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ORIGINAL ARTICLE

Comparative life cycle assessment of plastic and paper packaging for pasta

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Abstract
In this study life cycle assessment was performed to compare the environmental impact of traditional plastic packaging for pasta with an innovative paper packing. Two kinds of packaging solutions were involved in the study: a tight packaging, used for long pasta and a loose packaging, used for short pasta. The substitution of plastic with paper allows to decrease the environmental load according to relevant impact categories such as global warming potential and depletion of fossil fuels. On the other hand, the higher mass of paper packaging causes a higher environmental impact on impact categories such as eutrophication and ozone depletion. Quite interestingly, it was observed that tight packaging used for long pasta is characterized by an environmental impact reduction of around 30% due to the lower material consumption caused by the lower volume occupied by long pasta with respect to the short one. The advantages arising from the substitution of plastic with paper for packaging applications seem very limited, mainly due to the different properties of the two materials that require a larger paper amount to substitute plastic in the same application.

Keywords Packaging · Food · Carbon footprint · Plastic · Paper · Life cycle assessment

Introduction

Packaging is an integral part of modern food systems since it allows to transport liquid and solid foodstuff, it protects food preventing contaminations and prolonging its shelf life [1, 2]. In 2021 around 44% of the global plastic production (i.e. around 390 Mt) was related to the packaging and 60% of EU plastic waste was constituted by packaging material [3, 4]. Moreover, it is estimated that worldwide around 30% of plastic waste escapes the waste management circuit ending in land or marine environment, with an estimated quantity of 12,500 million tonnes of accumulated plastic waste by 2050 and the consequent hazards for human health and biodiversity [5–7]. Considering the different polymers used for the production of packaging, the average recycling rate is around 26% for polyethylene terephthalate (PET), 8% for polyethylene (PE) and 3% for polypropylene (PP) [8, 9]. Since the most critical aspect related to plastic waste is the short lifetime of single-use objects, to improve the recycling rate of plastic, the EU Packaging Directive 2018/852 set a target of a 50% of recycling rate for plastic packaging by 2025 and of 55% by 2030 [10–12]. Further implementations of plastic recycling should come from the update of the hierarchy of wastes (i.e. (i) prevention, (ii) reuse, (iii) recycling, (iv) recovery, (v) disposal), from the "plastic own resource" (a contribution of 0.8 €/kg on the plastic packaging waste that is not recycled) and from the regulation on waste shipments that prohibits the shipment to non-OECD countries of hazardous waste and waste destined for disposal [13–15].

Moreover, considering that each European generates around 180 kg of packaging waste per year (155 kg in 1997), the European Commission recently proposed a revision of the EU legislation on packaging and packaging waste that should (a) reduce the packaging waste of 15% by 2040 compared to 2018; (b) clarify the labelling of reusable packaging; (c) ban unnecessary packaging; (d) set design criteria with mandatory deposit return systems to make packaging fully recyclable by 2030; (e) set mandatory rates of recycled content in plastic packaging; (f) clear-up confusion on packaging labelling [16, 17].

In recent years the targets set by the EU together with the increased environmental concerns related to plastic waste,

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pushed the research on the possible replacement of virgin polymers with post-consumer-resins (PCRs), but the positive outcomes were limited due to the extensive processing and cleaning operations that are necessary to decontaminate plastic wastes. [18–22]. New packaging systems using bioplastics were developed in the last decade as alternatives to traditional polymers due to their renewable nature (raw materials not derived from fossil fuels) and/or their biodegradability. The share of bioplastics in the packaging market is very limited (1%) but it is growing fast with Europe being the largest regional market for bioplastic packaging [2, 23]. Unfortunately, the use of polymers from renewable sources may lead to problems due to the direct and indirect land-use changes of agricultural or forest soils for plant cultivation [24]. On the other hand, the use of biodegradable polymers can lead to problems in the municipal waste stream, due to the impossibility to treat them as organic materials like food wastes, or to insert them in recycling stream of traditional plastics with the consequence that they are often sent to incineration or landfilling [2, 25–27].

A different strategy used to limit plastic waste is the substitution of plastic packaging with paper [28]. Dolci et al. studied the possibility of waste prevention in the delivery system of pasta, cereals and rice comparing the environmental impact of plastic and cardboard packaging with a prevention scenario that considers the use of a "loose packaging" to be filled from gravity bin dispensers [29]. The study, mainly focused on waste prevention, showed that the distribution of loose pasta does not always imply a smaller amount of waste than the one based on single-use packages. Considering that the reported study does not consider paper as alternative packaging material and that no other study investigating the possible substitution of plastic with paper packaging was found in the open literature, this works aims at studying the environmental impact of two different packages for pasta: a traditional plastic packaging (made of polypropylene) and an alternative flexible packaging made of paper. Life Cycle Assessment (LCA) was used to evaluate the potential burden of the two products in the environment, considering the whole life cycle, from extraction of raw materials, to production, use, transports, reuse/recycling and final disposal. Primary data were collected from an Italian producer of pasta that experienced the use of both solutions.

Materials and methods

According to ISO 14040 [30] and 14,044 [31] standards, this LCA analysis has been divided into four different phases: goal and scope definition (Sect. "Goal and scope definition"), inventory analysis (Sect. "Life cycle inventory"), life cycle impact assessment (Sect. "Life cycle impact assessment") and interpretation of the results (Sect. "Discussion"). The SimaPro™ software release 9.5, supplied by Pré Sustainability (Amersfoort, Netherlands), was used for the processing of data.

Goal and scope definition

LCA has been applied to this study to:

- Evaluate the environmental performance of plastic packaging for pasta;
- Compare the environmental impact of plastic packaging with an alternative one made of paper.

System description

This work involves the study of the environmental impact of different packaging solutions: a tight package used for long pasta (spaghetti) and a loose package necessary for short pasta (penne) due to larger air volume inside. The two pasta types are the most common and a traditional plastic packaging is compared with an alternative flexible packaging made of paper. This study, according to the PCR 2019:13 [32], was performed with a so called "cradle to grave" approach, considering the extraction of raw materials, the production process, the filling, distribution and end-of-life. This study was focused on four packages able to contain 500 g of pasta each. The packages involved in the study are listed in Table 1. An example of tight and loose package made of paper is shown in Fig. 1.

Paper and plastic films were purchased in the form of coils, they were then labelled, filled with pasta, sealed and placed within board boxes that are then delivered on wooden pallets. It was estimated that around 3% of the packages are damaged during the filling operations and around 3% of cardboard boxes during the packaging. The sealing process is performed by heat-sealing in the case of plastic packages and through the application of a thin layer of hot-seal coating in the case of paper packaging. Considering that secondary packaging (i.e. board boxes and pallets) are used for the transportation of packages filled with pasta, and considering also that this study refers only to the packaging (see 2.1.2), it was necessary to allocate a fraction of the environmental impact of the electricity

Table 1 Packaging involved in the study

Sample	Material	Type of pasta	Type of package	Packaging mass [g]
1	Plastic	Short	Loose	5.12
2	Paper	Short	Loose	7.30
3	Plastic	Long	Tight	3.61
4	Paper	Long	Tight	5.33

(a) (b)

Fig. 1 Example of the paper package involved in the study: **a** tight packaging for long pasta (i.e. spaghetti) and **b** loose packaging for short pasta (i.e. penne rigate)

consumption in the filling and packaging processes, of secondary packaging and final distribution to the life cycle of packaging and the remaining to the life cycle of pasta. A mass allocation approach was followed, dividing the mass each package by the total mass of pasta + package. In particular, according to the data in Table 1, the following allocation factors were evaluated:

- Loose packaging (short pasta) – plastic: 5.12 g / (500 g + 5.12 g) = 0.01013;
- Loose packaging (short pasta): 7.30 g / (500 g + 7.30 g) = 0.01440;
- Tight packaging (long pasta) – plastic: 3.61 g / (500 g + 3.61 g) = 0.00718;
- Tight packaging (long pasta) – paper: 5.33 g / (500 g + 5.33 g) = 0.01055.

For the presentation of the results, the environmental impacts of the four packages were grouped into different categories to allow a clearer identification of the causes of the impacts:

- Package: includes all the activities related to the package production up to the exit gate of the production factory;
- Electricity: includes the labelling, filling and packaging operations and internal transports of Pastificio Felicetti;
- Transports: includes transports for material supply to—and packages distribution from—Pastificio Felicetti;
- Secondary packaging: includes the materials used for the delivery of filled packages;
- End-of-life: includes all the waste management operations related to primary and secondary packaging and to the packages.

Functional unit

The functional unit of the process was one package able to contain 500 g of pasta, as specified in the PCR 2019-13 [32]. The specific packaging solution was developed by an Italian producer of pasta (Pastificio Felicetti S.p.A., Predazzo (Trento, Italy)) as an alternative to common plastic packages. Around 580,000 tight and loose packages were used during the reference year considered for the study (2019).

System boundaries

The analysis was carried out referring to a "cradle to grave" approach. Therefore, the system boundaries included:

- Upstream processes:
    - Raw materials production (i.e. paper, polypropylene)
    - Primary and secondary packaging production (i.e. cardboard, packaging film, pallet)
- Core processes:
    - Manufacturing of paper and plastic packages
    - Transport of raw materials, components and secondary packaging to the production plant
- Downstream processes:
    - Transport to the filling plant
    - Filling of packages
    - Distribution of pasta packages
    - End of life of: packages, wastes due to filling process, secondary packaging material

Figure 2 shows the main processes included in the system boundaries of the study. The production of pasta and the use phase were excluded because beyond the aim of this work. The processes involved in the allocation process are highlighted.

Cut-off

As reported in the PCR, data for elementary flows to and from the product system contributing to a minimum of 99% of the declared environmental impacts have been included.

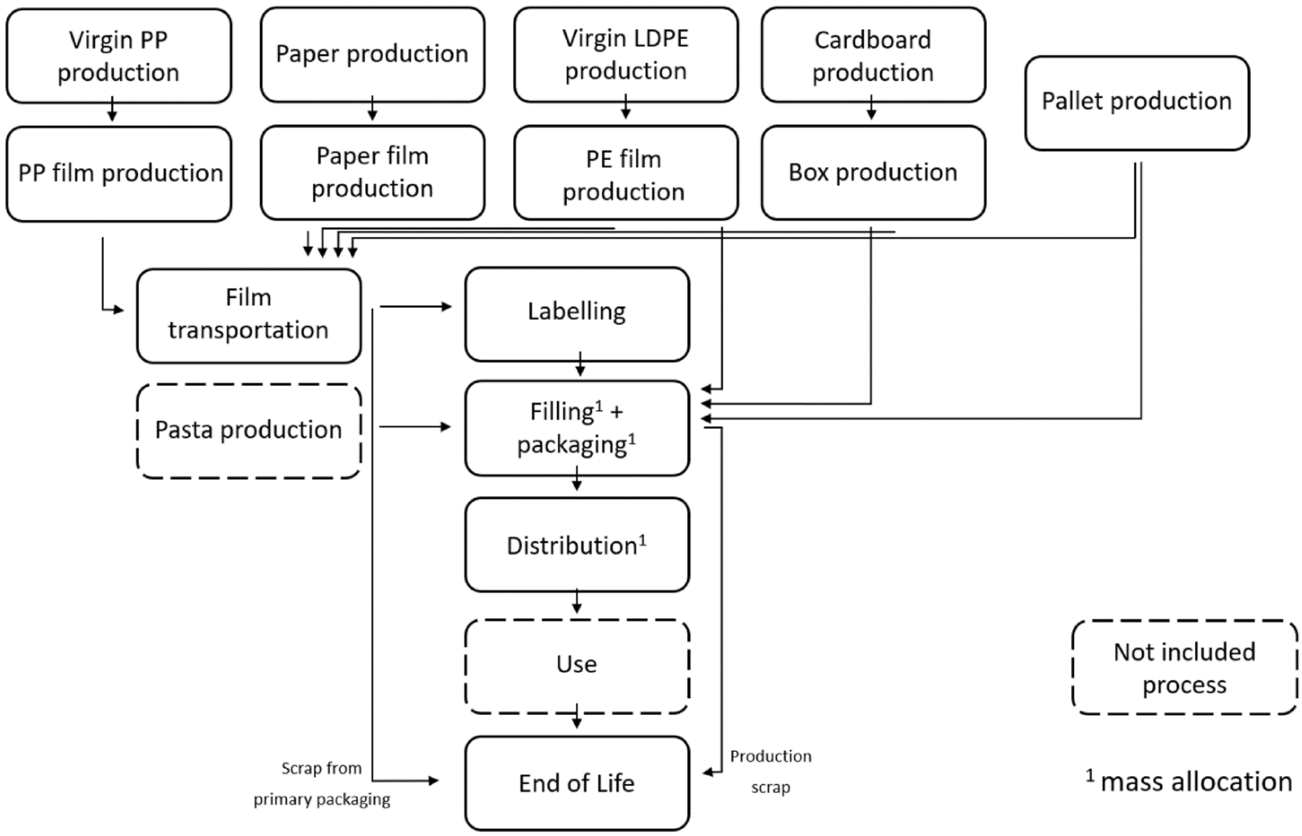

Fig. 2 Main processes included in the system boundaries of the study

Data quality

Data regarding downstream processes were provided by Pastificio Felicetti S.p.A. and were related to the production plants located in Predazzo (Italy). Data are referred to the year 2019. Background data (such as raw material extraction, vehicles, the Italian electricity mix, waste treatments, packaging film production), taken from the Ecoinvent v. 3.9 database (cut-off by classification approach), were used.

Selected impact indicators

The environmental impact assessment has been evaluated using the EPD 2018 method (v1.04) and the following impact indicators were included: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidation (PCO), abiotic depletion potential-elements (AD-E), abiotic depletion potential-fossil fuels (AD-FF), ozone depletion potential (ODP). The specific definition of these impact categories can be found in [33]. The net consumption of fresh water has been evaluated using the Recipe 2016 Midpoint (H) method [34].

Life cycle inventory

This section reports the primary data used to model the processes included in the system boundaries. In particular the inventory of materials used for the packaging, for the final delivery, of the amount of production scrap and primary packaging wastes is listed in Table 2, the inventory of the electricity consumption for labelling, filling and packaging processes, internal transports and distribution phase is presented in Table 3 and the inventory of the end-of-life scenarios applied to the different materials involved in the study is shown in Table 4 [35–37].

Paper and plastic films used for packaging are acquired in form of coils from production plants located in northern Italy and transported by lorry (Euro 5, weight > 32 tons) to the production plant of Felicetti. Packages are then labelled, filled with the specific amount of pasta, sealed and packed for delivery using an automated process. Packages are sealed by thermos welding, this is possible also for paper packages because during the assembly process a thin polymeric coating is applied in the welding area. Electricity from natural gas cogeneration was used to model the electricity consumption in the production plants of Felicetti. According to information provided by the producers of plastic and paper

Table 2 Inventory of the materials used as packaging for pasta, for the related printing process, of the production scrap and primary packaging wastes and of the materials used for the delivery of pasta after the packaging process (secondary packaging)

Packaging material	Input	Ecoinvent input	Amount per package loose packaging [g]	Amount per package tight packaging [g]	Distance (truck) [km]
Plastic	Polypropylene	Packaging film, polypropylene {RER}| market for | cut-off, S	4.91[a]	3.47[a]	250
	Printing ink	Printing ink, offset, without solvent, in 47.5% solution state {RER}| market for | cut-off, S	0.21	0.15	70
	Plastic scrap[b]	See Table 4	0.159	0.110	–
	Board box[c]	See Table 4	0.009	0.003	–
	Wood pallet[c]	See Table 4	0.209	0.140	–
	Board box[d]	Corrugated board box {RER}| market for | cut-off, S	33.1	15.4	114
	Wood pallet[d]	EUR-flat pallet {RER}| market for | cut-off, S	46.3	12.3	81
Paper	Paper	Kraft paper {RER}| market for | cut-off, S	6.54[a]	4.76[a]	650
	Hot-sealing coating	Ethylene vinyl acetate varnish, market for | cut-off, S	0.25	0.20	198
	Printing ink	Printing ink, offset, without solvent, in 47.5% solution state {RER}| market for | cut-off, S	0.51	0.37	220
	Paper scrap[b]	See table 4	0.220	0.160	–
	Board box[c]	See table 4	0.013	0.005	–
	Wood pallet[c]	See table 4	0.290	0.210	–
	Board box[d]	Corrugated board box {RER}| market for | cut-off, S	33.1	15.4	114
	Wood pallet[d]	EUR-flat pallet {RER}| market for | cut-off, S	46.3	12.3	81

[a]Gross mass including the plastic scrap from the packaging process

[b]Scrap from the packaging process

[c]Primary packaging wastes

[d]Secondary packaging used for the delivery of pasta

films, the Italian electricity mix was used. The Ecoinvent processes (*Packaging film, polypropylene {RER} | market for* and *Kraft paper {RER}| market for*) were modified accordingly. The distribution phase was modelled using real distribution data provided by Felicetti and considered the use of freight lorries Euro 5 of medium size (weight 16–32 ton) and a transoceanic ship for water transports. To allow a proper comparison between different packages, the distribution of the same amount of pasta to the same custumers was assumed. Since the main market for pasta Felicetti is Europe, European statistics have been applied to model the end-of-life scenarios of the packaging. Data for all waste and wastewater treatments have been sourced from the Ecoinvent v3.9 database. A distance of 50 km has been assumed for the transportation of wastes to the collection centre using a municipal collection service truck (weight 21 ton).

Results and discussion

Life cycle impact assessment

The absolute values of the environmental impact of loose packages, as well as the contribution of each stage considered within the analysis, are presented in Table 5 and in Fig. 2a, b. Observing these results it is possible to notice that the use of paper instead of plastic allows a reduction of the environmental impact of packages for some impact categories and an increase for others. In particular, the values are lower for the categories GWP, AD-E, AD-FF and water use while it is higher for the others. The lower values of the paper package in the abovementioned impact categories are mainly related to the high contribution of polypropylene production (due to its fossil origin) to AP, GWP, PCO, AD-FF. On the other hand, the production process of paper involves the use of sodium hydroxide (ODP) and requires the disposal of high amounts of ashes from the sludges of the production process (EP). Moreover, the benefits of using paper instead of plastic are limited by the fact that the paper package has to be thicker to reach satisfactory mechanical properties (i.e. higher mass) and by the lower filling speed that can be reached using paper, with a consequently higher electricity consumption (see Table 3). The **Carbon Footprint** indicator, corresponding to the impact category Global Warming Potential (GWP), is equal to 0.021 kg CO_2 eq for one plastic package and 0.014 kg CO_2 eq for one paper package, with a relative reduction of around 33%.

Table 3 Inventory of the electricity inputs for the printing process of packages, filling and packaging processes, for internal transports and the distribution phase

Input		Ecoinvent input	Amount per package short pasta Loose packaging	Amount per package long pasta Tight packaging
Plastic film	Package labelling [Wh]	Electricity, low voltage {IT}| market for electricity, low voltage | cut-off, S	3.22	2.19
	Filling + packaging [mWh]	Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 160 kW electrical, lambda = 1 | cut-off, S	14.5	7.1
	Internal transports [mWh]	Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 160 kW electrical, lambda = 1 | cut-off, S	19.2	7.3
	Final distribution – truck [ton*km]	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}| market for | cut-off, S	8.4	4.2
	Final distribution – ship [ton*km]	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | cut-off, S	5.2	2.6
Paper film	Package labelling [Wh]	Electricity, low voltage {IT}| market for electricity, low voltage | cut-off, S	4.12	3.12
	Filling + packaging [mWh]	Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 160 kW electrical, lambda = 1 | cut-off, S	33.5	19.6
	Internal transports [mWh]	Electricity, low voltage {Europe without Switzerland}| heat and power co-generation, natural gas, 160 kW electrical, lambda = 1 | cut-off, S	38.4	17.6
	Final distribution – truck [ton*km]	Transport, freight, lorry 16–32 metric ton, EURO5 {RER}| market for | cut-off, S	11.7	4.5
	Final distribution – ship [ton*km]	Transport, freight, sea, ferry {GLO}| market for transport, freight, sea, ferry | cut-off, S	7.3	2.8

Table 4 Inventory data of the end-of-life scenarios applied to each material

Material	Landfilling [%]	Incineration [%]	Recycling [%]	Reuse [%]	Source
Plastic (post-consumer resin)	24.9	42.6	32.5	–	[33]
Paper and cardboard	–	26.1	73.9	–	[34]
Pallet	2.0	5.7	80.0	12.3	[35]

As it is possible to observe from Fig. 3a, b the main contribution to the overall environmental impact comes from the package production of both plastic and paper packages. Minor contributions derive from the transport operations, electricity consumption and from end-of-life management. The secondary packaging has an almost negligible environmental impact for all categories. Comparing plastic and paper packages is possible to observe a substantial increase, in the case of paper packages, of the environmental impact of transports: this result is caused by the higher mass of paper package with respect to plastic one (5.3 g vs 3.6 g).

The absolute values of the environmental impact of tight packages, as well as the contribution of each stage considered within the analysis, are presented in Table 6 and in Fig. 4a–b. It is immediately clear that the tight packaging allows a reduction of the environmental impact with respect to the loose packaging due to the lower volume occupied by long pasta (spaghetti) that reduces the mass of packaging material, the mass of secondary packaging, the weight to be transported and to increase the speed of the filling process with lower electricity consumption, as reported in Tables 2, 3, 4. Generally speaking, the results follow the same trend already described in the case of loose packaging. The use of paper instead of plastic allows a reduction of the environmental impact of packages for the impact categories in which the contribution

Table 5 Life cycle impact assessment for loose plastic and paper packaging

Impact category	Unit	LCIA results		
		Loose packaging		Difference (%)
		Plastic	Paper	
AP	kg SO_2 eq	8.36E−05	8.66E−05	3.6
EP	kg PO_4^{3-} eq	1.98E−05	5.71E−05	187.8
GWP	kg CO_2 eq	2.10E−02	1.41E−02	−32.8
PCO	kg NMVOC	8.49E−05	8.81E−05	3.8
AD-E	kg Sb eq	8.04E−08	6.47E−08	−19.6
AD-FF	MJ	4.74E−01	1.71E−01	−63.9
ODP	kg CFC^{-11} eq	5.01E−10	1.01E−09	101.5
Water use	m^3	1.93E−04	1.81E−04	−6.1

of polypropylene is high: GWP, AD-E and AD-FF. On the other hand, the contribution of paper is higher in the category ODP for the use of sodium hydroxide (ODP) and EP due to the the disposal of high amounts of ashes from the sludges of the production process. The **Carbon Footprint** indicator, corresponding to the impact category Global Warming Potential (GWP), is equal to 0.014 kg CO_2 eq for one plastic package and 0.0091 kg CO_2 eq for one paper package, with a relative reduction of around 37%. From Fig. 3a, b, it can be noticed that, similarly to loose packaging, the main contribution to the overall environmental impact comes from the package production both plastic and paper package. Minor contributions derive from the transport operations, electricity consumption and from the end-of-life management. The use of secondary packaging is almost negligible. The higher mass of the paper package leads, also in this case, to a higher contribution of transports and electricity with respect to the plastic one at expenses of the impact of raw materials.

From the comparison of the four products (taking the plastic loose package for short pasta as reference), shown in Fig. 5, it can be appreciated the environmental difference between loose and tight packages. In particular, it can be noticed a reduction for all the impact categories of around 25–30%, both considering plastic and paper package. Regarding the comparison between plastic and paper, it can be seen that paper allows considerable reductions only for two impact categories (GWP, AD-FF), while for impact categories EP and ODP much higher impacts can be observed.

Table 6 Life cycle impact assessment for tight plastic and paper packaging

Impact category	UNIT	LCIA results		
		Tight packaging		Difference (%)
		Plastic	Paper	
AP	kg SO_2 eq	5.47E−05	5.30E−05	−3.2
EP	kg PO_4^{3-} eq	1.32E−05	3.98E−05	202.3
GWP	kg CO_2 eq	1.44E−02	9.08E−03	−36.7
PCO	kg NMVOC	5.55E−05	5.28E−05	−4.9
AD-E	kg Sb eq	5.53E−08	4.45E−08	−19.4
AD-FF	MJ	3.29E−01	1.09E−01	−66.9
ODP	kg CFC^{-11} eq	3.46E−10	7.08E−10	105.0
Water use	m^3	1.33E−04	1.29E−04	−3.1

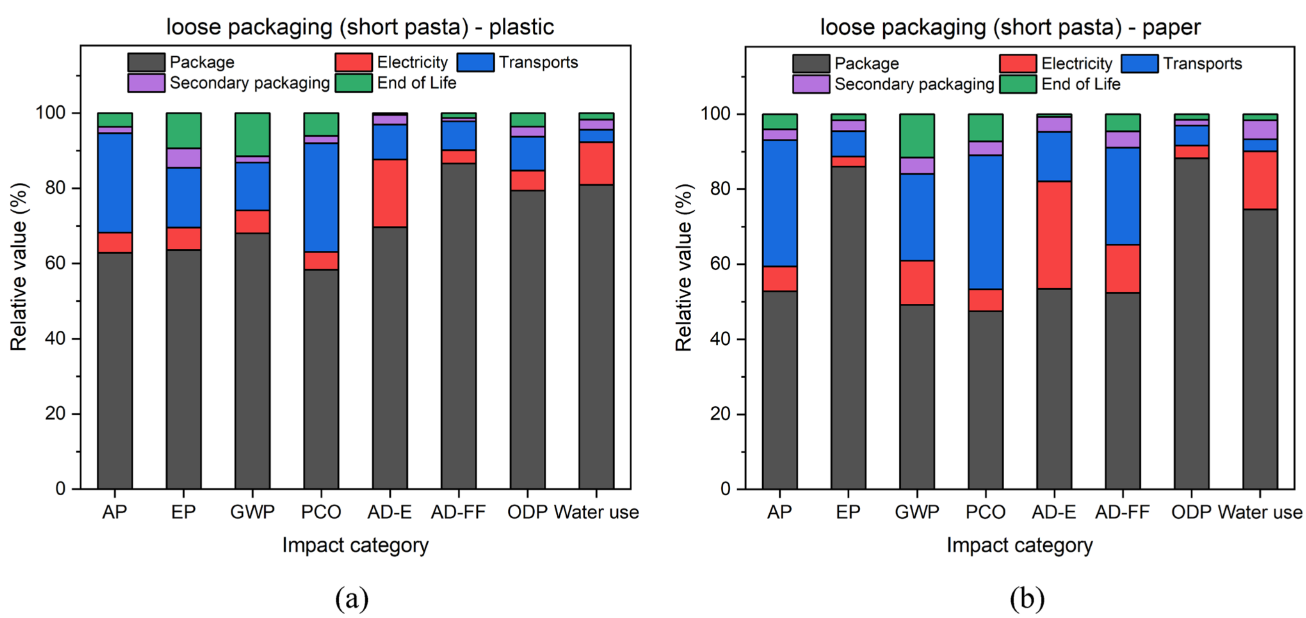

Fig. 3 Contribution of each process/material to the environmental impact of loose packaging for short pasta made of **a** plastic and **b** paper

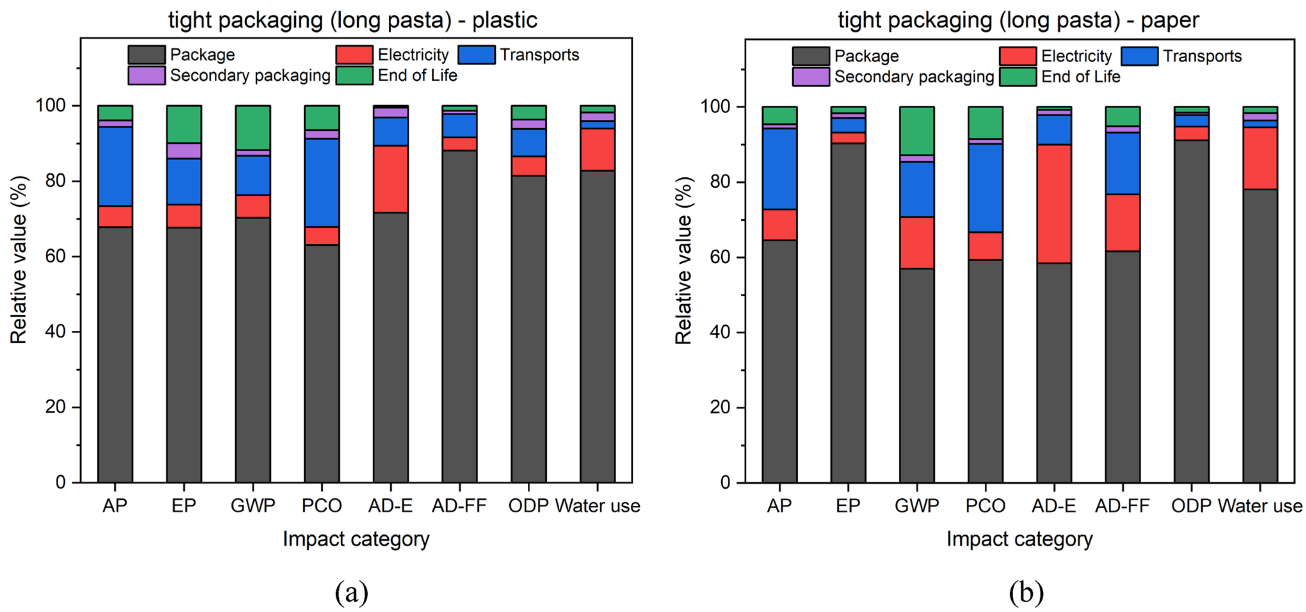

Fig. 4 Contribution of each process/material to the environmental impact of tight packaging for long pasta made of **a** plastic and **b** paper

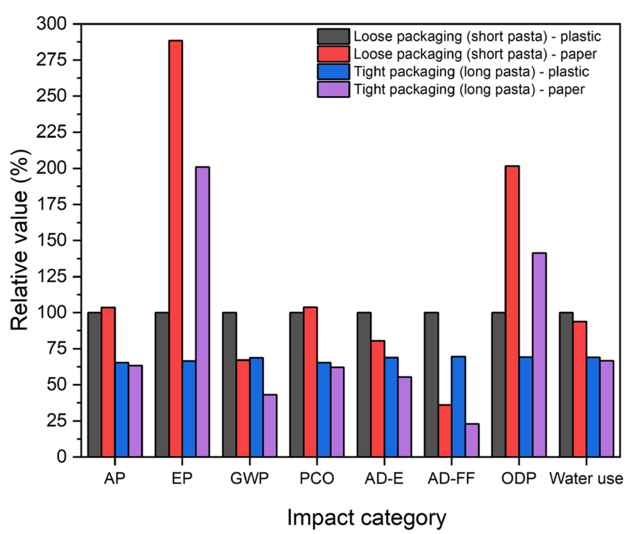

Fig. 5 Comparison between the environmental impact of the loose plastic package for short pasta (taken as reference) and the other packaging solutions

Sensitivity analysis

A sensitivity analysis was performed changing some of the assumptions adopted in the model of the four products:

- Raw materials;
- Production of electricity used for packaging manufacturing.

The sensitivity analysis was performed on all the four products involved in the study.

Raw materials

The contribution of raw materials (paper and plastic) for the manufacturing process of packages resulted higher than 50% for all the packaging solutions. In the sensitivity analysis, it was assumed that the materials used for the package production had a recycled content of 15 wt%. Specific processes for plastic and paper films were created in Simapro using inventory data from Ecoinvent 3.9.

Compared to the standard process that uses virgin materials for the production of packaging films, the use of materials with a partial substitution of virgin material with recycled one (15 wt%), allow a reduction of the environmental burdens for all the indicators (Tables 7, 8). Both for loose and tight packaging, the Carbon Footprint is reduced by 9% in the case of plastic and around 5% in the case of paper.

Production of electricity used for packaging manufacturing

The contribution of electricity consumption for the manufacturing process of packages resulted up to 10% in the case of paper packages and around 4% in the case of plastic ones. In the sensitivity analysis, the electricity was assumed to be produced according to the expected energy mix of Italy in 2050: photovoltaic 48%, wind 28%, hydropower 7%, geothermal 3%, nuclear 7.5%, natural gas 5%, energy recovery from wastes 1.5% [38, 39]. A specific process was created in Simapro using inventory data from Ecoinvent 3.9.

Compared to the standard process that uses the current Italian energy mix, the use of a decarbonized energy mix with a high share of renewable resources (such as the one forecasted for Italy in 2050), allow a reduction of the environmental burdens for all the indicators (Tables 9, 10). In this case, the reduction is more limited due to the limited energy consumption involved in the manufacturing process of the packages. Both for loose and tight packaging, the Carbon Footprint is reduced by 2% in the case of plastic and of around 4% in the case of paper.

Table 7 Life cycle impact assessment of the loose packaging: comparison between the use of virgin and partially recycled material for the film production

Impact category	Unit	Loose packaging—plastic			Loose packaging—paper		
		Virgin film	15% recycled content	Δ %	Virgin film	15% recycled content	Δ %
AP	kg SO_2 eq	8.36E−05	7.61E−05	−8.9	8.66E−05	8.26E−05	−4.6
EP	kg PO_4^{3-} eq	1.98E−05	1.87E−05	−5.4	5.71E−05	5.07E−05	−11.2
GWP	kg CO_2 eq	2.10E−02	1.91E−02	−9.0	1.41E−02	1.34E−02	−4.8
PCO	kg NMVOC	8.49E−05	7.74E−05	−8.9	8.81E−05	8.33E−05	−5.4
AD-E	kg Sb eq	8.04E−08	7.26E−08	−9.7	6.47E−08	6.21E−08	−4.1
AD-FF	MJ	4.74E−01	4.17E−01	−12.0	1.71E−01	1.64E−01	−4.4
ODP	kg CFC^{-11} eq	5.01E−10	4.65E−10	−7.2	1.01E−09	9.99E−10	−1.1
Water use	m^3	1.93E−04	1.72E−04	−11.0	1.81E−04	1.67E−04	−7.9

Table 8 Life cycle impact assessment of the tight packaging: comparison between the use of virgin and partially recycled material for the film production

Impact category	Unit	Tight packaging—plastic			Tight packaging—paper		
		Virgin film	15% recycled content	Δ %	Virgin film	15% recycled content	Δ %
AP	kg SO_2 eq	5.47E−05	4.96E−05	−9.2	5.30E−05	5.00E−05	−5.6
EP	kg PO_4^{3-} eq	1.32E−05	1.24E−05	−5.9	3.98E−05	3.52E−05	−11.6
GWP	kg CO_2 eq	1.44E−02	1.31E−02	−9.1	9.08E−03	8.58E−03	−5.5
PCO	kg NMVOC	5.55E−05	5.06E−05	−8.8	5.28E−05	4.93E−05	−6.6
AD-E	kg Sb eq	5.53E−08	4.98E−08	−10.0	4.45E−08	4.27E−08	−3.9
AD-FF	MJ	3.29E−01	2.89E−01	−12.3	1.09E−01	1.04E−01	−4.8
ODP	kg CFC^{-11} eq	3.46E−10	3.21E−10	−7.3	7.08E−10	7.00E−10	−1.1
Water use	m^3	1.33E−04	1.18E−04	−11.1	1.29E−04	1.19E−04	−7.9

Table 9 Life cycle impact assessment of the loose packaging: comparison between the use of the current energy mix and the expected decarbonized energy mix for 2050 in Italy

Impact category	Unit	Loose packaging—plastic			Loose packaging—paper		
		Italian grid 2019	Italian grid 2050	Δ %	Italian grid 2019	Italian grid 2050	Δ %
AP	kg SO_2 eq	8.36E−05	8.30E−05	−0.7	8.66E−05	8.58E−05	−0.9
EP	kg PO_4^{3-} eq	1.98E−05	1.99E−05	0.3	5.71E−05	5.72E−05	0.1
GWP	kg CO_2 eq	2.10E−02	2.05E−02	−2.2	1.41E−02	1.35E−02	−4.1
PCO	kg NMVOC	8.49E−05	8.38E−05	−1.3	8.81E−05	8.67E−05	−1.6
AD-E	kg Sb eq	8.04E−08	8.30E−08	3.3	6.47E−08	6.80E−08	5.2
AD-FF	MJ	4.74E−01	4.67E−01	−1.5	1.71E−01	1.62E−01	−5.3
ODP	kg CFC^{-11} eq	5.01E−10	4.93E−10	−1.5	1.01E−09	1.00E−09	−1.0
Water use	m^3	1.93E−04	1.90E−04	−1.7	1.81E−04	1.77E−04	−2.3

Table 10 Life cycle impact assessment of the tight packaging: comparison between the use of the current energy mix and the expected decarbonized energy mix for 2050 in Italy

Impact category	Unit	Tight packaging—plastic			Tight packaging—paper		
		Italian grid 2019	Italian grid 2050	Δ %	Italian grid 2019	Italian grid 2050	Δ %
AP	kg SO_2 eq	5.47E−05	5.43E−05	−0.8	5.30E−05	5.24E−05	−1.1
EP	kg PO_4^{3-} eq	1.32E−05	1.32E−05	0.3	3.98E−05	3.99E−05	0.1
GWP	kg CO_2 eq	1.44E−02	1.41E−02	−2.1	9.08E−03	8.64E−03	−4.9
PCO	kg NMVOC	5.55E−05	5.48E−05	−1.3	5.28E−05	5.18E−05	−2.0
AD-E	kg Sb eq	5.53E−08	5.71E−08	3.2	4.45E−08	4.70E−08	5.7
AD-FF	MJ	3.29E−01	3.24E−01	−1.4	1.09E−01	1.02E−01	−6.3
ODP	kg CFC^{-11} eq	3.46E−10	3.41E−10	−1.5	7.08E−10	7.01E−10	−1.0
Water use	m^3	1.33E−04	1.31E−04	−1.6	1.29E−04	1.26E−04	−2.4

Discussion

From this study, it is clear that a significant reduction of the environmental impact of food packaging solutions cannot be performed by simply replacing plastic with paper, due to the different properties of these two materials that involve multiple differences along the supply chain. In particular paper, even though obtained from natural sources, is characterized by lower mechanical properties with respect to plastic with the consequent need to increase the thickness (and therefore the mass) of the material used for the same purpose. A considerable reduction of the environmental impact of the products can be obtained, as shown in the sensitivity analysis, with the partial substitution of virgin material with recycled one and with the use of a decarbonized energy grid. However, it is important to point out that the products compared in this study have exactly the same function (to contain 500 g of pasta), with the same performances in terms of product durability, protection and shelf life. These conditions, verified by the producer of pasta, were the basis for the choice of switching from plastic to paper packaging. It should be also considered that, in the next years, the improvement of the recycling techniques of plastic waste may lead to much higher recycling rates with a substantial reduction of the environmental impact of plastic. Very interestingly (but not surprisingly), the first objective that should be pursued to decrease the environmental impact of packaging, is the reduction of the volume of the transported material. In this study, the simple change of pasta shape, from short to long, allows an environmental impact reduction related to packaging (from loose to tight) of around 30% in each impact category. From the perspective of the Circular Economy Action Plan promoted by the EU within the European Green Deal, it seems essential the implementation of sorting and recycling strategies for plastic, on one side, and the improvement of technologies able to produce high-performing paper products, minimizing thus limitations and technological issues (e.g. the lower speed of the filling process), on the other side [40–42]. Finally, it should be also considered that the environmental impact of packaging represents only a small fraction (1–2%) of the entire life cycle of pasta and, therefore, any effort oriented to the reduction of environmental impacts should necessarily involve other life cycle stages such as preparation (cooking), final transportation, and primary production [43].

Conclusions

In this study, the environmental impact of loose and tight plastic packages for short and long pasta was compared with that of paper packages used as alternatives materials through the LCA technique. The comparative analysis of plastic and paper packages shows that their environmental impact is mainly caused by the extraction and manufacturing of raw materials, followed by transport and end-of-life operations. The use of paper instead of plastic allows a reduction of the environmental impact in some impact categories (GWP, AD-E and AD-FF) while an increase is observed in others (EP, ODP) due to the larger mass of the paper package. In the case of loose packaging, the **Carbon Footprint** indicator, corresponding to the impact category Global Warming Potential (GWP), is equal to 0.021 kg CO_2 eq for one plastic package and 0.014 kg CO_2 eq for one paper pocket, with a relative reduction of around 32%. Referring to the annual production of around 290,000 packages for short pasta and 290,000 for long pasta, the replacement of traditional plastic with paper would result in a reduction of around 2030 kg of CO_2 eq emissions and of 88 GJ of used fossil resources. In the case of tight packaging for long pasta, it is 0.0144 kg CO_2 eq for one plastic package and 0.0091 kg CO_2 eq for one paper pocket, with a relative decrease of around 37%. Moreover, a comparison between tight and loose packages for long and short pasta highlights a reduction of around

30% in all the considered impact categories, regardless of the material used for the packaging, due to the lower volume occupied by long pasta. This shows that for this kind of products the design oriented to the minimization of material use plays a more relevant role with respect to the substitution of plastic materials with alternative ones.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors declare that they have no conflict of interest.

Ethical approval All the authors have read and understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors.

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