Journal of Cleaner Production 519 (2025) 145951

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

LCA exercise on different packages for cherry tomatoes. Effect of considering packaging performance regarding air ventilation

Inês Pinto Mota [a], Ana Neto Carneiro [a], Paula Quinteiro [b], Giancarlo Colelli [c], Fátima Poças [a,d,*]

[a] Universidade Católica Portuguesa, CBQF Centro de Biotecnologia e Química Fina-Laboratório Associado, Escola Superior de Biotecnologia, Rua Diogo Botelho 1327, 4169-005, Porto, Portugal

[b] Centre for Environmental and Marine Studies (CESAM), Department of Environment and Planning, University of Aveiro, Campus Universitário de Santiago, 3810-193, Aveiro, Portugal

[c] Department of the Science of Agriculture, Food and Environment, University of Foggia, Foggia, Italy

[d] CINATE – Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Portugal

ARTICLE INFO

Keywords:
LCA
Cellulosic based packaging
PET trays
Tomato cherry
End-of-life

1. Introduction

Packaging is fundamental for food protection and conservation, contributing to the safety, quality, traceability, logistics, handling and consumption of convenience of foods (Wikström et al., 2019; Lindh et al., 2016; Poças et al., 2010). Packaging encompasses a set of functions of protection, preservation, communication and service, and impacts different aspects that need to be considered. Besides the direct environmental impacts, due to the different materials and energy inputs and correspondent outputs and emissions, when comparing different packaging systems for a specific product, consumer behaviour and the packaging performance need to be integrated.

Food waste in the EU is estimated at approximately 180 kg per person per year. Current measures aim to reduce food waste by 30 % by 2025 and 50 % by 2030, compared to the 2014 baseline (EU, 2024). It is recognised that packaging can prevent food waste along the supply chain which represents a negative impact on the environment (Dörnyei et al., 2023). Packaging can offer a significant opportunity to lower the overall environmental impact of products, and its integration in foods life cycle models have been recognised for a long time (Wikström and Williams, 2010). Therefore, the importance of shelf-life in reducing food waste and, consequently, in the environmental effects of the packaging system needs to be analysed and incorporated into environmental assessments for food packaging (Casson et al., 2022).

Packaging also has an environmental cost, and the waste generated from packaging significantly influences the environmental impact of packaged foods (Sasaki et al., 2023; Sazdovski et al., 2021). Mandatory packaging essential requirements to reduce overpackaging and packaging waste, besides promoting circulability are laid down in the (PPWR) Packaging and Packaging Waste Regulation under discussion (Poças and Selbourne, 2023; EU, 2025). Therefore, the balance between over- and underpackaging, i.e., the breakeven between the reduction of food loss versus increasing the impacts due to alternative packaging, should be based on sound methodologies. Life Cycle Assessment (LCA) is one of the methodologies mostly used to study the impact of different packaging solutions. However, still few LCA studies consider the effect of shelf-life on the overall environmental performance of food packaging systems (Frigerio et al., 2023).

Considering only the packaging life cycle or considering the potential food waste effects result in different best environmentally performing packaging. For instance, when comparing different systems for beef (Casson et al., 2022) and raspberries (Frigerio et al., 2023) the

* Corresponding author. Universidade Católica Portuguesa, CBQF Centro de Biotecnologia e Química Fina-Laboratório Associado, Escola Superior de Biotecnologia, Rua Diogo Botelho 1327, 4169-005, Porto, Portugal.

E-mail address: fpocas@ucp.pt (F. Poças).

https://doi.org/10.1016/j.jclepro.2025.145951
Received 11 October 2024; Received in revised form 26 May 2025; Accepted 6 June 2025
Available online 19 June 2025

relationship between shelf-life and potential food waste was empirically modelled by establishing a ratio between the shelf-life provided by the reference package and the shelf-life of the alternatives considered in the study, using food waste data from the market and a probability function proposed by Conte et al. (2015). The packaging system providing the longest product shelf-life represented the lowest impact in many environmental impact categories. However, the relationship between shelf-life and waste is complex and it does not depend only on the packaging material but also on other factors, such as growing and handling treatments and temperature. A study on the baby leaf spinach using two packaging options (oriented polypropylene (OPP) and polylactic acid (PLA)), considering the product waste, showed higher impacts for the longer shelf-life (Lin et al., 2024).

Consumer behaviour is also a key aspect when targeting the reduction of packaging waste due to their consumption preferences and post-use behaviour, namely the integration in collection schemes and sorting (Poças and do Céu Selbourne, 2023). A lack of knowledge about the environmental impact of specific product attributes among consumers is recognised and a comparison with results from LCAs shows that consumers have difficulties in correctly assessing the environmental impact of packaging material (Bock and Meyerding, 2023). Additionally, consumer behaviour patterns relative to product storage and consumption and attitude facing shelf-life and expiration date have also been integrated as scenario analyses in LCA studies, as they influence the waste and packaging disposal data (Yokokawa et al., 2018).

Fresh fruits and vegetables are highly perishable products and the contribution of the packaging to the overall product's environmental impact is between 11 % and 31 % (Qin and Horvath, 2022). The packaging for these products presents several specific technical requirements, such as mechanical protection, resistance under high humidity and gas perforation. Decay indexes have been integrated in LCA studies addressing packaging for fresh fruits and vegetables, in a few works. Sasaki et al. (2022) studied four packaging systems for strawberries with different cushioning conditions, impacting in product damage area ratio caused by vibration during transportation. A connection was established between the damaged fruit area ratio and the environmental impact for climate change. The findings reveal that environmental loads for this impact, resource consumption (RC), and urban air pollution (UAP) decreased by up to 50.4 %, 36.3 %, and 53.3 %, respectively, when strawberries were packaged. This highlights that packaging can help reduce food losses during transport, lowering the environmental impact of strawberry supply and avoiding the need for increased production to make up for losses. In a different study, fruit attributes (firmness, soluble solids concentration and softness) before and after the distribution simulation were used to grade peaches and to compare the protective performance of six packaging systems. The physical performance was integrated into the LCA of each package system. It was concluded that a reduction in material use and change in format (changing foam sheets to foam netting), provides for sufficient peach protection while reducing environmental and economic impact (Lytle et al., 2024). Functionalised packages, such as modified atmosphere packaging, antimicrobial, antioxidant and intelligent packaging are good examples where the trade-off analysis is fundamental. Although with higher impact, these systems may provide for lower overall life cycles impact when compared to conventional packaging (Yokokawa et al., 2018; Settier-Ramirez et al., 2022). Fresh-cut salads packaged in an active system incorporating oregano essential oil showed a longer shelf-life with reduced waste as compared to the conventional packaging (Villanova-Estors et al., 2023). Despite of the increased environmental loads for packaging production, modified atmosphere packaging reduced the overall load of spinach supply chain because of waste reduction, compared to polypropylene packaging (Sasaki et al., 2024).

A scoping review of food packaging life cycle assessments that account for packaging-related food waste was recently published elsewhere, indicating that such LCAs are limited in the literature. Most of the LCAs studies focused on food categories associated with high environmental impacts such as animal-based products (meat and dairy) and highly perishable products (fresh fruits and vegetables) and plastic was the most frequently evaluated packaging material. The review highlighted a need for greater attention to food waste across more food categories in future food packaging LCAs and to considering more in deep packaging attributes relevant to different food product categories (Hemachandra et al., 2024), as well as different materials and not only plastics. This latter aspect is mostly relevant, given the present global trend to replace plastic packaging by other materials. Most of fruits and vegetables packaging LCA studies address reusable versus recyclable (Accorsi et al., 2022; (Espinoza-Orias and Lundquist, 2025) Yadav et al., 2024), bulk transportation and not primary packaging (Rasines et al., 2024; Oliver-Villanueva et al., 2025), bioplastics (Bishop et al., 2021). The impact of domestic storage conditions (consumer behaviour) was addressed for broccoli (Rasines et al., 2023). For tomato, studies have focused on processed rather than on the fresh product, given the relevant levels of energy consumption (Bock and Meyerding, 2023; Eslami et al., 2025).

There is a gap in the literature on studies addressing: (1) the whole and complete packaging system, both the primary and secondary packaging, accounting for the impacts in the product pre-filling and post-filling stages, as well as end-of-life methods; (2) the different performance regarding the product weight loss due to packaging materials and configurations that affect quality and the economic value at purchase; (3) the effect of new PPWR target rates on the environmental impacts. To explore these aspects a combined approach using comparative LCA and experimental data was applied; Furthermore, specific data were collected in packaging converters and tomato fillers for processes not readily available in the usual databases.

The present study compared five packaging solutions for cherry tomatoes, used in the Portuguese market, about their environmental impacts throughout the life cycle, considering the full packaging system: the primary package, the transport packaging (used to transport the primary packages before filling) and the secondary and tertiary packaging (used to transport the primary packages after tomato filling). Real transport scenarios were applied, and specific operations of converting packaging materials (plastic film perforation and paperboard cup production) were based on data collected from industries. Actual rates for different end-of-life (EoL) approaches were supplied by the municipality waste managing association. The impact of implementation of the new PPWR targets was assessed. Finally, the impact of performance of primary packages regarding tomato moisture loss was studied based on experimental laboratory data. The effect of normalising the package perforation area on the environmental impact categories was studied. The objective was to compare from the environmental perspective the most common packaging systems used in the Portuguese retail and provide information for decisions regarding the package selection.

2. Material and methods

The study followed a packaging cradle-to-grave approach and was conducted according to ISO 14040:2021 and ISO 14044:2021 (ISO, 2021a,b). The data was collected from June 2023 to January 2024.

2.1. Packages selected, functional unit and system boundaries

The functional unit (FU) – the quantified performance of a product system for use as a reference, according to ISO 14040 and 14 044 (ISO, 2021a and 2021b) for the packaged product is defined based on the delivery of one consumed unit and not one produced unit. Therefore, the different packages' performance is accounted as a function of the amount of produced food considered for the whole system's life cycle (Frigerio et al., 2023; Yokokawa et al., 2018). For the present study, the FU was defined as the primary packaging unit for 250 g of fresh cherry tomatoes, the net weight most common in the market considering the package characteristics presented in Table 1.

Several packages of cherry tomatoes were collected from medium and large retailers in the north of Portugal. The packages were characterised, regarding material and type of closing system. A selection of the market most representative five packages was considered, as shown in Fig. 1:

(1) Thermoformed clamshell made of polyethylene terephthalate (PET).
(2) Thermoformed tray made of PET with a horizontally formed flow-pack of biaxially oriented polypropylene (OPP).
(3) Cup made from polyethylene-coated paperboard with a thermoformed lid made of PET.
(4) Tray made of paperboard with a horizontally formed flow-pack of OPP.
(5) Tray made of corrugated board with a horizontally formed flow-pack of OPP.

The horizontally formed flow-pack will be called as bag in the following text for simplicity.

The packages were further characterised in detail (Table 1). The thickness, weight, material composition, the perforation area and the material grammage were determined experimentally. The thickness and the perforation area were measured respectively with a micrometer and a calliper (Mitutoyo Corporation) and the weight of each empty package was determined with a balance (XS205 Dual Range, Mettler Toledo). The identification of the different plastics was performed by (FTIR) Fourier-transform infrared spectroscopy (spectrum100, PerkinElmer).

Fig. 2 presents the system boundaries, encompassing the production and transport of the raw materials for each primary package, secondary (corrugated board tray) and tertiary packaging (stretch film for palettizing), the production or conversion into trays, lids and films accordingly, the tomato filling, closing and grouping operations (which depend on the package) and retailing. After domestic consumption, the packages are collected and transported to a sorting centre. The different sorted streams are forwarded for their specific end-of-life (EoL) processes. The potential tomato waste generated throughout the supply chain was considered the same among the different packages under study. Tomatoes are offered for sale before the skin starts to shrivel which occur at much longer periods of time. However, the tomato loses weight through dehydration, because of the moisture barrier of the different packages. The weight loss at the selling data does not typically correspond to a visible quality change but corresponds to an economic value loss (less weight int the package). Therefore, weight loss was considered in the study and was determined experimentally as described in section 2.3. The transports considered were: to the empty primary packaging production/conversion stakeholders, to the tomato filler, to the distributor and retailer and to the EoL treatment.

Tomato production was excluded because the aim of the study was to compare the environmental impacts of packaging and not the packaged product, also cherry tomato production is the same for all scenarios, regardless of the packaging material. The relative contribution of packaging in the overall chain of fresh tomato commercialization has already been addressed elsewhere (Qin and Horvath, 2022; Torres Pineda et al., 2021). In the present study, the tomato production, transportation and treatment up to the packaging operation, including the infrastructures are all the same for the different packages under study. Only the packaging machines and respective operations are different. These variables were considered and respective data were collected. The transport of workers and equipment were also excluded, as well as the production of capital goods (buildings and equipment) since it is expected that the contribution of the excluded processes to the overall environmental impacts is most likely minimal (Quinteiro et al., 2022).

Packaging labels were excluded from the system limits due to a lack of data and because in all cases they have a very insignificant weight compared to the overall package weight, below 5 % (Table S1). In the case of the cup made from PE-coated paperboard it is a printed label, which was also not considered for coherence across the systems studied. The transport of the transport packaging to primary package production/conversion and the transport of secondary and tertiary packaging to the packaging filler were not considered because these transports are the same for all packaging systems. The wooden pallets were not included in the modelling because of the following reasons: the lifespan of a pallet is relatively long; pallets are reused several times and the environmental impact attributed to each cycle would be relatively small compared to boxes and stretch film, which are discarded after the single use; data on their origin, reuse rate, hygienic treatments were not readily available and it would be difficult to model them accurately in the context of the study.

2.2. System description (primary, secondary and packaging for transport)

The primary packages under study (Fig. 1) are following described: A) clamshell, tray and lid for packages 1, 2 and 3; B) bag for packages 2, 4 and 5, and C) cup for package 3. D) Production of tray for packages 4 and 5. Fig. S1 shows the flowchart of the production for these packages.

A) Clamshell (package 1), tray (package 2) and lid for package 3

PET and rPET granules are subjected to an extrusion process to form a sheet. This sheet is then thermoformed into clamshells, trays and lids. These components are packed (transportation packaging) and delivered to the tomato filling unit (Fig. S1A).

The filling operation for packages 1 and 2 is manual by the operator, while for package 3 is automatic. The closing operation is manual for packages 1 and 3. Package 2 is closed automatically by a bag-closing system. All these packages are, after filled, placed in secondary and tertiary packaging followed by transportation to the distributor (warehouse), then to the retailer and the final consumer.

B) Bag for packages 2, 4 and 5

The film of the bag is produced by the extrusion of PP pellets. The film has perforations to allow for ventilation required by the tomato respiration and transpiration mechanisms. Therefore, the film is

Table 1
Characteristics of the packages: material composition and geometric details.

Package		Material	Thickness (mm)	Weight (g)	Perforation area (cm^2)	Grammage (g/cm^2)
1	Clamshell	80 % rPET+ 20 % PET	0.34	11.9	6.8	0.032
2	Tray	80 % rPET+ 20 % PET	0.40	6.9	n.a.	n.a.
	Bag	PP	0.02	1.6	3.78	0.0019
3	Cup	90 % Paperboard virgin +10 % PE	0.70	8.6	n.a.	n.a.
	Lid	80 % rPET+ 20 % PET	0.44	4.0	3.33	0.032
4	Tray	Paperboard (mix of virgin and recycled fibres)	0.60	14.3	n.a.	n.a.
	Bag	PP	0.02	2.1	3.78	0.0019
5	Tray	Corrugated board (mix of virgin and recycled fibres)	1.30	9.1	n.a.	n.a.
	Bag	PP	0.02	1.9	3.78	0.0019

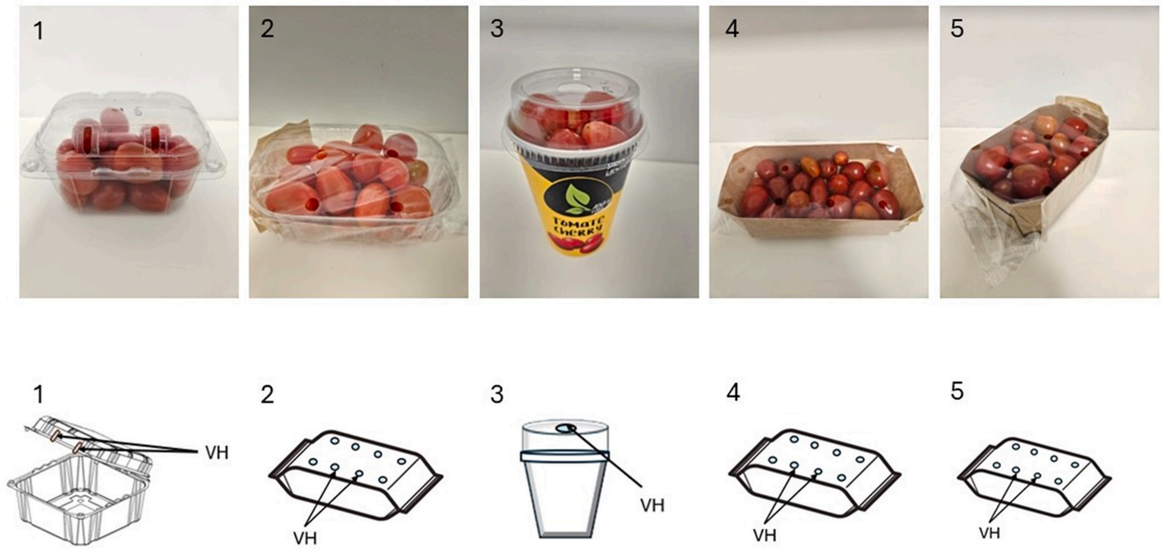

Fig. 1. Packages selected for the study and detail of ventilation holes (VH).

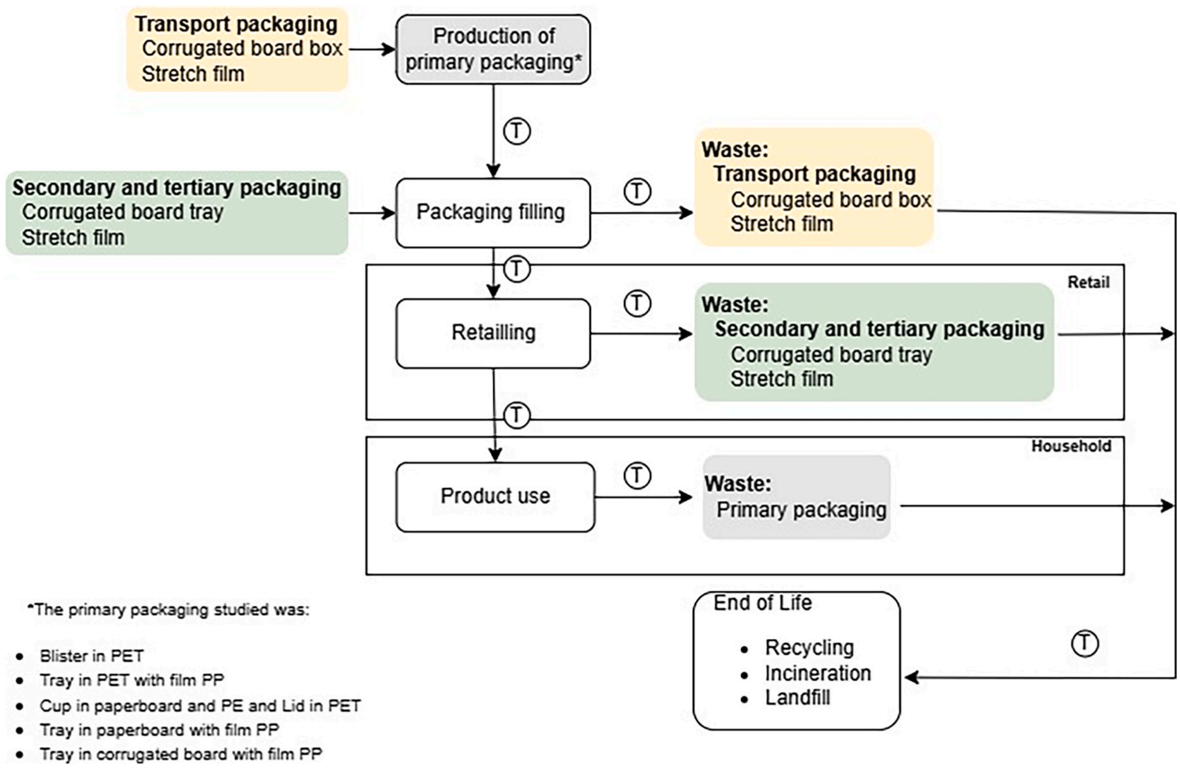

Fig. 2. System boundaries.

transported to a flexible packaging converter for perforation, repackaged and sent to the tomato filler. The closing operation of the bag and subsequent operations are described above (A) (Fig. S1B).

C) Cup for package 3

The production of the cup requires the production of the paperboard and the production of PE pellets which undergo an extrusion coating process, thus forming the bi-layer material. This composite material is then cut to form the body and bottom of the cups. These operations are performed in a paperboard coating company. Then is transported to a converter that assembles the parts (glueing and sealing), following transportation to the tomato filler. The cup is filled with tomato in an automatic machine and the lid is manually placed by the operator. The filled primary packages are assembled in secondary/tertiary packages and transported as described in (A) (Fig. S1C).

D) Tray for packages 4 and 5

The production of the tray begins with the production of the paperboard (package 4) or corrugated board in case of package 5. These materials go through a cutting, creasing and glueing process, after which are placed in the transport packaging and sent to the tomato filler. The trays are filled with tomato and go through the automatic flow-pack process to form the bag with the PP film previously described (B), then they are placed in a new secondary/tertiary package and transported to a distributor (warehouse) and then to the retailer and final consumer, as described in (A) (Fig. S1D).

After consumption, all packages are disposed of and collected for central sorting and finally transported according to the EoL treatment (recycling, incineration or landfill).

The primary tomato packages are transported to the filling plant in standard corrugated board boxes measuring 40x60 × 50 cm (transport packaging). This is valid for the 3 types of trays, clamshell and cup. The PP film for packages 2, 4 and 5 is supplied in coils in pallets with stretch low density polyethylene (LDPE) film.

After filling with tomato, the packages are transported in corrugated board trays (secondary packaging) measuring 40x30 × 14 cm. The trays are then palletised and secured with stretch film.

Table 2 shows the data for packages used in the transport of each package under study (empty) and shows the data for secondary packaging, according to information provided by the different stakeholders.

2.3. Performance of each package regarding tomato weight loss

The packages under study were compared regarding their performance in protecting the tomato from weight loss. Fruit post-harvest ripening is a complex mechanism that affects the product quality. In the case of tomato, it is reflected in changes in colour, texture, flavour, and chemical compositions and these are related directly or indirectly with moisture loss. Moisture loss occurs through transpiration mechanism which is linked to other metabolic processes. Weight loss rate is largely determined by the packaging. This is a parameter always used to monitor the product quality, because it is a reliable indicator of overall ripening mechanisms. Furthermore, moisture loss has a direct effect in commercial terms because of the price per package versus price per kilogram of product. Therefore, this parameter was selected and monitored during storage (Sousa et al., 2017).

Five units of each type considered in the study were filled with approximately 250 g of cherry tomato (FU) and sealed or closed. All the packages were weighed initially and after 3, 7 and 10 days of storage at 23 °C and 50 % relative humidity. The weight loss was determined as the percentage decrease in the final tomato weight relative to the initial weight (PM1200, Balance Mettler).

2.4. Life cycle inventory

Table 3 presents the inventory data for the cherry tomatoes' packages under analysis. Data on primary, secondary and tertiary packaging production processes (relative to plastics and paper/paperboard materials production and air emissions) were obtained from the Ecoinvent database v3.9.1 (Wernet et al., 2016). Specific converting processes were average primary data obtained through interviews of 4 packaging producers or converter companies in Portugal, or collected experimentally using samples from the market and provided by the tomato filler company. Data for converting processes of primary packaging (plastic film perforation and lamination of paperboard, cutting and glueing operations) were obtained through experimental data supplied by industrial companies.

Table 2
Transport, secondary and tertiary packaging.

Transport of empty packages to the tomato filler				
Package		Tray units/box or pouches film/roll	Boxes or rolls/ pallet	Functional unit/ pallet
1	Clamshell	1200	20	24 000
2	Tray	2600	20	52 000
	Bag	9520	60	571 200
3	Cup	1100	25	27 500
	Lid	1100	25	27 500
4	Tray	700	25	17 500
	Bag	9520	60	571 200
5	Tray	490	12	5880
	Bag	9520	60	571 200

Transport of packages filled with the tomato to the retailer			
Package	Trays units/box	Boxes/pallet	Functional unit/pallet
1	6	128	768
2	6	96	576
3	12	80	960
4	6	96	576
5	6	96	576

Table 3
Life cycle inventory data for the packages with 250 g of cherry tomatoes.

	Unit	Package				
		1	2	3	4	5
Input:						
Primary packaging						
Tray/Cup:						
PET	g	2.38	1.38	n.a.	n.a.	n.a.
rPET	g	9.54	5.50	n.a.	n.a.	n.a.
PE	g	n.a.	n.a.	0.86	n.a.	n.a.
Paperboard	g	n.a.	n.a.	7.74	14.32	n.a.
Corrugated board	g	n.a.	n.a.	n.a.	n.a.	9.07
Bag/Lid:						
PET	g	n.a.	n.a.	0.81	n.a.	n.a.
rPET	g	n.a.	n.a.	3.23	n.a.	n.a.
PP	g	n.a.	1.64	n.a.	2.21	1.96
Transport packaging (empty tomato packages)						
PE stretch film	g	0.0063	0.0031	0.011	0.0088	0.026
Corrugated board box	g	0.057	0.045	0.27	0.081	0.18
Secondary and tertiary packaging						
PE stretch film	g	0.20	0.26	0.16	0.26	0.27
Corrugated board tray	g	8.81	12.40	4.15	6.38	9.57
Energy						
Electricity	kWh	n.a.	0.036	0.012	0.036	0.036
Outputs:						
Primary packaging	g	11.92	8.52	12.64	16.53	11.03
Waste						
PET	g	11.92	6.88	n.a.	n.a.	n.a.
PE	g	0.21	0.26	1.03	0.27	0.30
PP	g	n.a.	1.64	n.a.	2.21	1.96
Paperboard	g	n.a.	n.a.	n.a.	14.32	n.a.
Corrugated board	g	8.87	12.45	4.42	6.46	18.82

n.a.-not applicable.

2.4.1. Packaging materials considerations

For packages 1, 2, and 3, it was considered that during the production of the clamshell, tray, and lid by extrusion and thermoforming, there was a material loss of 6 %, according to information from suppliers. Information provided indicated that scraps from converting operations were reprocessed internally and reincorporated. Data for film extrusion for the bags for packages 2, 4, and 5, was obtained from Ecoinvent v3.9.1 database (Wernet et al., 2016) with no material losses. Data on extrusion and thermoforming (packages 1, 2, lid of 3) processes were sourced from Ecoinvent database, adapting these processes with the respectively Portuguese losses for these processes. For the perforation process of bags film, the losses are 3 % based on information provided by the converter company.

Regarding the cup for package 3, the extrusion process in the Ecoinvent database (Wernet et al., 2016) was used, and considered 3 % losses. In the process of cutting the segments of the cup, there are losses of approximately 21 %, and in the assembly process, there are losses of 0.1 %, according to the companies performing these operations.

Data from the production of primary packages 4 and 5 (paperboard and corrugated board), was retrieved from Ecoinvent database, considering losses of 8 % and 5 %, respectively. These wastes were subjected to secondary recycling according to the producers.

The PP resin used to make the film for the flow-pack originates from Asia and the correspondent region energy mix was used. PET for clamshell, tray and lid was produced in Europe.

Data on the electricity consumption necessary for filling/closing and sealing the packages were collected and supplied by the tomato filler.

The electricity used for bag perforation (5E-4 kW/h for package 2.7E-4 kW/h for package 4.6E-4 kW/h for package 5) and the extrusion coating process of package 3 (1.5E-3 kW/h) was supplied after experimental determination, respectively by the flexible film converter and the company producing the coated paperboard. These data were complemented with information from the Ecoinvent database, particularly concerning the production processes of primary, secondary, and tertiary packaging, with electricity generation adapted to the Portuguese electricity mix. Packages 1 and 2 (the clamshell and the tray) were produced in the Netherlands, and packages 3, 4 and 5 were produced in different locations in Portugal and for this reason the electrical mixes used were corresponding to each country.

The transport profiles considered for this study are real scenario, based on information obtained through interviews. The type of transport used in the different routes and estimated average distances travelled are shown in Table 4. Interviews with packaging suppliers and converters, as well as the tomato filling company, were conducted to establish the supply chain for each of the five packages under study, from raw materials production to the EoL, and for tomato distribution.

Packages 1 and 2, the clamshell and tray travel 2242 km by truck from the manufacturer to the tomato filler. The film for the bag in packages 2, 4, and 5 travels 68 km to the film converter (perforation process) plus 315 km to the tomato filler. For package 3, the distance from the lid producer to the tomato filler was considered 367 km, and for the cup, it was 283 km from the coating company to the converter and then 367 km to the tomato filler. For packages 4 and 5, the distance from the producer to the tomato filler was 378 km.

The distribution phase consisted of 61 km by truck from the tomato filler to the main distributor warehouse and 271 km to the retail store.

Table 4
Transport profile.

Package	Material	Distance (km)	Transport mode
1	Clamshell	2242	Lorry, Euro 5 (16–32 ton)
	Full packaging	332	Lorry with refrigeration machine, Euro 5 (7.5–16 ton)
	Packaging waste	267	Municipal lorry (21 ton) and Lorry, Euro 5 (7.5–16 ton)
2	Tray	2242	Lorry, Euro 5 (16–32 ton)
	Film	383	Lorry, Euro 5 (16–32 ton)
	Full packaging	332	Lorry with refrigeration machine, Euro 5 (7.5–16 ton)
	Packaging waste	267	Municipal lorry (21 ton) and Lorry, Euro 5 (7.5–16 ton)
3	Lid	367	Lorry, Euro 5 (16–32 ton)
	Cup	651	Lorry, Euro 5 (16–32 ton)
	Full packaging	332	Lorry with refrigeration machine, Euro 5 (7.5–16 ton)
	Packaging waste	267	Municipal lorry (21 ton) and Lorry, Euro 5 (7.5–16 ton)
4	Tray	378	Lorry, Euro 5 (16–32 ton)
	Film	383	Lorry, Euro 5 (16–32 ton)
	Full packaging	332	Lorry with refrigeration machine, Euro 5 (7.5–16 ton)
	Packaging waste	236	Municipal lorry (21 ton) and Lorry, Euro 5 (7.5–16 ton)
5	Tray	378	Lorry, Euro 5 (16–32 ton)
	Film	383	Lorry, Euro 5 (16–32 ton)

Transport to households was not considered in this study, by a "short chain typology" implying proximity between the locations of consumption and energy production (Paolotti et al., 2017). The secondary packaging waste disposed of in the store is transported 13.7 km to the sorting station. Depending on the type of waste and respective EoL: PET for recycling waste travels 31.2 km; PE and PP recycling waste travels 201 km; paper and paperboard recycling waste travels 6.5 km; plastic, paper, and paperboard waste for landfilling and incineration travels 14.4 km. Data on the environmental impacts of the trucks were taken from Ecoinvent.

The tomato filler is located in Sintra (west of Lisboa), the distributor is in the industrial area North of Lisboa and the retailer is in the centre of Porto. It is assumed that the final consumer lives (point of consumption) in the centre of Porto close to the retailer.

2.4.2. End of life

The EoL for each package under study and respective transport and secondary packaging was defined based on data from the Portuguese Environment Agency (APA) and interviews with professionals from the Municipalities Association for Sustainable Waste Management of Greater Porto (LIPOR).

The post-consumer packaging waste is collected (commingled), transported to LIPOR and then sorted and distributed for treatment: recycling, incineration with energy recovery or landfilling. The following distribution among the different management options was considered:

- PET and PE film: 35 % is recycled, 60 % is incinerated and 5 % is sent to landfill
- PP film: 30 % is recycled, 65 % is incinerated and 5 % is sent to landfill
- Paper and paperboard: 70 % is recycled, 25 % is incinerated and 5 % is landfilled
- The cup (sample 3) is coated with PE film on only one side; therefore, it can be recycled together with uncoated paper and paperboard (Agência Portuguesa do Ambiente, 2023). Nevertheless, it is recognised that recycling is effective at a lower rate compared to plastics. The following rates were assumed: 10 % is recycled, 85 % is incinerated and 5 % is sent to landfill.

The recycling operations of the packaging waste were not included in the present packaging cycle.

Once these materials have been collected and sorted, they will be distributed to the respective recycling centres. Recycling of plastic components is performed by different recyclers and in different locations: PET is recycled in the North of Portugal, PP and PE in the Centre of Portugal and paperboard is sent to Porto surroundings. Incineration and landfilling facilities are also located in the Porto area.

The study was conducted using the cut-off method, i.e. no credit was given to the current system for generating recyclable material, and the environmental benefits related to recycling (such as reducing the need for virgin raw materials) will be utilized in the next life cycle (ISO 14044, 2021).

2.5. Life cycle impact assessment (LCIA)

The midpoint approach was followed in line with most published reports addressing packaging systems (Bher and Auras, 2024). A quantitative impact assessment was performed for six impact categories, according to the packaging materials and production and converting processes associated: global warming (GW), ozone formation-human health (OF-HH), terrestrial acidification (TA), freshwater eutrophication (FE), mineral resource scarcity (MRS) and fossil resource scarcity (FRS). The characterisation factors applied were from the ReCiPe 2016 midpoint v.1.08 method (Huijbregts et al., 2017). For the assessment of the effects of global climate change, the environmental impact category of GW was selected. The remaining categories were selected to provide a more comprehensive assessment of the packaging systems selected for the study. The SimaPro 9.5.0 (Pré Sustainability, 2024) was used for inventory and impact assessment modelling.

Biogenic carbon was considered for paperboard and corrugated board used in some of the packages under study. These are bio-based materials derived from renewable resources mainly wood pulp, an in Portugal eucalyptus and pine. These materials sequester biogenic carbon during the growth of the trees. This sequestered carbon is released at the end of its useful life, depending on the disposal method: in the recycling process the carbon remains stored in the recycled fibers, extending their life cycle; in the incineration process the carbon is released as biogenic CO_2, which is considered carbon neutral in the methodology used; in the landfill process some carbon is released as methane (CH_4), which is accounted for in the global warming potential (CEPI, 2023).

The other packaging systems in plastic PET, rPET and PP are fossil-based polymers derived from petrochemical resources. Despite the environmental benefits of rPET - such as reduced depletion of fossil resources and lower energy requirements during production - neither PET, rPET nor PP are considered bio-based. These materials do not contain biogenic carbon content, as their carbon comes from fossil sources. During the incineration process, fossil carbon is released as CO_2, contributing to GW (ISO, 2018).

3. Results and discussion

3.1. Overview of results

Fig. 3 shows a comparison between the 5 packages for each impact category, in percentage taking as 100 the value of the packaging that presents the highest value within each category. Table 5 shows the same comparison but in absolute values. Overall, the best performing is package 3 for nearly all impact categories, except for MRS. For this impact category package 5 present the best performance. The impact value of GW is 52 % higher for package 1 when compared to package 3. Taking this latter package as a reference, OF-HH is 39 % higher for package 4 and FRS is 57 % higher for package 1. Package 1 presents the worst performance for the GW and FRS impact categories.

For the GW and FRS impact categories, package 1 had a higher impact than the other packaging systems, due to the thermoforming of the clamshell, more specifically due to the electricity consumption that is used in the process. A difference of 30 %–40 % between the impacts for these categories of packaging 1 and 2 can be noted, even though both are mainly made of PET, but with a slightly different packaging weight. For these impact categories, all samples containing paperboard (packages 3, 4 and 5) showed values of around 60 %. The process that most contributes to this is the production of the cardboard tray, namely the energy required to produce the paper.

The worst performing package is 4, with the highest potential environmental for OF-HH, TA, FE and MRS impact categories, followed by, in this order, the GW and FRS. Differences in order to 20 %- 40 % are observed between packages 4 and 5 for these categories, which may be attributed to the remarkable difference in the tray weight in package 4 (Table 3). TA values varied by 53 % between packages 3 and 4. For this category, package 3, also with a relevant proportion of paperboard, presented the lowest value. The FE impact category showed a difference in values of around 53 % between packaging systems 4 (maximum impact) and packaging 3 (minimum impact). The results for the MRS category also show that package 4 has the largest impact, but the similar package 5 has the smallest (with a 75 % difference), the difference being caused by the weight of the trays.

3.2. Hotspot analysis

Fig. 4 shows the contribution of processes to all impact categories for each package. The processes were grouped into i) processes of production and conversion of primary packaging (the packages under study), ii) processes for obtaining secondary and tertiary packaging, iii) transportation of different items to tomato filling, iv) transportation to the retailer, v) transportation of waste, and vi) the EoL processes (incineration and landfilling of plastics and paperboard).

For all impact categories analysed, the three main hotspots for all packaging systems studied, are the production of primary packaging, the supply of secondary and tertiary packaging and the incineration of plastic. To produce primary packages, the processes with the highest contribution are, respectively:

- clamshell and tray thermoforming (packages 1 and 2),
- the paperboard production is slightly higher than the combined contribution of plastic pellets production and extrusion energy for package 3
- paperboard production for the trays of packages 4 and 5.

In the GW category, package 1 the production of the clamshell

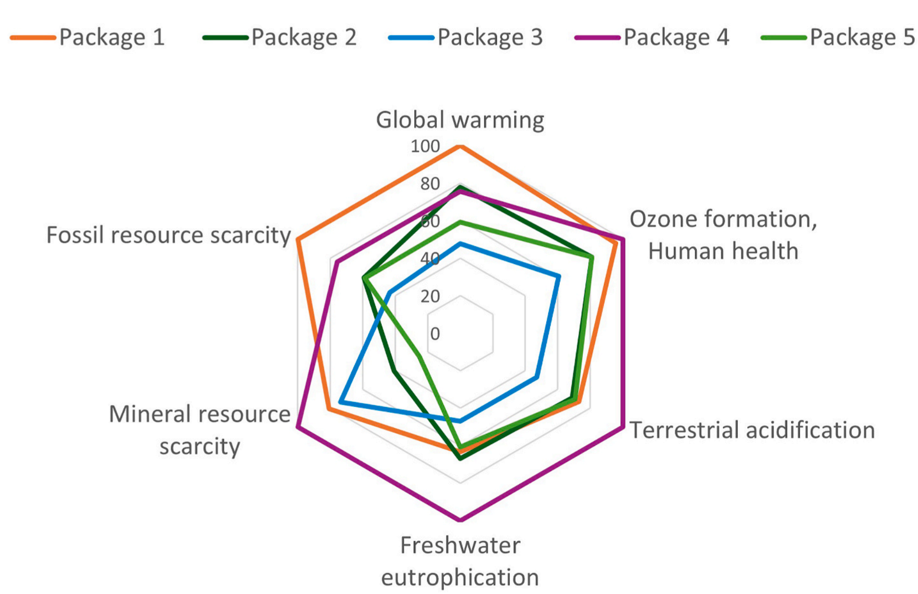

Fig. 3. Comparison of environmental impacts of the five packages.

Table 5
Comparison of environmental impacts of the five packaging systems.

Impact category	Unit	Package 1	Package 2	Package 3	Package 4	Package 5
Global warming	kg CO_2 eq	7.64 E−02	5.94 E−02	3.64 E−02	5.77 E−02	4.52 E−02
Ozone formation, Human health	kg NOx eq	1.20 E−04	1.10 E−04	8.00 E−05	1.30 E−04	1.10 E−04
Terrestrial acidification	kg SO_2 eq	1.20 E−04	1.20 E−04	8.0 E−05	1.70 E−04	1.20 E−04
Freshwater eutrophication	kg P eq	2.00 E−05	2.00 E−05	1.00 E−5	3.00 E−5	2.00 E−5
Mineral resource scarcity	kg Cu eq	4.00 E−05	2.00 E−05	4.00 E−5	6.00 E−5	1.00 E−5
Fossil resource scarcity	kg oil eq	2.25 E−02	1.33 E−02	9.74 E−03	1.70 E−2	1.32E-02

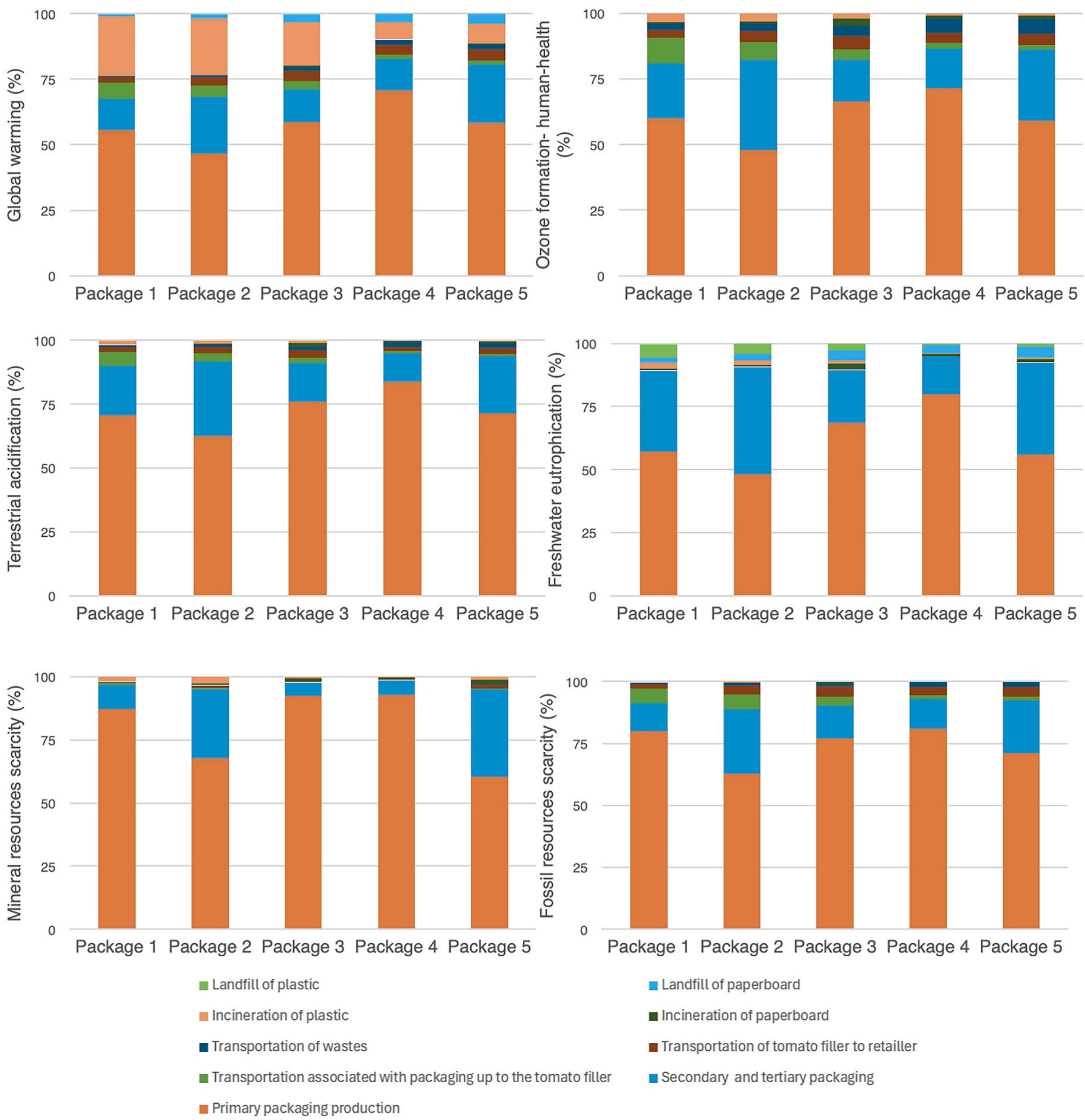

Fig. 4. Contribution of the processes by impact category for each sample (hotspot analysis.

contributes to 56 % of total GW, plastic incineration 23 % and obtaining secondary and tertiary packaging is responsible for 12 %. The aspect that contributes most to the 56 % of GW is the production of the raw material, polyethylene terephthalate, which due to its fossil origin generates large carbon dioxide (CO_2) emissions.

The contributors to package 2 are 47 % to produce PET tray and PP bags, and a similar share for secondary/tertiary packaging and plastic incineration, in the order of 21 %. These high impact values for GW associated with packaging production are caused by the high energy consumption in plastic extrusion and the resulting greenhouse gases (GHG) emissions. The main causes of the impacts resulting from electricity generation, in particular the contribution of CO_2 emissions to GW.

Impacts of package 3 are due to the cup and lid production with 59 % and secondary and tertiary packaging values of around 12 %. Plastic incineration has a contribution value of 16 % for the GW category. The production of the cup is the most contributing step of this packaging for this impact category. Paperboard production for trays and bags of packages 4 and 5 have, respectively 71 % and 58 %, of the contribution to GW. In packages 3,4 the production of paperboard is the main cause of the values associated with GW, resulting in a significant increase in CO_2 emissions from electricity generation. Also, for packaging 5, the use of energy to manufacture corrugated board is one of the largest sources of CO_2.

For the other impact categories TA, OF-HH, MRS and FRS, the primary packaging production phase is always responsible for more than 50 % of the total impact for all packages, followed by secondary and tertiary packaging systems with 10–35 %. For the TA impact category, the main responsible emissions are nitric oxide (NO), ammonia (NH_3) and sulfur dioxide (SO_2), which are released into the atmosphere and subsequently deposited in the soil, causing changes in its acidity. For the OF-HH impact category, the release of different volatile organic compounds (VOCs), which in turn react with NOx compounds and in the presence of light, form tropospheric ozone (Huijbregts et al., 2017). In the MRS category, the high values in the packaging production phase can be directly linked to the extraction of metals such as aluminium and steel used in the equipment. The impact on the FRS category is directly related to the energy required in the production processes, whether to produce packages 1 and 2 in PET, but also for samples 3–5, mainly in cellulose.

In the FE impact category, the contribution of end-of-life processes is more relevant than for other categories. Plastic incineration varies from 0.3 % for package 4 to 2 % for package 1. The same can be observed for paperboard incineration from 0.5 % for package 1–3 % for package 3. However, also in this category packaging production and secondary packaging systems are the main contributors.

3.3. Effect of new PPWR target rates for EoL approaches

The different approaches at the EoL were changed and compared with the previous analysis (scenario 1). For scenario 1 the share between recycling, incineration and landfilling currently in the Porto region was applied. These were respectively 35 %, 60 %, 5 % for plastics and 70 %, 25 %, and 5 % for paperboard. Based on the Packaging and Packaging Waste Regulation (EU, 2025), the targets for 2030 are set as follows: recycling plastic 55 %, paperboard 85 %; incineration with energy recovery 45 % for plastics and 15 % for paper. Elimination of landfilling of both plastics and paper and board is foreseen in this new Regulation. These new targets were applied as scenario 2 and studied regarding the changes in the impact category of GW.

Results are presented in Table 6. Package 3 (coated paperboard and PET lid) is the one with the greatest reduction in impact for category GW, with an 8.0 % reduction compared to scenario 1, followed by package 2 with 7.6 % and package 1 with 6.9 %, these two packages composed of PET and PP. Packages 4 and 5 have the lowest reduction, with around 6 % when the increase in the recycling rate is applied according to PPWR target rates. This is because these packages are mainly in paperboard and corrugated board, for which high recycling rates are already observed in scenario 1.

Table 6
Impact of new targets in PPWR for EoL approaches.

	Global warming (kg CO_2 eq)	
Package	Scenario 1	Scenario 2
1	7.64 E−02	7.11 E−02
2	5.94 E−02	5.49 E−02
3	3.64 E−02	3.35 E−02
4	5.77 E−02	5.43 E−02
5	4.52 E−02	4.24 E−02

3.4. Impact of including packaging performance indicators in the LCA analysis

The analysis of the performance of each package regarding tomato weight loss, which is due to moisture evaporation and transpiration mechanisms (Sousa et al., 2017) was included. The tomato moisture loss was measured experimentally over 10 days of storage at 23 °C and 50 % relative humidity. The tomato samples were packaged in the 5 primary packages under study. The results indicate that the package that allowed the highest weight loss was package 4 (8.0 % ± 0.9 %). Packages 1, 2 and 5 showed similar performance with tomato weight loss around 7 %. Package 3 was the best performing with only 3.2 % ± 0.1 % of tomato weight loss. As shown in Table 1, this is the package with the smallest perforation area. This packaging was also the best performer in terms of the different impact categories, including GW.

The transfer of moisture out of the packaging was considered to occur mainly through perforations in the clamshell, bag or lid, depending on the package. Therefore, in this study, the perforation area of packages 1, 2, 4 and 5 was reduced so that the area available for moisture transfer becomes the same as that of package 3, to bring the moisture loss to equivalent values to those observed in package 3. By decreasing the perforation area, an increase in material weight was calculated with material grammage, keeping the material thickness at the original value. The impact in the different categories of this package weight increase was assessed.

Fig. 5 shows a comparison of the impacts when the perforation area is the original area shown in Table 1 (PA1) and the impacts when reducing the area to the observed in package 3 (PA2). The results show that the packaging with the greatest increase in value for all the impact categories is package 2, with the MRS category having the greatest increase at 15 %, followed by the FRS category at 9 % and then the FE category at 8 %. The greatest increase in these impact categories reflects the fact that the package is made entirely of PET and PP plastics and their corresponding impact on the environment. The impact categories GW, OF-HH and TA showed a lower increase for this package, between 6 and 7 %. The package with the lowest increase for all impact categories was package 4, followed by package 5 and finally package 1. These results highlight that considering the performance of the different packages in keeping the tomato moisture, reinforces the best performance of package 3.

The process of moisture loss has an impact on the quality of the product, although at the levels typically observed for tomatoes, it does not imply the loss of the product. Nevertheless, the aim was to illustrate how product decay mechanisms can be incorporated in the LCAs studies following different approaches than those typical, based on changing the functional unit.

4. Conclusion

This study showed that different materials used to produce packaging for the same purpose (tomato), have different environmental impacts, and also offer different barrier to product moisture loss which influence the quality of the product. It made a step forward on collecting detailed data associated to the specific operations of filling the product and to the packages used, including the primary and transportation systems.

Paperboard tray with PP bag (Package 4) is the worst performing overall, particularly for the impact categories OF-HH, TA, FE, and MRS. The cup made in PE-laminated paperboard with a plastic lid (Package 3) is the best performing across all categories except for MRS. Notably, the GW impact value is 52 % higher in clamshell in PET (Package 1) compared to package 3. Using package 3 as a reference, the OF-HH impact is 39 % higher for package 4, and the FRS impact is 57 % higher in package 1. Additionally, package 1 shows poor performance in both the GW and FRS impact categories. Meanwhile, packages 2 (PET trays with PP bag) and 5 (corrugated board tray with PP bag) have the

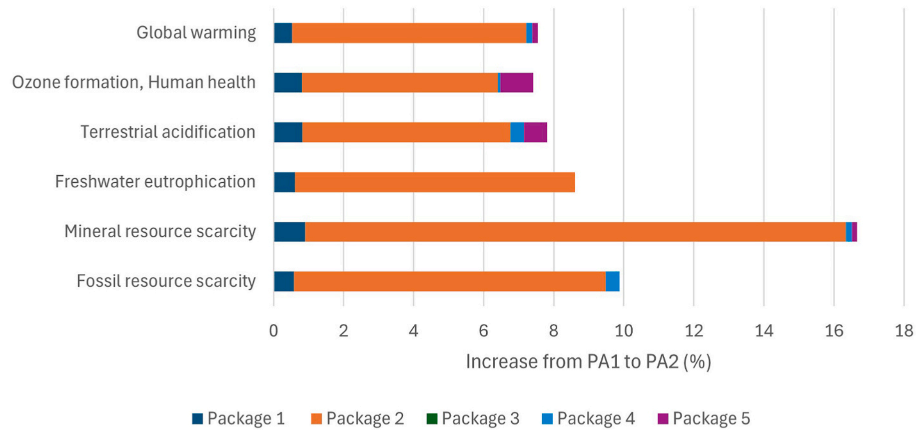

Fig. 5. Comparison of the impacts when the ventilation area is the original (PA1) and reduced to the package 3 area (PA2).

lowest impacts in MRS and the highest impacts in OF-HH.

This study showed also that the main hotspot is the production of primary packaging. In this respect the optimisation of the amount of material used for each tray was found a key aspect. For example, package 4 showed the worst impact although produced in paperboard, as compared to package 5 which is lighter in corrugated board weight. The second most relevant hotspot is the supply of secondary and tertiary packaging. Following, the incineration of plastic for all packaging systems studied was the more relevant contributor.

The processes that contribute the most are the thermoforming of clamshell and trays, the production of paperboard combined with the production of plastic granules and the extrusion energy and production of paperboard for trays.

It should be highlighted the impact of the packaging chain organisation that influence the different converting operations and the need for transportation between them. For example, the fact that clamshells are imported instead produced locally, and the need to produce tailor made perforations in the lidding films that add on the transportation distance, are relevant for the impacts. This is a critical aspect because in the present case, the high PET recyclability is not reflected in a lower impact. This aspect can only be analysed using real collected data like in the present study, which is not often reported in other published studies.

The potential impact of new EoL target rates foreseen in PPWR implementation was studied and the main conclusions were that package 3 will achieve the largest reduction in GW impact with 8.0 %, followed by package 2 with 7.6 % and package 1 with 6.9 %. Packages 4 and 5 show the lowest reductions, around 6 %, due to their already high base recycling rates in Porto region.

Finally, when studying the impact of including packaging performance indicators in terms of weight loss, the results indicated that package 4 resulted in the highest weight loss and package 3 recorded the lowest weight loss. When comparing the impacts when the perforation area for product ventilation is the original area with a simulated reduced area to that equivalent to area of package 3, the highest decrease in environmental performance was for package 2. These results emphasise the superior performance of package 3 in preserving tomato moisture with the lowest environmental impact.

In summary, packaging made entirely of plastic showed the largest environmental impact in the market conditions observed today. However, paperboard packaging that is oversized also has showed a large impact. In this aspect, the results of the present study highlight that the trend in replacing well designed plastic by paperboard trays is not beneficial in all cases, despite the consumer preference. Increasing the percentage of recycling and incineration accordingly to new PPWR targets will be the best approach to reducing environmental impacts.

5. Limitations of the study

Some limitations and shortcomings may be identified in this study related to the definitions and models assumed and inherent to the LCA methodology. Additionally to the exclusions already addressed, the process of film stretching immediately after the extrusion was not considered. Additives in plastic and cellulosic components of the packaging systems were also not accounted. No information was provided and the experimental determination although possible was out of the project scope. The lack of transparency in formulations, availability of additive datasets, and additive data completeness are often major barriers to additive inclusion in plastic LCAs (Logan et al., 2024). The same considerations apply to labels and printing inks. The relative label weights were all below 5 % and the lowest value was recorded for package 3 (<1 %). However, this package was the only one with a large printed surface area, which may balance with the reduced label contribution.

As quality monitoring parameter of tomato, only the weight loss was considered. The effect of other tomato attributes the consumer may be more sensitive to, like colour, texture and flavour, can be relevant in the packaging selection and could be included in the analysis. Consumer perception and attitude are fundamental aspects in driving tomato industry in the selection of the packaging system and the effective rates of recovery and recycling, that highly affect the results, are also consumer dependent.

Regarding the LCA methodology, although standardized and one of the mostly applied for packaging assessment, the currently accepted methods do not yet include emerging effects such as the generation of microplastics and loss of biodiversity (Miller, 2022). Generation of microplastics is an impact relevant when comparing plastics and non-plastics materials. Additionally, plastic and paperboard packages may also release chemicals such as printing inks components, mineral oils, PFAS and plasticisers into the environment. These aspects were not considered in the present study.

Furthermore, when comparing different packaging solutions, most LCA studies shown that no single option reduces all environmental impacts (Miller, 2022). Multi attribute analysis is recommended when addressing trade-offs and drafting conclusions (Prado and Heijungs, 2018). This can be particularly interesting in combining the environmental assessment with data from consumer preferences and with uncertainty analysis to enhance interpretation of results (Hemachandra et al., 2024).

It is recognised that LCA approach has potential drawbacks related to the data requirements, assumptions and uncertainty, and to the results interpretation. A major limitation is associated to the use of specific impact categories which may not capture all relevant environmental or social impacts, therefore not providing a holistic view of sustainability.

Despite these challenges, LCA remains a valuable tool for assessing the environmental impacts of products and processes. From the results presented, industry can identify opportunities for improvement and make decisions toward more sustainable tomato supply at commercial level.

CRediT authorship contribution statement

Inês Pinto Mota: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ana Neto Carneiro:** Writing – original draft, Methodology, Formal analysis, Data curation. **Paula Quinteiro:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Formal analysis. **Giancarlo Colelli:** Writing – review & editing, Validation, Conceptualization. **Fátima Poças:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Funding

This work was supported by National Funds from FCT - Fundação para a Ciência e a Tecnologia under the scope of project CBQF UIDB/50016/2020 and project CESAM UID/50006 + LA/P/0094/2020. Paula Quinteiro acknowledges the FCT for the contract 2023.06946.CEECIND (https://doi.org/10.54499/2023.06946.CEECIND/CP2840/CT0013). This article is based upon collaborative work under the scope of COST Action Circul-a-bility CA19124 – Rethinking Packaging for Circular and Sustainable Food Supply Chains of the Future www.cost.eu. The authors thank the support granted by the Recovery and Resilience Plan (PRR) and by the Next Generation EU European Funds to Universidade Católica Portuguesa, through the Green Agenda for Business Innovation "From Fossil to Forest – Sustainable packaging and products to replace fossil plastic" (Project no.8 with the application C644920945-00000036).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank Dr. Patricia Carvalho from LIPOR (Municipalities Association for Sustainable Waste Management of Greater Porto) for the useful discussions and data provided regarding the characterization of packaging EoL rates in the Porto region.

Abbreviations

APA	Portuguese Environment Agency
OPP	Biaxially oriented polypropylene
CO_2	Carbon dioxide
EoL	End-of-life
EU	European Union
FE	Freshwater eutrophication
FRS	Fossil Resource scarcity
FTIR	Fourier-transform infrared spectroscopy
FU	Functional unit
GHG	Greenhouse gases
GW	Global warming
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LDPE	Low density polyethylene
LIPOR	Municipalities Association for Sustainable Waste Management of Greater Porto
MRS	Mineral resource scarcity
NH_3	Ammonia
NO	Nitrogen oxide
OF-HH	Ozone formation- Human Health
OPP	Oriented polypropylene
PA	Perforation area
PE	Polyethylene
PET	Polyethylene terephthalate
PFAS	perfluoroalkyl substances
PLA	Polylactic acid
PP	Polypropylene
PPWR	Packaging and Packaging Waste Regulation
RC	Resource consumption
rPET	Recycled polyethylene terephthalate
SO_2	Sulfur dioxide
TA	Terrestrial acidification
UAP	Urban air pollution
VH	perforation holes
VOCs	Volatile organic compounds

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145951.

Data availability

Data will be made available on request.

References

Accorsi, R., Battarra, I., Guidani, B., Manzini, R., Ronzoni, M., Volpe, L., 2022. Augmented spatial LCA for comparing reusable and recyclable food packaging containers networks. J. Clean. Prod. 375 (2022), 134027.

APA (Agência Portuguesa do Ambiente I.P.). 2023. Relatório do Estado do Ambiente 2022/2023. Portuguese Environment Agency. https://rea.apambiente.pt/sites/default/files/rea/REA%202022_2023_pdf_vfinal_11_10_2023.pdf.

Bher, A., Auras, R., 2024. Life cycle assessment of packaging systems: a meta-analysis to evaluate the root of consistencies and discrepancies. J. Clean. Prod. 476, 143785. https://doi.org/10.1016/j.jclepro.2024.143785.

Bishop, G., Styles, D., Lens, P.N.L., 2021. Environmental performance of bioplastic packaging on fresh food produce: a consequential life cycle assessment. J. Clean. Prod. 317 (2021), 128377.

Bock, M., Meyerding, S.G., 2023. Consumer perception of food product packaging materials sustainability versus life cycle assessment results: the case of processed tomatoes—A quantitative study in Germany. Sustainability 15 (23), 16370. https://doi.org/10.3390/su152316370.

Casson, A., Giovenzana, V., Frigerio, V., Zambelli, M., Beghi, R., Pampuri, A., Tugnolo, A., Merlini, A., Colombo, L., Limbo, S., Guidetti, R., 2022. Beyond the eco-design of case-ready beef packaging: the relationship between food waste and shelf-life as a key element in life cycle assessment. Food Packag. Shelf Life 34, 100943. https://doi.org/10.1016/j.fpsl.2022.100943.

Confederation of European Paper Industries, 2023. Key statistics 2023: European pulp & paper industry. https://www.cepi.org/. December 2024.

Conte, A., Cappelletti, G.M., Nicoletti, G.M., Russo, C., Del Nobile, M.A., 2015. Environmental implications of food loss probability in packaging design. Food Res. Int. 78, 11–17. https://doi.org/10.1016/j.foodres.2015.11.015.

Dörnyei, K.R., Uysal-Unalan, I., Krauter, V., Weinrich, R., Incarnato, L., Karlovits, I., Colelli, G., Chrysochou, P., Fenech, M.C., Pettersen, M.K., Arranz, E., Marcos, B., Frigerio, V., Apicella, A., Yildirim, S., Poças, F., Dekker, M., Johanna, L., Coma, V., Corredig, M., 2023. Sustainable food packaging: an updated definition following a holistic approach. Front. Sustain. Food Syst. 7, 1119052. https://doi.org/10.3389/fsufs.2023.1119052.

Eslami, E., Carpentieri, S., Pataro, G., Ferrari, G., 2025. Comparative life cycle assessment (LCA) of packaging materials for tomato-based products to pave the way for increasing tomato processing industry sustainability. Sustainability 17, 3648. https://doi.org/10.3390/su17083648.

Espinoza-Orias N., Lundquist L. 2025. Life cycle assessment of reusable food and beverage packaging systems: A proposal of good practice. Journal of Cleaner Production 499 (2025) 145207. https://doi.org/10.1016/j.jclepro.2025.145207.

EU (European Commission), 2025. Packaging and packaging waste. Official Journal of the European Communities No L 22 (1), 2025. https://eur-lex.europa.eu/eli/reg/2025/40/oj.

EU (European Commission), 2024. Food waste. Food Safety. https://food.ec.europa.eu/safety/food-waste_en.

Frigerio, V., Casson, A., Limbo, S., 2023. Comparison of different methodological choices in functional unit selection and results implication when assessing food-packaging environmental impact. J. Clean. Prod. 396, 136527. https://doi.org/10.1016/j.jclepro.2023.136527.
Hemachandra, S., Hadjikakou, M., Pettigrew, S., 2024. A scoping review of food packaging life cycle assessments that account for packaging-related food waste. Int. J. Life Cycle Assess. 29, 1899–1915. https://doi.org/10.1007/s11367-024-02349-z.
Huijbregts, M.A., Steinmann, Z.J., Elshout, P.M., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., Van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/s11367-020-01761-5.
International Organization for Standardization, 2021a. Environmental Management - Life Cycle Assessment - Principles and Framework. ISO, Geneva, Switzerland. ISO 14040:2021).
International Organization for Standardization, 2021b. Environmental Management — Life Cycle Assessment — Requirements and Guidelines. ISO, Geneva, Switzerland. ISO 14044:2021).
International Organization for Standardization, 2018. Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification. ISO, Geneva, Switzerland. ISO:14067,2018).
Lin, H., Black, M.J., Walsh, L., Giordano, F.S., Borrion, A., 2024. Life cycle assessment of baby leaf spinach: reduction of waste through interventions in growing treatments and packaging. J. Clean. Prod. 449, 141723. https://doi.org/10.1016/j.jclepro.2024.141723.
Lindh, H., Williams, H., Olsson, A., Wikström, F., 2016. Elucidating the indirect contributions of packaging to sustainable development: a terminology of packaging functions and features. Packag. Technol. Sci. 29 (4–5), 225–246. https://doi.org/10.1002/pts.2197.
Logan, H., DeMeester, S., Astrup, T.F., Damgaard, A., 2024. Additive inclusion in plastic life cycle assessments, part II. Review of additive inventory data trends and availability. J. Ind. Ecol. 1–13. https://doi.org/10.1111/jiec.13534, 2024.
Lytle, B., Batt, G.S., Hurley, R.A., Gasic, K., 2024. The effect of packaging types on fresh peaches in the direct-to-consumer environment: distribution testing, life cycle assessment and economic impact. Packag. Technol. Sci. 37 (7), 667–684. https://doi.org/10.1002/pts.2811.
Miller, A.S., 2022. The capabilities and deficiencies of life cycle assessment to address the plastic problem. Front. Sustain. https://doi.org/10.3389/frsus.2022.1007060.
Oliver-Villanueva, J.-V., Armengot-Carbó, B., Lorenzo-Saéz, E., Lerma-Arce, V., 2025. Sustainable environmental analysis of wooden boxes for fruit and vegetable packaging and transport in comparison with corrugated cardboard boxes. Sustainability 17, 557. https://doi.org/10.3390/su17020557.
Paolotti, L., Martino, G., Marchini, A., Boggia, A., 2017. Economic and environmental assessment of agro-energy wood biomass supply chains. Biomass Bioenergy 97, 172–185. https://doi.org/10.1016/j.biombioe.2016.12.020.
Poças, F., do Céu Selbourne, M., 2023. Drivers, advances, and significance of measures for effective circular food packaging. Front. Sustain. Food Syst. 7, 1140295. https://doi.org/10.3389/fsufs.2023.1140295.
Poças, M.F., Oliveira, J.C., Pereira, J.R., Hogg, T., 2010. Consumer exposure to phthalates from paper packaging: an integrated approach. Food Addit. Contam. 27 (10), 1451–1459. https://doi.org/10.1080/19440049.2010.490790.
Prado, V., Heijungs, R., 2018. Implementation of stochastic multi attribute analysis (SMAA) in comparative environmental assessments. Environmental Modelling and Software 109, 223–231. https://doi.org/10.1016/j.envsoft.2018.08.021.
Pré Sustainability, 2024. Pré sustainability. https://pre-sustainability.com/.
Qin, Y., Horvath, A., 2022. What contributes more to life-cycle greenhouse gas emissions of farm produce: production, transportation, packaging, or food loss? Resour. Conserv. Recycl. 176, 105945. https://doi.org/10.1016/j.resconrec.2021.105945.
Quinteiro, P., Gama, N.V., Ferreira, A., Dias, A.C., Timmons, A.B., 2022. Environmental assessment of different strategies to produce rigid polyurethane foams using unrefined crude glycerol. J. Clean. Prod. 371. https://doi.org/10.1016/j.jclepro.2022.133554.
Rasines, L., Castillejo, N., San Miguel, G., Aguayo, E., 2023. Can household storage conditions reduce food waste and environmental impact? A broccoli case study. Sci. Total Environ. 892, 164779. https://doi.org/10.1016/j.scitotenv.2023.164779, 2023.
Rasines, L., San Miguel, G., Corona, B., Aguayo, E., 2024. Addressing the circularity and sustainability of different single-use and reusable crates used for fresh fruit and vegetables packaging. Food Packag. Shelf Life 46, 101391. https://doi.org/10.1016/j.fpsl.2024.101391.
Sasaki, Y., Orikasa, T., Nakamura, N., Hayashi, K., Yasaka, Y., Makino, N., Shobatake, K., Koide, S., Shiina, T., 2022. Optimal packaging for strawberry transportation: evaluation and modeling of the relationship between food loss reduction and environmental impact. J. Food Eng. 314, 110767. https://doi.org/10.1016/j.jfoodeng.2021.110767.
Sasaki, Y., Orikasa, T., Shinozaki, R., Nakamura, N., Hayashi, K., Yasaka, Y., Makino, N., Shobatake, K., Koide, S., Shiina, T., 2023. Ideal packaging for ripened peaches determined through modeling the relationship between food loss reduction and life cycle environmental impacts. Packag. Technol. Sci. 36 (4), 253–263. https://doi.org/10.1002/pts.2708.
Sasaki, Y., Orikasa, T., Takaoka, R., Nakamura, N., Hayashi, K., Yasaka, Y., Makino, N., Shobatake, K., Koide, S., Shiina, T., 2024. A novel simplified model to evaluate environmental impact based on life cycle assessment methodology–Case study of spinach considering food waste reduction through modified atmosphere packaging. Future Foods 10, 100456. https://doi.org/10.1016/j.fufo.2024.100456.
Sazdovski, I., Bala, A., Fullana-i-Palmer, P., 2021. Linking LCA literature with circular economy value creation: a review on beverage packaging. Sci. Total Environ. 771, 145322. https://doi.org/10.1016/j.scitotenv.2021.145322.
Settier-Ramirez, L., López-Carballo, G., Hernández-Muñoz, P., Tinitana-Bayas, R., Gavara, R., Sanjuán, N., 2022. Assessing the environmental consequences of shelf-life extension: conventional versus active packaging for pastry cream. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2021.130159.
Sousa, A.R., Oliveira, J.C., Sousa-Gallagher, M.J., 2017. Determination of the respiration rate parameters of cherry tomatoes and their joint confidence regions using closed systems. J. Food Eng. 206, 13–22. https://doi.org/10.1016/j.jfoodeng.2017.02.026.
Torres Pineda, I., Duk Lee, Y., Sang Kim, Y., Min Lee, S., Sub Park, K., 2021. Review of inventory data in life cycle assessment applied in production of fresh tomato in greenhouse. J. Clean. Prod. 282, 124395. https://doi.org/10.1016/j.jclepro.2020.124395.
Villanova-Estors, R., Murcia-Velasco, D., Correa-Guimarães, C., López-Carballo, G., Hernández-Muñoz, P., Gavara, R., Navas- Garcia, L., 2023. Environmental consequences of shelf-life extension: conventional versus active packaging for fresh-cut salads. Agronomy. https://doi.org/10.3390/agronomy13112749.
Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230.
Wikström, F., Williams, H., 2010. Potential environmental gains from reducing food losses through development of new Packaging–a life-cycle model. Packag. Technol. Sci. 23 (7), 403–411. https://doi.org/10.1002/pts.906.
Wikström, F., Williams, H., Trischler, J., Rowe, Z., 2019. The importance of packaging functions for food waste of different products in households. Sustainability 11 (9), 2641. https://www.mdpi.com/2071-1050/11/9/2641.
Yadav, P., Silvenius, F., Katajajuuri, J.-M., Leinonen, I., 2024. Life cycle assessment of reusable plastic food packaging. J. Clean. Prod. 448 (2024), 141529.
Yokokawa, N., Kikuchi-Uehara, E., Sugiyama, H., Hirao, M., 2018. Framework for analyzing the effects of packaging on food loss reduction by considering consumer behavior. J. Clean. Prod. 174, 26–34. https://doi.org/10.1016/j.jclepro.2017.10.242.