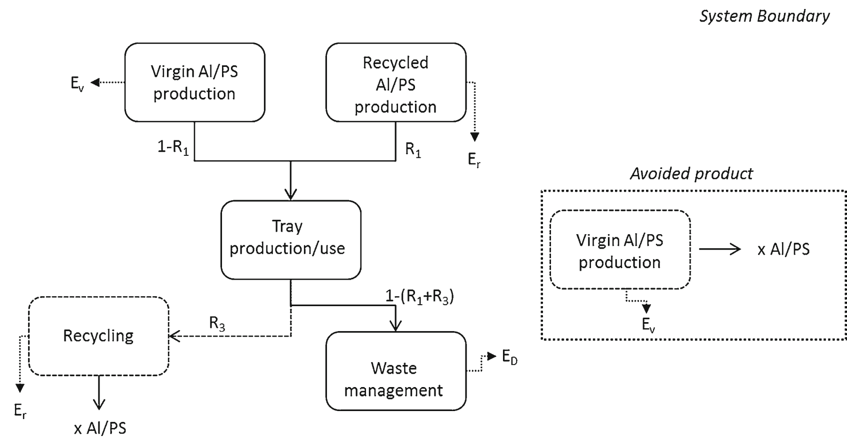


Fig. 2 End-of-life flowchart when applying the “recycled content” approach

Fig. 3 End-of-life flowchart when applying the "system expansion" approach. R_3 is the amount of primary material recycled at end-of-life and $x_{AL/PS}$ is the amount of virgin material saved, by taking into consideration the efficiency of the recycling process



eq. Such emissions were calculated using the Italian energy country mix, which has a high impact due to the high share of energy produced by fossil fuels. Emissions associated to the use of a ceramic tray, needed to cook the poultry product of the PS alternative, and its washing were not relevant, as they were <0.005 kg CO_2 eq.

Cradle-to-grave emissions for the two alternatives are reported in Table 6. Taking into consideration the sum of the four contributions, applying the cutoff method at end-of-life, PS and AL tray emissions were equal to 1.07 and 1.18 kg CO_2 eq, respectively. The difference between the two values (ΔCO_2 eq=0.11 kg, 9.3 %) are lower when considering the whole life cycle of the two alternatives than when considering only their production and waste management (ΔCO_2 eq=0.236 kg).

When the substitution method was applied to end-of-life, emissions of the PS and AL trays were 1.04 and 0.99 kg CO_2 eq, respectively. According to this last approach, the AL tray would be more sustainable than the PS tray.

3.2 Cumulative Energy Demand

Results of CED are reported in Fig. 5. CED was equal to 21.18 MJ for the AL alternative and 20.11 for PS (Δ_{CED}=1.17 MJ, equal to 5.05 %) when considering the "recycled content" scenario. On the contrary, when the "substitution" scenario was chosen, the AL alternative resulted more sustainable than the PS one (Fig. 6): indeed, for the first option, CED was 18.4 MJ and, for the second one, CED was 19.4; the difference was 5.5 %. This result is in agreement with the ones obtained with GGP. The category "nonrenewable–fossil" was the one with the most impact for both scenarios.

Table 5 CO_2 eq emissions of the two packaging alternatives

Unit process	AL tray [kg CO_2 eq]	PS tray [kg CO_2 eq]
Tray	2.88×10^{-1}	4.89×10^{-2}
Packaging of input materials	3.37×10^{-3}	2.60×10^{-3}
Transport	5.64×10^{-3}	8.84×10^{-3}
Labels and glue	7.50×10^{-2}	7.60×10^{-2}
Total package	0.372	0.136

These impacts refer to phase 1 of Fig. 1. Packaging of input materials are the ones related to PVC, PE films, and corrugated boards; transport refers to all the transports involved in phase 1; labels and glue refer to the four labels and granulated glue

3.3 ILCD midpoint

Figure 7 shows the results of impact assessment using the ILCD method for the "recycled content" scenario. According to this perspective, the AL tray is less sustainable than the PS alternative for all the impact categories considered, except for water resource depletion. Water depletion is higher for the PS alternative due to the water needed for washing of the ceramic tray during the use stage. When considering the "substitution" scenario (Fig. 8), the situation was heterogeneous; indeed, the AL tray was more sustainable for 9 categories out of 16: climate change (GWP), ozone depletion (ODP), particulate matter (PM), photochemical ozone formation (POCP), acidification (AP), terrestrial eutrophication (EP_t), marine eutrophication (EP_m), land use, and water resource depletion. It is worth noting that, according to the "substitution scenario," the AL tray was more sustainable for all the impact categories classified as level I (recommended and satisfactory) by ILCD: GWP, ODP, and PM. The AL tray was less sustainable, especially for human toxicity categories, classified as level III (recommended, but to be applied with caution), and resource depletion (level II).

4 Discussion

The two end-of-life scenarios previously described lead to obtaining opposite results according to the "from-cradle-to-

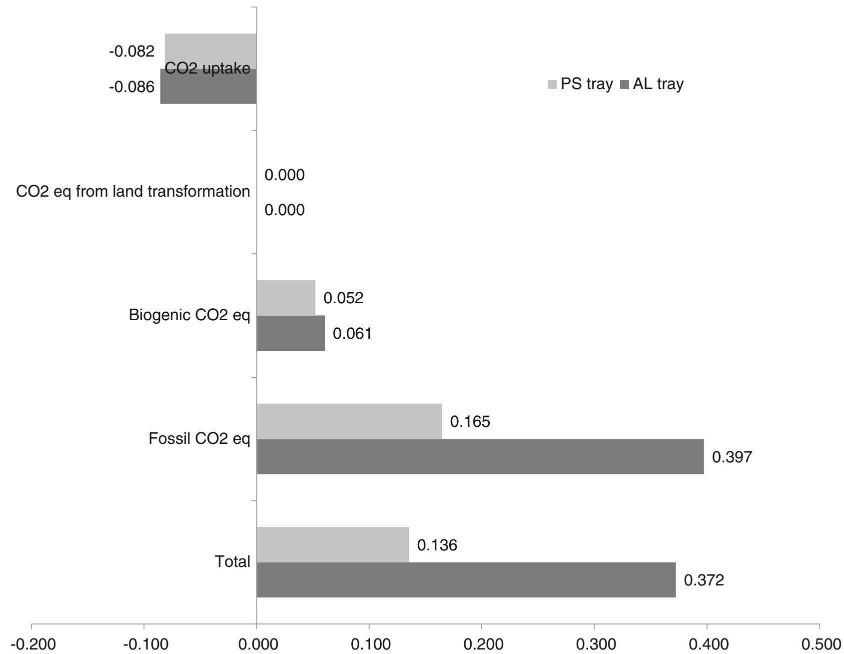


Fig. 4 CO_2 eq emissions, according to the GGP, of the two packaging alternatives (including trays, labels, glue…). End-of-life and use phase are excluded from this diagram

grave" perspective. In the "recycled content" scenario, the PS tray was more sustainable, while in the "system expansion" scenario, the AL tray held lower emissions.

In this section, a discussion of the results and further considerations will be carried out considering the first scenario (recycled content) because it best describes the actual emissions associated to the system considered, since it accounts only for positive (and negative) emissions related to the system itself. The "system expansion" scenario needed a hypothesis on the avoided burdens and, if inventory data on these processes are not extremely precise and appropriate, results may be misleading. So, according to authors such as Frischknecht (2010), we considered the "recycled content" scenario, based on a strong sustainability perspective, as the best option for the case considered here.

According to the "recycled content" scenario, it can be highlighted by the data reported in Section 3 that a careful design of the AL tray entailed lower emissions associated to the cooking stage. CO_2 eq emissions were about 13 % lower than the ones related to the cooking stage of the PS tray: the aim of lowering CO_2 eq emissions during the use stage was largely satisfied by the AL tray. However, these CO_2 eq savings were not high enough in order to obtain higher sustainability over the whole life cycle of the AL tray. One of the aims of a fully sustainable tray alternative may be to reach higher sustainability during each stage of its life cycle: data presented until now showed that the PS tray was more sustainable during the production stage (or cradle-to-gate), the AL tray was more sustainable during the cooking stage, and both trays show similar emissions during end-of-life management. According to available data, it is not possible to attain any improvement for the PS tray during the use stage; instead, it is feasible to lower the emissions associated to AL tray production. Indeed, as it was described previously, the AL tray considered here had a large content of primary aluminum (70 %), which is known to be a material with high impact. GGP calculated for primary aluminum (data from EcoInvent database) is equal to 12.4 kg CO_2 eq/kg aluminum, while the GGP of secondary aluminum varies in the range 0.42–1.4 kg CO_2 eq/kg aluminum. So, emissions associated to the "cradle-to-gate" stage of the AL tray might be significantly lowered if it was produced using a higher amount of secondary material: by considering an AL tray

Table 6 "Cradle-to-grave" emissions (in kilograms CO_2 eq) of the two alternatives

Impact category	AL tray Recycled content	PS tray	AL tray Substitution	PS tray
Total (kg CO_2 eq)	1.18	1.07	0.99	1.04
Fossil CO_2 eq (kg CO_2 eq)	1.20	1.10	1.02	1.07
Biogenic CO_2 eq (kg CO_2 eq)	0.07	0.06	0.07	0.06
CO_2 eq land transformation (kg CO_2 eq)	0.00	0.00	0.00	0.00
CO_2 uptake (kg CO_2 eq)	−0.09	−0.09	−0.09	−0.09

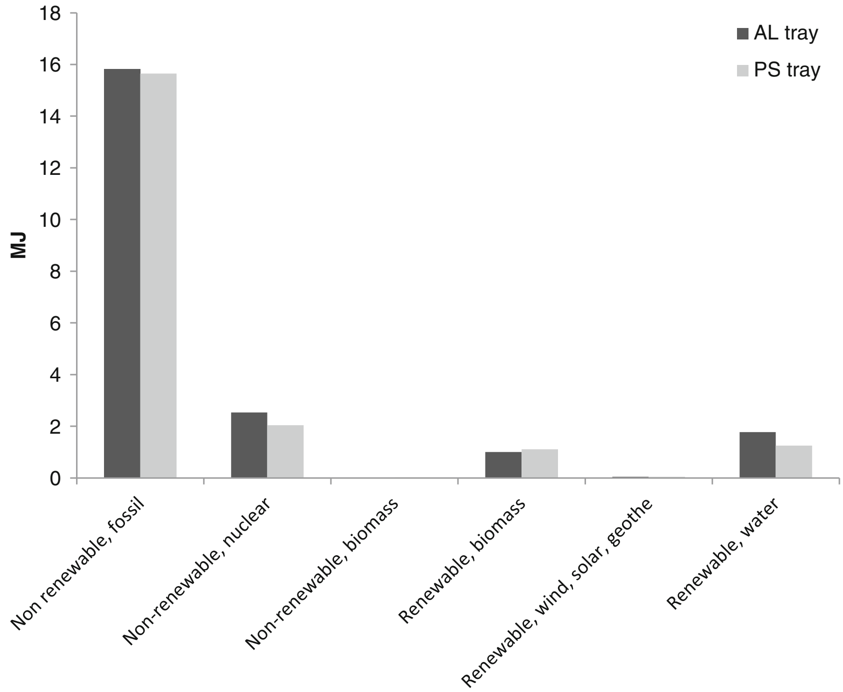


Fig. 5 Impacts of the two alternatives (cradle-to-grave) calculated by CED, according to the "recycled content" scenario

with 100 wt% of secondary aluminum (AL_{100}), CO_2 eq emissions can be lowered down to 0.176 kg CO_2 eq. This value is still higher than that of the PS tray (Table 5), so it is not possible to obtain higher sustainability for each stage for a single packaging. However, when considering the entire life cycle of the AL tray (from-cradle-to-grave), using 100 % secondary aluminum, a significant lowering of overall CO_2 eq emissions can be attained (Fig. 9); indeed, even when considering a cutoff scenario at end-of-life, which is least favorable to the AL tray alternative, its emissions were equal to 0.984 kg CO_2 eq and they were significantly lower (about 8 %) than the ones related to the PS tray (1.07 kg CO_2 eq) (Table 6).

In order to assess whether the differences found were significant, a sensitivity analysis for the GGP result was performed using the Monte Carlo method (1,000 iterations) and by calculating the distribution of the difference of the two alternatives. Results, obtained by comparing AL tray−PS tray and AL_{100}−PS tray, showed that, in the first case, the PS tray is always more sustainable (AL>PS

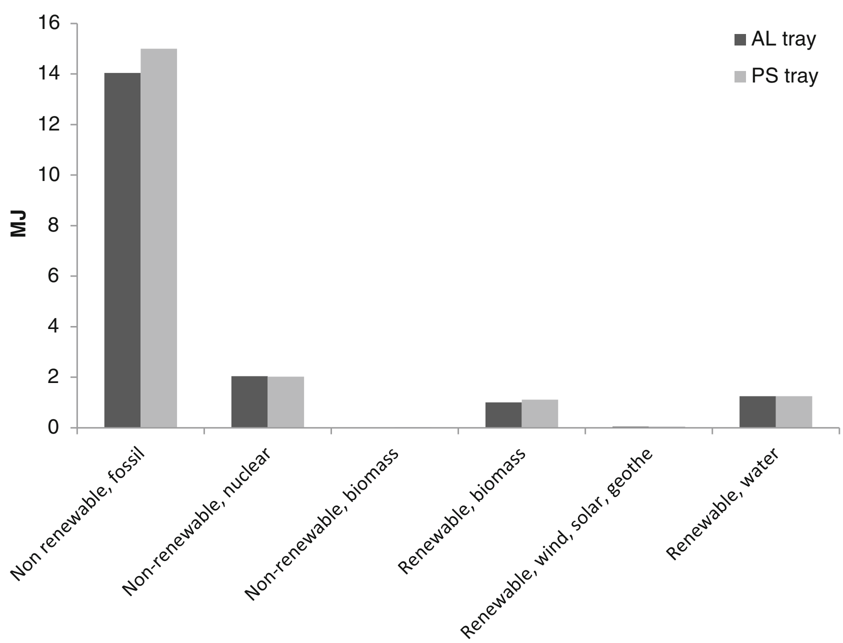
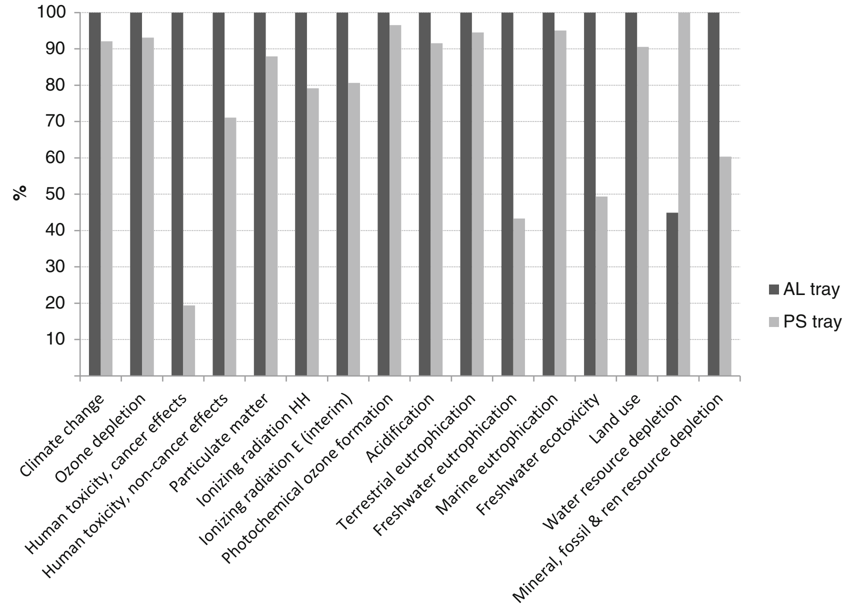


Fig. 6 Impacts of the two alternatives (cradle-to-grave) calculated by CED, according to the "substitution" scenario

Fig. 7 Impacts of the two alternatives (cradle-to-grave) calculated by the ILCD midpoint method, according to the "recycled content" scenario



100 %); on the contrary, in the latter, the AL_{100} tray was always more sustainable (AL_{100}<PS 100 %).

The minimum amount of secondary aluminum needed in the tray composition, in order to equal the impact of the PS tray over the entire life cycle (cradle-to-grave), can be estimated. Indeed, when using 69 wt% of secondary aluminum and 31 wt% of primary aluminum, emissions of the PS and AL trays (calculated with GGP) were the same.

It may be argued that the use phase is strongly dependent on the country considered due to the different electric energy country mix: Table 7 reports the impact variances of the use phase in six different European countries (Italy, Germany, France, UK, Holland, and Denmark), where:

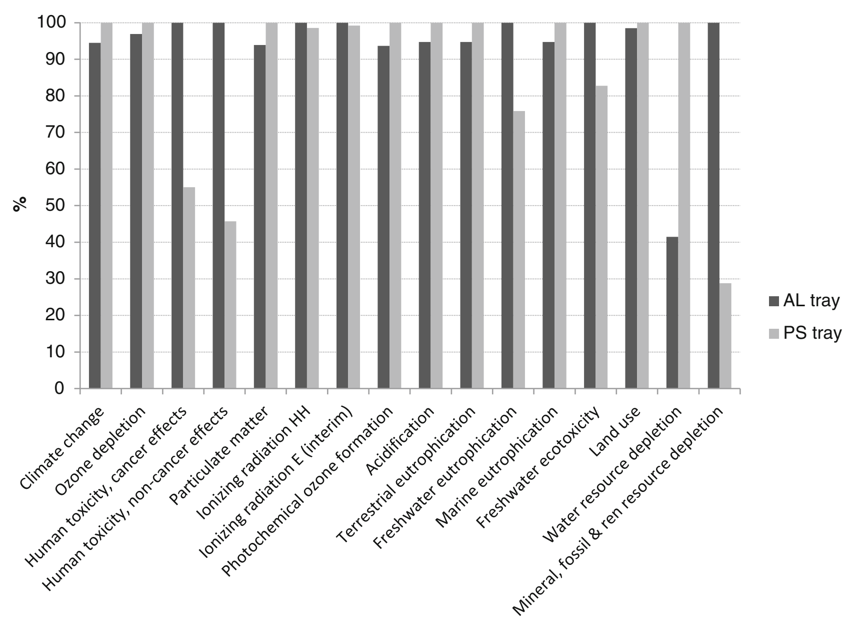
$$\Delta_{\text{tray}} = \left(I_{\text{ALtray}} - I_{\text{PStray}}\right) \tag{2}$$

where I_{ALtray} is the impact (in kilograms CO_2 eq) of the production stage and end-of-life of the AL tray and I_{PStray} is the impact (in kilograms CO_2 eq) of the production stage and end-of-life of the PS tray;

$$\Delta_{\text{cooking}} = \left(I_{\text{ALuse}} - I_{\text{PSuse}}\right) \tag{3}$$

where I_{ALuse} is the impact (in kilograms CO_2 eq) of only the use stage of the AL tray in a specific country

Fig. 8 Impacts of the two alternatives (cradle-to-grave) calculated by the ILCD midpoint method, according to the "substitution" scenario



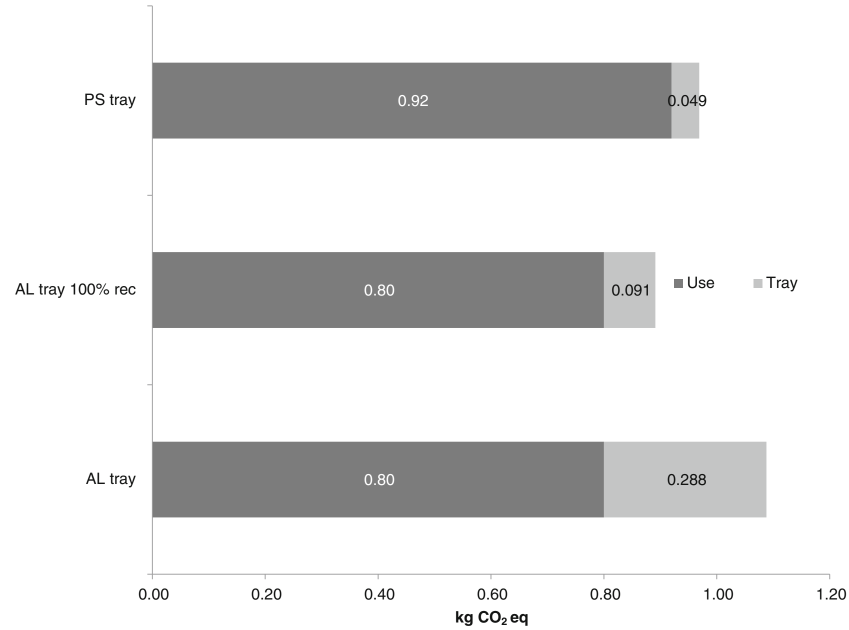


Fig. 9 CO_2 eq emissions associated to tray production (excluding labels, glue…) and use stage

and I_{PSuse} is the impact (in kilograms CO_2 eq) of only the use stage of the PS tray in a specific country; and:

$$\Delta_{\text{life cycle}} = \left(I_{\text{AL life cycle}} - I_{\text{PS life cycle}}\right) \tag{4}$$

where $I_{\text{AL life cycle}}$ is the impact (in kilograms CO_2 eq) of the whole life cycle (cradle-to-grave) of AL trays having a content of secondary aluminum equal to 30 wt% ($AL_{70–30}$), 100 wt% (AL_{100}), and 69 wt% ($AL_{31–69}$) in a specific country and $I_{\text{PS life cycle}}$ is the impact (in kilograms CO_2 eq) of the whole life cycle (cradle-to-grave) of PS trays in a specific country.

It can be noted, from the data reported in Table 7, that $AL_{70–30}$ is the less sustainable option compared to the PS tray in all countries considered. Instead, AL_{100} is more sustainable in all countries, except France due to the high share of nuclear source in the French energy country mix, which helps in lowering global CO_2 eq emissions. $AL_{31–69}$ was more sustainable in UK, Germany, and Holland, less sustainable in France, and showed the same values as the PS tray in Denmark and Italy.

According to the previous discussion about GGP, AL_{100} impacts, compared to those of the PS tray, were calculated using the CED and ILCD methods. CED results are reported in Fig. 10 and it can be observed that AL_{100} impacts were lower than those of the PS tray: the impact reduction was equal to −9.9 % (18.1 and 20.1 MJ, respectively). This result is in agreement with the one reported for GGP.

ILCD method results are shown in Fig. 11. According to the "from-cradle-to-gate" perspective, the AL_{100} tray was more sustainable for 9 impact categories out of 16, with 3 categories classified as level 1 (climate change, ozone depletion, and particulate matter), 4 out of 7 categories of level 2 (photochemical ozone formation, acidification, terrestrial eutrophication, and marine eutrophication), and 2 categories of level 3 (land use and water resource depletion). Two categories showed almost equal results between the AL_{100} and PS trays: ionizing radiation HH and ionizing radiation E; these last two categories are classified as level 2 and interim (still immature to be recommended), respectively. The higher

Table 7 Impacts of the different alternatives considered in different European countries

	Δ Tray	Country	Δ Cooking	Δ Life cycle		
				$AL_{70–30}$−PS	AL_{100}−PS	$AL_{31–69}$−PS
	[kg CO_2 eq]		[kg CO_2 eq]	[kg CO_2 eq]		
$I_{AL70–30}-I_{PS}$	0.380	Italy	−0.120	0.260	−0.086	0.000
$I_{AL100}-I_{PS}$	0.034	Germany	−0.135	0.245	−0.101	−0.015
$I_{AL31–69}-I_{PS}$	0.120	France	−0.020	0.360	0.014	0.100
		UK	−0.127	0.253	−0.093	−0.007
		Holland	−0.143	0.237	−0.109	−0.023
		Denmark	−0.120	0.260	−0.086	0.000

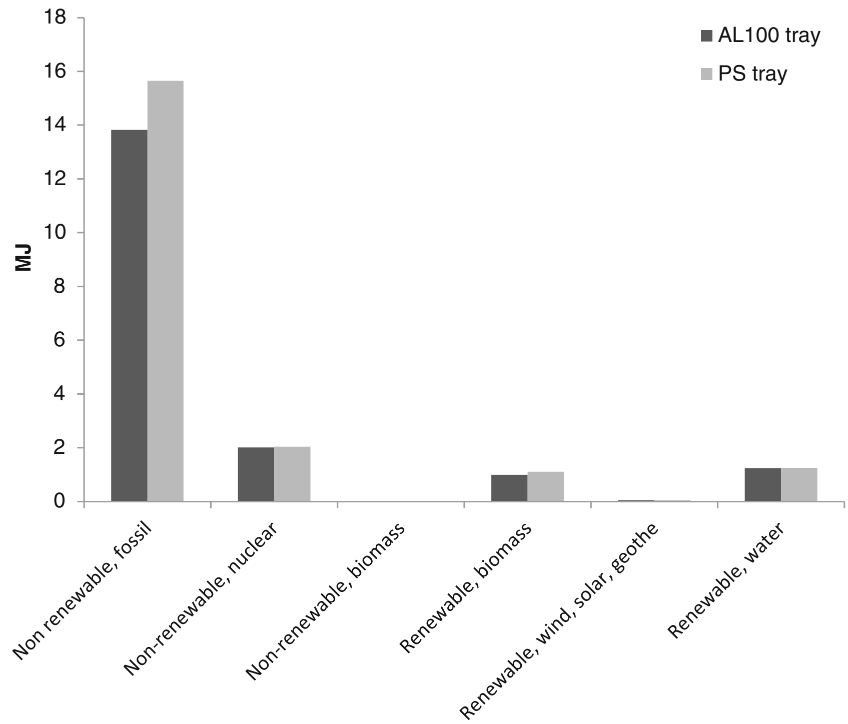


Fig. 10 Impacts of the packaging alternatives (cradle-to-grave) calculated by CED, according to the "recycled content" scenario, including the AL tray produced with 100 % of secondary material

sustainability of the AL_{100} tray, with respect to the PS tray, for the previously cited nine impact categories is due to the lower energy needed for the use stage: indeed, by comparing only the production of the three trays (AL, AL_{100}, and PS), as shown in Fig. 12, it is worth noting that the production of the PS tray held better results for all the impact categories. So, it is only by considering from-cradle-to-grave impacts that AL_{100} becomes a more sustainable option for nine impact categories.

In order to assess whether the differences found are significant, a sensitivity analysis on ILCD midpoint results was performed using the Monte Carlo method (1,000 iterations) and by calculating the distribution of the difference of the two alternatives ($AL_{100}-PS$). It is possible to observe, from the results shown in Fig. 13, that for the nine categories where AL_{100} was more sustainable, the differences were significant in eight cases out of nine: 100 % of runs were favorable to AL_{100} for climate change, particulate matter, acidification, photochemical ozone formation, terrestrial eutrophication, marine eutrophication, and water resource depletion, while 99 % of runs were favorable for ozone depletion. Only in one case was the significance of the difference

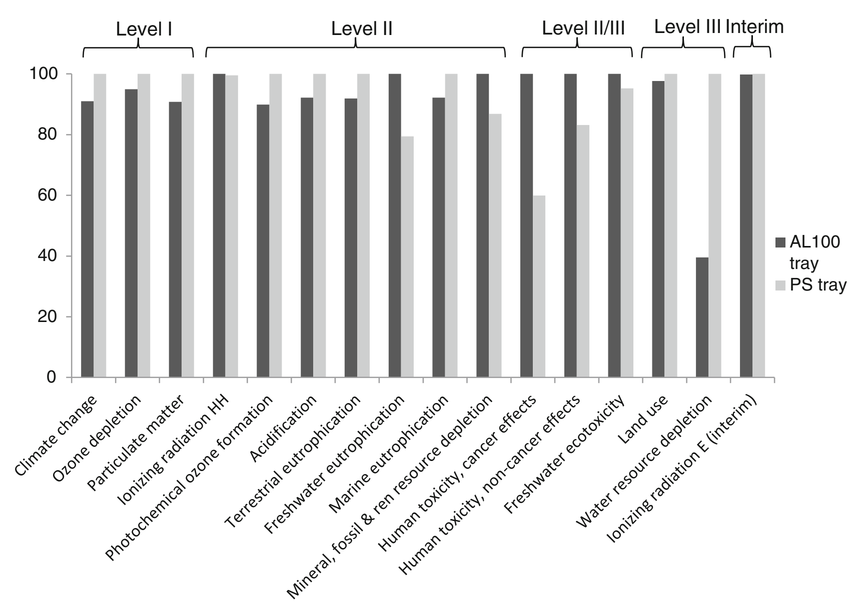
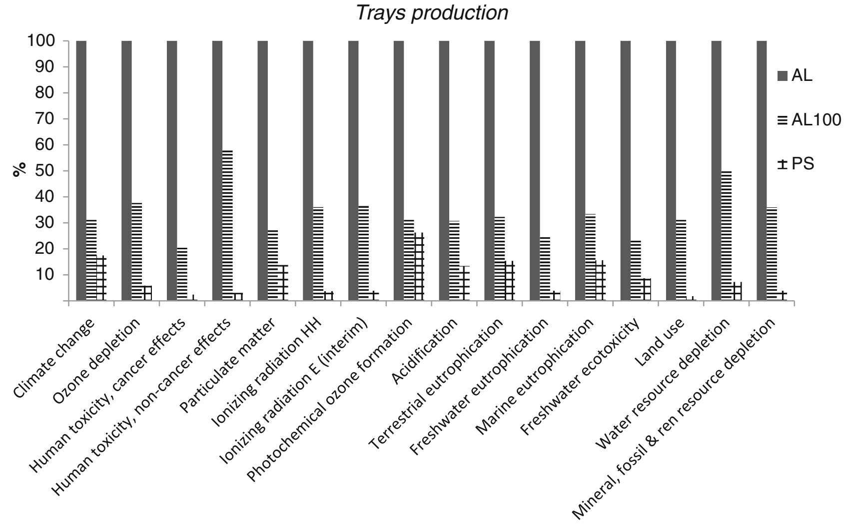


Fig. 11 Impacts of the packaging alternatives (cradle-to-grave) calculated by the ILCD 2011 midpoint method, according to the "recycled content" scenario, including the AL tray produced with 100 % of secondary material

Fig. 12 Production impacts of the three trays: AL, AL_{100}, and PS with the ILCD 2011 midpoint method



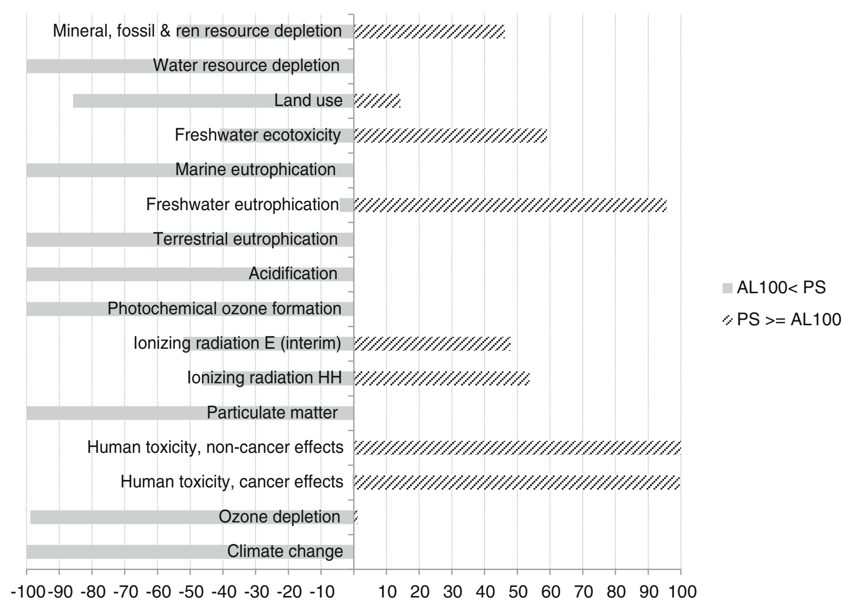
lower: 84 % for land use. When considering the impact categories where AL_{100} was less sustainable, only human toxicities, cancer and noncancer (AL_{100}>PS 100 %), and freshwater eutrophication (AL_{100}>PS 96 %) were significant. Differences related to the remaining impact categories were not significant.

5 Conclusions

This paper investigated the sustainability of two packaging alternatives: a polystyrene-based tray (PS tray) and an aluminum-based tray (AL tray). The production stage of the two trays showed that the PS tray is more sustainable than the aluminum one; nevertheless, the AL tray was specifically designed to allow for energy savings during the cooking stage of the poultry product contained in the tray. So, according to a "from-cradle-to-grave" perspective, it was found that the cooking stage (use stage in the paper) had the most impact over the entire life cycle of the two alternatives: So, the specific design of the tray itself allowed significant lowering of the overall emissions. In particular, in this paper, it is shown that the AL tray was less sustainable than the PS one, according to a "recycled content" scenario, but it was more sustainable when a "substitution" scenario was applied: this was true when considering GGP and CED.

When considering an AL tray made of totally recycled material (AL_{100}), even if the tray itself is still less sustainable than a polystyrene one, the choice of the AL tray becomes the most sustainable option due to the lower impacts during the cooking stage. A multicategory method such as the ILCD midpoint method shows that the AL tray, according to the

Fig. 13 Sensitivity analysis (Monte Carlo method) calculated as the difference of $AL_{100}-PS$ impacts with the ILCD 2011 midpoint method



"recycled content" scenario, is less sustainable than the PS tray, but when "substitution" and AL_{100} were considered, the AL tray was more sustainable for 9 impact categories out of 16.

We recommend, when designing new packaging for food that requires cooking before consumption, to also take into account the cooking stage of the food itself, in order to verify if it is possible to lower the emissions associated to such a high impact stage.

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