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Comparative Life Cycle Assessment (LCA) of Packaging Materials for Tomato-Based Products to Pave the Way for Increasing Tomato Processing Industry Sustainability

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Abstract: Background: The tomato processing industry is a vital sector, with tomatoes being the primary vegetable for industrial transformation. To individuate potential actions to make the tomato processing industry more sustainable, a Life Cycle Assessment (LCA) was conducted for an Italian tomato processing company located in southern Italy. Methods: Foreground data were collected from the company, while background data were sourced from the Ecoinvent database. The assessment employed the CML-IA baseline (V3.5) method for midpoints and IMPACT 2002+ for endpoints. Results: The research revealed that a can of peeled tomatoes (400 g) and a bottle of tomato puree (500 g) were responsible for global warming potential (GWP) of 0.666 kg CO₂eq and 0.479 kg CO₂eq, respectively. The packaging phase is the primary contributor to adverse environmental effects and has been considered as the primary focus for improvement. The end-of-life (EoL) scenarios demonstrated that recycling packaging materials could significantly reduce CO₂ emissions by 46% and 48% for metal and glass packaging, respectively. Conclusions: Moreover, the replacement of tinplate cans with glass jars as alternative packaging materials for peeled tomatoes, and glass bottles with carton-based containers or stand-up pouches as alternative packaging materials for tomato puree emerged as more environmentally friendly options across various environmental impact categories.

Keywords: tomato processing industry; packaging; life cycle assessment; recycling; sustainability



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1. Introduction

Food production plays a central role in the 2030 Agenda for Sustainable Development, a global commitment aimed at eliminating poverty and hunger while concurrently reducing environmental and socio-economic impacts. As outlined by the United Nations (2015), this ambitious agenda recognizes that to achieve long-term sustainability, it is of utmost importance to implement actions to redesign food production processes [1]. Climate change presents the single biggest threat to sustainable development everywhere and its widespread, unprecedented impacts disproportionately burden the poorest and most vulnerable populations. Urgent actions to counteract climate change and its impact are integral to successfully achieving all SDGs [2].

The food industry is one of the largest industrial sectors and holds immense potential to shape the ecological footprint [3]. All phases, from the cultivation of crops to their transformation, distribution, and post-consumption waste management, play a part in the environmental impact of food production. Although the direct emissions of agriculture

represent a significant portion of global GHG emissions, it is crucial to recognize that, beyond the farm gate, the industrial transformation processes play a significant role in determining the environmental footprint of food production [4].

The tomato processing industry holds a significant position across the globe, providing a wide range of products such as ketchup and sauces, canned tomatoes with either peeled or whole fruits, and purees. However, as consumers' concerns and consciousness of sustainability continue to increase and drive their selection of food products, prioritizing the environmentally friendly ones, it becomes imperative for the tomato processing industry to adopt practices that mitigate its environmental impact [5]. In this regard, Life Cycle Assessment (LCA) emerges as a pivotal tool, enabling stakeholders to navigate the complexities of the industry while striving for a greener future [1].

LCA offers a comprehensive framework for evaluating the environmental impact of products and processes across their entire life cycle. By considering the full spectrum of inputs, outputs, and environmental factors associated with each stage, LCA provides a holistic understanding of a product's environmental footprint [6]. Through the utilization of LCA to determine the environmental footprint of the tomato processing industry, crucial insights into the hidden environmental costs associated with various stages of production can be obtained, from the cultivation of tomatoes to the processing, packaging, distribution, and waste management stages. This knowledge empowers stakeholders to identify inefficiencies, target hotspots, and individuate and implement effective strategies for reducing the industry's overall environmental footprint [7].

Within the complete life cycle of tomato processing, it becomes evident that the packaging stage presents substantial environmental challenges [8–11]. A variety of packaging materials are employed to meet the diverse needs of tomato-based products, with tins and glass bottles standing out as commonly used options.

Tomato products such as peeled, chopped, diced, whole, etc., are traditionally packaged in tin cans, which hold a market share of about 87% [12].

There is no evidence of the utilization of paper-based packaging, rigid plastics, and flexible pouches for these products due to the protective action exerted by the container on the integrity of the tomato fruits and pieces.

The limited adoption of these types of packaging materials is mainly due to factors related to product shelf life and barrier properties of the packaging material. Metal cans and glass bottles provide superior protection against oxygen, light, and moisture, which are critical factors in preserving the quality, taste, and nutritional value of tomato-based products over time. On the other hand, while flexible pouches, often used for intermediate products (pouches of 250–300 kg of tomato puree), offer advantages such as reduced weight and lower transportation costs, they generally have lower barrier performance compared to metal and glass [13]. Despite advancements in multilayer films and high-barrier materials, flexible pouches may still allow higher oxygen and moisture permeability, potentially compromising the stability and safety of tomato products, especially those requiring long-term storage. These properties make glass and tin materials ideal choices for tomato product packaging according to specific product needs and market preferences compared to other types of packaging such as pouch and multilayer packaging [14].

However, numerous LCA studies have revealed that the packaging phase of the tomato processing industry carries the highest environmental impact for purée in glass bottles [9,15], diced tomato, peeled tomato, tomato paste, and sauce in tins and steel drums [9,16–19] and ketchup in polypropylene bottles [20]. This significant environmental impact stems from multiple factors, including the extraction of raw materials, manufacturing processes, and transportation of packaging materials, all of which con-

tribute to greenhouse gas emissions. This exacerbates concerns related to climate change and resource depletion [21,22].

By individuating more sustainable packaging selection practices, the tomato processing industry can mitigate its environmental footprint, contribute to the circular economy, and align with global sustainability goals. Collaborative efforts among industry stakeholders, policymakers, and consumers can be the drivers of the necessary changes to identify and implement a more environmentally conscious packaging phase in the tomato processing industry [23]. To reach this goal, LCA could shed some light on the potential actions to drive positive changes, enhance sustainability, and guide decision-makers toward a more environmentally responsible and resilient tomato processing industry [24]. There are some studies considering re-designing polypropylene bottles for ketchup [20], reducing the glass weight for tomato puree [15], and removing plastic caps in the packaging of tinplate cans in tomato puree [25], offering potential solutions to alleviate the environmental consequences of the system. While some studies have examined the environmental impacts of tomato-based products, there is currently a lack of comprehensive studies with a specific focus on the packaging phase. In particular, there is a need to assess all possible packaging types to determine the most environmentally friendly option, taking into consideration the end-of-life (EoL) of the packaging materials. Conducting a thorough evaluation of the packaging options for tomato-based products using LCA can provide valuable insights into the environmental performance of different packaging materials and help identify the most sustainable choice.

To bridge the gap regarding the packaging phase, this article presents a real case study conducted on a tomato processing company situated in southern Italy. The primary objective of this research is twofold: to evaluate the LCA of the tomato processing industry to evaluate the environmental impact in different stages to define the hotspots and then to explore potential improvement scenarios within the packaging phase by sensitivity analysis. This study will answer the questions of whether it is more efficient to use packaging materials with higher environmental impact and higher recyclability, whether recycling packaging materials can cover the environmental load generated by them, or whether it is more effective to shift to packaging materials with less environmental impacts and less recyclability. In this respect, the sensitivity analysis is carried out by evaluating the EoL scenarios of packaging materials and evaluating possible alternative packaging materials. By comparing their respective environmental profiles, the study seeks to assess the potential benefits and drawbacks associated with each option to identify opportunities for enhancements and the promotion of sustainability across the tomato processing industry.

2. Materials and Methods

2.1. Description of Tomato Puree and Peeled Tomato Production Processes

In this research, the case study is a tomato processing company located in the south of Italy receiving approximately 54,000 tons of tomatoes from July to September and processing 42 tons/h of tomatoes to produce peeled tomatoes in tinplate cans of different weights of 230 g, 400 g, 2.5 kg, and 3.0 kg and tomato puree in glass bottles in different weights of 320 g, 350 g, 500 g, and 700 g. To simplify the description, the processing lines are divided into three main stages, the preliminary stage, the processing stage, and the packaging stage, as described in the following sections.

2.1.1. Tomato Puree Production

Preliminary Stage (Receiving, Washing, and Sorting)

In the preliminary processing stage, fresh tomatoes are loaded into a hydraulic flume directed in two washing stages and sorted (manually and optically) before being fed into

the thermal units. The inputs in this phase are fresh tomatoes, water, and electricity used from pumps providing the water at the washing stages, and the outputs are washed tomatoes, wastewater, and solid wastes, including leaves, branches, soil, and stones from the washing stages, as well as defective and damaged tomatoes separated from optical and manual sorting steps, and sludge from wastewater treatment. The tomato wastes and sludge generated in the preliminary stage are considered avoided products applied for animal feed and agricultural purposes after some modification, respectively.

Processing Stage (Chopping, Hot Break, Juice Extraction, Evaporation, and Pasteurization)

In the processing stage, tomatoes are fed into the cutting section, and then into the hot break (HB), where chopped tomatoes are steam-heated to inactivate pectolytic enzymes before being pumped to the extraction unit, which has two output products: refined juice for concentration and by-products, namely tomato peels, seeds, and pulp given to farmers as animal feed. The refined juice, with 4.7–5% solid content, is concentrated in an evaporation unit at ~8.5 °Brix and pre-heated up to 102 °C in a tube-in-tube pasteurization unit. The main inputs in this stage are methane used to produce steam in the boilers providing thermal energy as well as electricity and water. Moreover, citric acid (used to adjust the pH) and sodium chloride enter the tanks and are both considered in the system boundaries of the process.

Packaging Stage (Primary, Secondary, and Tertiary Packaging)

In the primary packaging phase, tomato puree is packaged in glass bottles in an in-container filler, capped in a capping unit, and transported on a belt in a pasteurization tunnel (98 °C) for pasteurization using steam as the heating medium. After the heating and holding phases, the bottles are cooled down, utilizing cold water flumes. Dried bottles enter a packaging machine for labeling. In the secondary packaging phase, labeled bottles are placed in carton trays, wrapped with a shrinking film (low-density polyethylene) (LDPE), and sent to a tertiary packaging phase, where trays are placed on pallets and wrapped again with LDPE film. Pallets are then transported by electrical and diesel vehicles in the warehouse before being delivered to customers.

2.1.2. Peeled Tomato Production Line

In the peeled tomato production line, the preliminary and packaging phases are similar to those of the tomato puree production line, while the processing phase is different. After washing and sorting (manually and optically), tomatoes are fed onto the steam peelers, where tomatoes undergo a thermophysical peeling process. Peeled tomatoes are then sorted in optical and manual sorting steps to remove tomato fruits that are not properly peeled or that do not comply with commercial standards. The byproducts of the peeling and sorting stages are provided to farmers as animal feed. Peeled tomato (60%) and tomato juice at 8.5 °Brix (40%) are filled in tinplate cans in an automatic filler, provided with a seamer where lids are crimped to the cans and finally loaded in the pasteurizers for heating, holding, and cooling stages, and, after being dried, enter a labeling machine. In the secondary packaging stage, labeled cans are placed on carton boards and wrapped with LDPE film. In the tertiary packaging phase, boxes containing cans are placed on wood pallets, wrapped with LDPE film, and transferred with electric and diesel vehicles in the warehouse of the company before being delivered to customers.

2.2. Life Cycle Assessment Methodology

A widely accepted methodology for assessing the environmental impact of a product or service throughout its entire life cycle is LCA. It follows a standardized approach, as established by the ISO standards 14040 and 14044 [26,27]. This methodology enables the un-

derstanding, evaluation, quantification, and analysis of all potential environmental impacts. A comprehensive LCA analysis typically entails four distinct steps or sub-sections: defining the objective and scope of the study, conducting a life cycle inventory (LCI), performing a life cycle impact assessment (LCIA), and interpreting the obtained results [7]. Through this structured process, a holistic comprehension of the environmental implications associated with a particular product or service can be achieved. The system under investigation and its environmental performance were modeled using SimaPro software (v 9.0.048).

2.2.1. Definition of the Goal and Scope of the Study

Defining the goal and scope of an LCA study is a crucial step that establishes the boundaries and objectives of analyzing a system, encompassing all relevant stages and activities throughout the product's life cycle and ensuring the reliability, comparability, and usefulness of the results for decision-making [7].

The primary objective of this study is to conduct a baseline LCA to assess the environmental impact associated with the production of packed peeled tomato and tomato puree in a company based in southern Italy. The focus on the cultivation, processing, packaging, transportation, and end-of-life stages allows for a comprehensive system assessment. The goal is to identify potential improvements and develop strategies to reduce the environmental impacts associated with the hotspot stage through the scenarios evaluated by sensitivity analysis. The study explores the effects of variations in these parameters on the relevant impact categories and quantifies the potential benefits that can be achieved.

Functional Unit

In LCA analysis, the functional unit (FU) plays a vital role as it quantitatively describes the performance of the product, service, or process being studied [26]. The FU serves as a reference unit for standardizing inventory data, enabling the comparison of environmental impacts among different products or processes [27].

Within the context of the food industry, the FU is commonly defined based on the mass of the product under analysis. This definition takes into account all the inputs and outputs associated with the manufacture of the product, considering the entire life cycle of the product, from raw material acquisition to disposal [7]. In this study 400 g of peeled tomato (60% peeled tomato/40% preserving juice) in a tinplate can and 500 g of tomato puree in a glass bottle, which are the package sizes most commonly available for consumers in the Italian market, are considered as FUs.

System Boundaries and Key Assumptions

Figure 1 provides an overview of the system boundaries for the tomato processing industry of this case study. It encompasses all stages involved, starting from the upstream processes, such as the cultivation phase, the production of energies, ingredients, and packaging materials, followed by the core processes that encompass all the steps involved in tomato processing, including the pre-processing, processing, and packaging phases, and lastly, the downstream processes, involving the distribution of tomato products to retailers in Italy, and the EoL for primary packaging material in Italy, while the EoL of secondary and tertiary packaging is out of the system boundaries.

However, it is important to note that certain aspects are outside the system boundaries of this case study. For instance, the transportation of fresh tomatoes and the processing/packaging of materials from suppliers to the company are not included. Additionally, non-consumable materials like facilities, pallets, and the land used for the company are also outside the scope of this study. It is important to mention that the company's by-products, including tomato waste, which is currently provided to farmers as animal feed, and leaves, branches, and sludge applied as fertilizers in agriculture, are not included within the system

boundaries of LCA due to their potential environmental benefits [9]. Moreover, the study follows the “Polluter-Pays (PP) allocation method”, which assigns responsibility to waste generators for the full environmental impact of their actions until the waste reaches the gate of the waste processing plant. As a result, system expansion and the avoided burdens from recycling are not taken into account in this particular study [28].

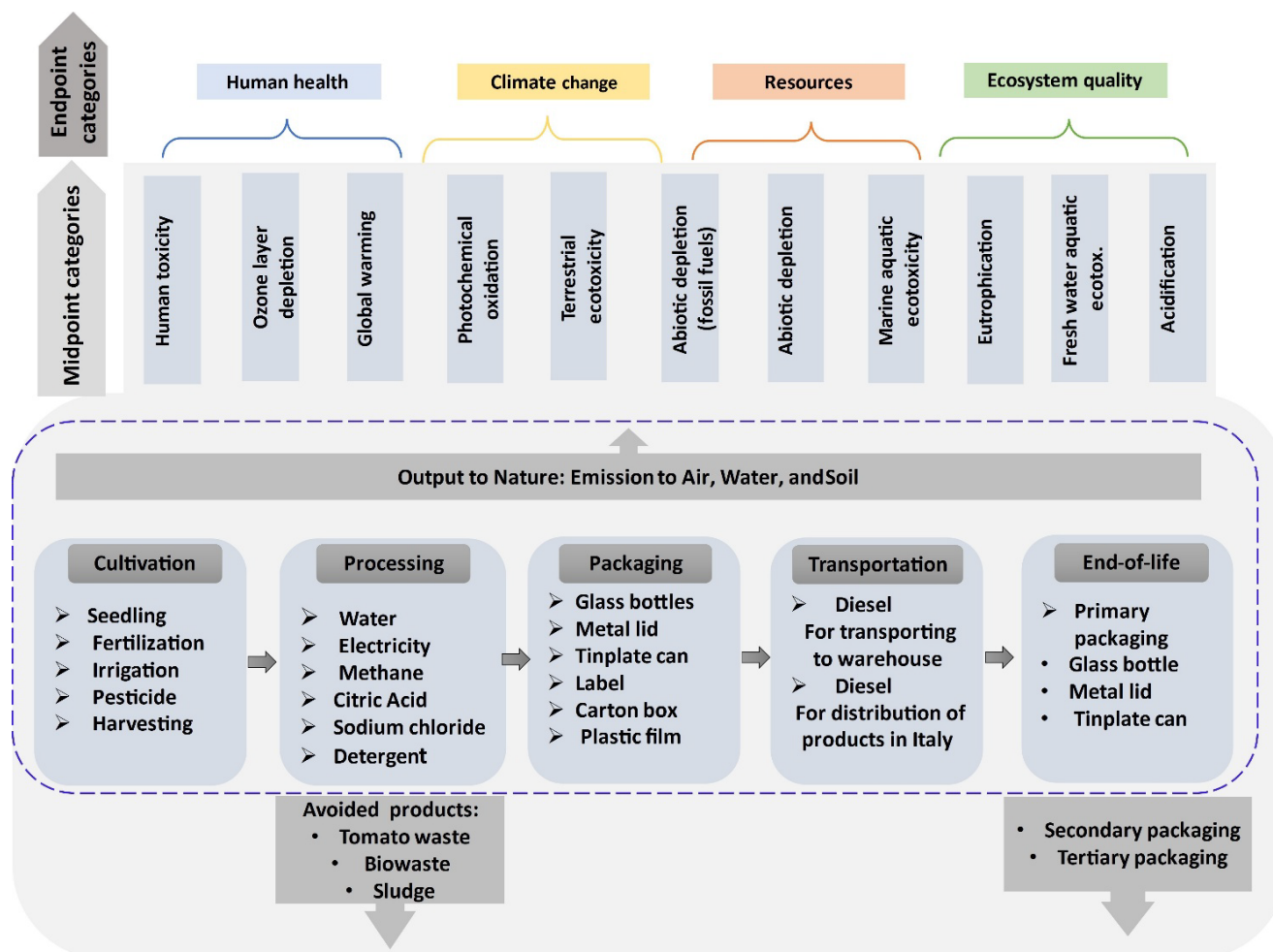


Figure 1. The blue dashed line shows the system boundaries in the case study of the tomato processing industry.

2.2.2. Data Collection and Life Cycle Inventory

Life Cycle Inventory serves as a foundation for assessing the environmental footprint of a product by providing valuable insights into the resources consumed and the emissions generated at each life cycle stage [29].

This study relies on both foreground and background data to ensure a comprehensive analysis. The foreground data, encompassing details on the quantity and type of raw materials, ingredients, energy, and packaging materials, were obtained from the company, also through questionnaires administered in person and interviews with technicians. To complement the foreground data, background data from the Ecoinvent database (V3.5) were incorporated. This extensive database provides comprehensive information regarding the production of electricity, methane, chemicals, tomatoes, ingredients, and all packaging materials used in this study [30]. To ensure that the analysis reflects the specific characteristics and circumstances of the Italian context, efforts have been made to incorporate information that aligns with the Italian context wherever possible. However, where specific

data on the Italian scenario were unavailable, the study relies on data representing the European situation.

In the present study, the primary emphasis is not on the LCA of the agriculture phase. However, to ensure comprehensive analysis, the data regarding the cultivation of processing-grade tomatoes in open fields in Italy (2011–2019) were obtained from Ecoinvent (V3.5). This dataset incorporates all the essential steps involved in the tomato cultivation process, such as seeding, fertilization, pesticide production, and application, as well as irrigation and harvesting [30]. For the processing phase, precise measurement and monitoring of key resources, including water, electricity, and methane, were obtained from sensors installed in the production area and on the two production lines of peeled tomato and tomato puree analyzed. However, it is important to note that to produce the different tomato-based products in the company, some production stages are shared. As a result, specific data for each individual product were unobtainable, leading to the challenge of allocation. According to ISO 14044 guidelines, when specific data for individual products are unavailable, physical relationships between products can be used to allocate inputs and outputs. As a result, the consumption of resources for the common stages was allocated to the various products proportionally to the volume of each product produced [27].

As far as water-related emissions during the processing stage are concerned, wastewater produced during tomato processing is discharged into the municipal sewage system after exiting the wastewater treatment plant and is considered the final waste flow in the assessment. The eventual presence and amount of pollutants were determined by carrying out laboratory tests on wastewater samples collected at the company site. Air pollution is generated during the processing phase due to methane combustion in the boilers to provide thermal energy in various tomato processing stages. Diesel fuel is used in vehicles used to transport the final products to the warehouse. Information on emissions from burning methane and diesel fuels and their environmental impact was sourced from the Environmental Protection Agency (EPA) database [31]. For the transportation of the tomato products to the Italian market the company relies on freight lorries with a capacity of 16–32 metric tons powered by diesel fuel, and the maximum traveled distance considered in the assessment is 600 km. To evaluate the direct emissions resulting from the combustion of diesel fuel during the transportation of the final products within Europe, relevant data were obtained from the Ecoinvent database [30]. Table S1 provides a detailed life cycle inventory for the processing, packaging, and transportation phases for peeled tomato and tomato puree production.

2.2.3. Impact Assessment

The evaluation of the potential environmental impacts associated with the usage of various types of resources to produce goods and the resulting emissions of pollutants was performed using a set of indicators. The LCA methodology chosen to elaborate characterization factors is the CML-IA baseline, developed by the Centre of Environmental Science (CML) at Leiden University in the Netherlands [32].

The CML-IA baseline methodology is widely recognized and utilized in LCA studies due to its robustness and comprehensiveness. It provides a comprehensive set of characterization factors for 11 midpoint impact categories, which are universally recognized for the assessment of environmental impacts. These categories include Abiotic Depletion (AD), Abiotic Depletion-Fossil Fuels (AD-FF), Global Warming Potential (GWP100a), Ozone Layer Depletion (OLD), Human Toxicity (HT), Freshwater Aquatic Ecotoxicity (FE), Marine Aquatic Ecotoxicity (ME), Terrestrial Ecotoxicity (TE), Photochemical Oxidation (PO), Acidification (AC), and Eutrophication (EP) [32]. Furthermore, in this study, the IMPACT 2002+ method was employed to classify the environmental impacts of peeled tomato and

tomato puree on climate change (CC), human health (HH), resources (R), and ecosystem quality (EQ) at the endpoint level.

3. Results and Discussion

3.1. Contribution at the Midpoint Level: From Cultivation to Transportation

The interpretation of the LCA revealing the potential environmental impacts from tomato cultivation to transportation is reported in Table 1. Moreover, Figure 2 reports the contribution of the total environmental impacts of each stage involved in producing a can of peeled tomato and a bottle of tomato puree.

Table 1. Life cycle impact indicators of PT: a can of peeled tomato (400 g), TP: a bottle of tomato puree (500 g).

Product	Impact Category	Unit	Total	Cultivation	Processing	Packaging	Transportation
PT TP	AD	kg Sb eq	1.26×10^{-5} 3.04×10^{-6}	1.441×10^{-6} 9.17×10^{-7}	7.82×10^{-8} 1.16×10^{-7}	1.10×10^{-5} 1.82×10^{-6}	1.387×10^{-7} 1.39×10^{-7}
PT TP	AD (FF)	MJ	6.90×10^0 5.66×10^0	1.222×10^0 7.77×10^{-1}	2.84×10^{-1} 5.54×10^{-1}	4.63×10^0 3.51×10^0	7.639×10^{-1} 7.64×10^{-1}
PT TP	GWP100a	kg CO ₂ eq	6.66×10^{-1} 4.79×10^{-1}	1.311×10^{-1} 8.34×10^{-2}	4.54×10^{-2} 7.42×10^{-2}	4.40×10^{-1} 2.57×10^{-1}	4.976×10^{-2} 4.98×10^{-2}
PT TP	OLD	kg CFC-11 eq	5.64×10^{-8} 5.48×10^{-8}	1.586×10^{-8} 1.01×10^{-8}	2.44×10^{-9} 5.11×10^{-9}	2.87×10^{-8} 2.99×10^{-8}	9.362×10^{-9} 9.36×10^{-9}
PT TP	HT	kg 1,4-DB eq	5.20×10^0 8.32×10^{-1}	6.348×10^{-2} 4.04×10^{-2}	1.12×10^{-2} 1.99×10^{-2}	5.11×10^0 7.50×10^{-1}	1.651×10^{-2} 1.65×10^{-2}
PT TP	FE	kg 1,4-DB eq	1.14×10^0 2.76×10^{-1}	3.778×10^{-2} 2.40×10^{-2}	1.86×10^{-2} 3.37×10^{-2}	1.08×10^0 1.92×10^{-1}	4.524×10^{-3} 4.52×10^{-3}
PT TP	ME	kg 1,4-DB eq	1.67×10^3 8.41×10^2	1.148×10^2 7.30×10^1	4.67×10^1 1.04×10^2	1.49×10^3 6.42×10^2	1.329×10^1 1.33×10^1
PT TP	TE	kg 1,4-DB eq	7.78×10^{-3} 1.87×10^{-3}	5.544×10^{-4} 3.53×10^{-4}	1.96×10^{-4} 2.78×10^{-4}	6.96×10^{-3} 1.16×10^{-3}	7.115×10^{-5} 7.11×10^{-5}
PT TP	PO	kg C ₂ H ₄ eq	1.86×10^{-4} 1.29×10^{-4}	3.304×10^{-5} 2.10×10^{-5}	8.23×10^{-6} 1.38×10^{-5}	1.36×10^{-4} 8.34×10^{-5}	9.111×10^{-6} 9.11×10^{-6}
PT TP	AC	kg SO ₂ eq	3.72×10^{-3} 3.42×10^{-3}	8.579×10^{-4} 5.46×10^{-4}	3.83×10^{-4} 5.80×10^{-4}	2.23×10^{-3} 2.00×10^{-3}	2.521×10^{-4} 2.52×10^{-4}
PT TP	EP	kg PO ₄ eq	1.79×10^{-3} 1.12×10^{-3}	6.711×10^{-4} 4.27×10^{-4}	1.96×10^{-4} 2.59×10^{-4}	8.59×10^{-4} 3.60×10^{-4}	6.055×10^{-5} 6.06×10^{-5}

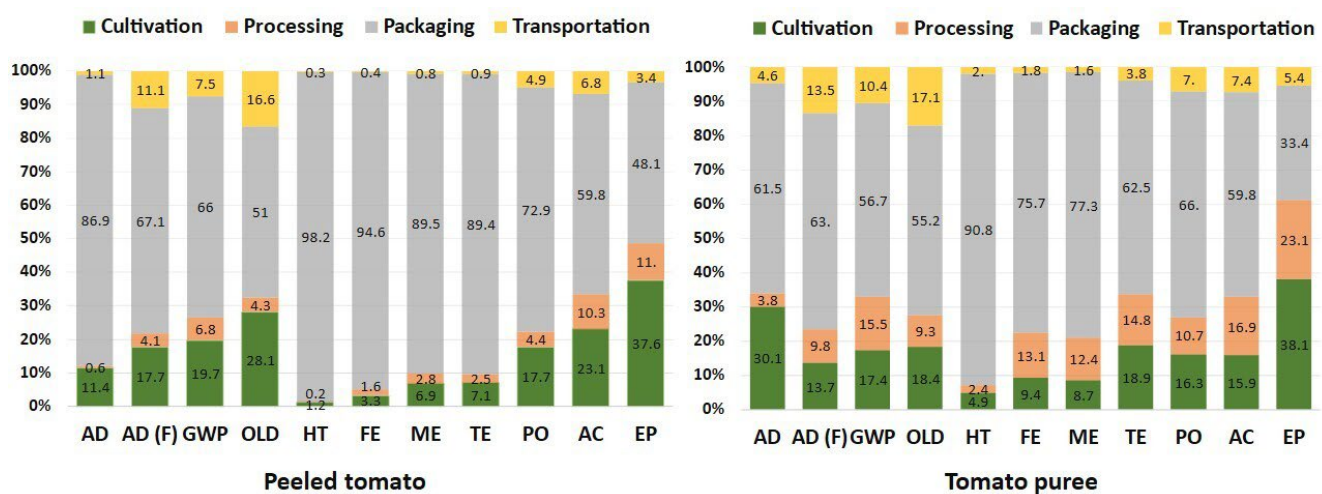


Figure 2. Environmental impact contributions at the midpoint level for a can of peeled tomato (400 g) and bottle of tomato puree (500 g).

The study reveals that to produce a can of peeled tomato, 0.666 kg CO₂ is generated, and the packaging phase is the most significant contributor to the GWP, accounting for 66% of the total emissions. Cultivation, transportation, and processing also play a role, contributing 19.7%, 6.8%, and 7.5% to the GWP, respectively. This suggests that focusing on packaging improvements could lead to substantial reductions in the overall environmental impact of canned peeled tomatoes. It is worth noting that packaging significantly (approximately 90%) contributes also to human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, and terrestrial ecotoxicity, and more than 50% in other impact categories, except eutrophication. Similarly, for tomato puree production in glass bottles, 0.479 kg CO₂ is generated, and packaging is identified as the primary contributor to the GWP, accounting for 56.7% of the total emissions. Cultivation, processing, and transportation contribute to 17.4%, 15.5%, and 10.4% of the GWP, respectively. The packaging stage is responsible for more than 60% of the contribution in human toxicity and freshwater, marine, and terrestrial ecotoxicity and more than 55% in the other impact categories, except for eutrophication. These results emphasize the importance of addressing packaging-related emissions in the production of tomato puree. The high contribution of packaging to the environmental impacts can be attributed to the substantial energy and resource consumption involved in the manufacturing of packaging materials [21]. The cultivation process is a matter of concern for eutrophication, predominantly due to the use (by human actions) of nitrate and phosphate-based fertilizers in agricultural practices [9].

These findings indicate that interventions targeting packaging materials and practices could yield significant environmental benefits in the production of packed peeled tomatoes and tomato puree. Among these strategies, namely using more sustainable packaging materials, optimizing packaging designs, and improving recycling and waste management systems, could significantly help to reduce the environmental impacts associated with these products.

Table 2 provides an overview of the CO₂eq emissions in the tomato processing industry evaluated in different LCA studies. Our findings are consistent with those evaluated by other authors. For instance, Del Borghi et al. [9] conducted an LCA study on tomato processing products in Italy and reported that the production of 400 g of peeled tomato in a tinplate can result in 0.607 kg CO₂eq emissions, with the packaging being the main contributor (0.330 kg CO₂eq). In another study by Arnal et al. [33] on peeled tomato production, it was found that the production of 400 g of peeled tomato in a tinplate can lead to 0.60 kg CO₂eq emissions, with packaging accounting for the majority (more than 90%) of the impact.

Table 2. Overview of reported CO₂ emissions by different studies for tomato-based products.

Functional Unit	Country	Considering Phase	Methodology	Environmental Hotspots	CO ₂ eq (kg)	R-Year
1 kg of tomato paste and diced tomato in tinplate cans	USA	Cultivation Processing Packaging Transportation	Not available	Packaging processing	1.46–1.65 Tomato paste 0.711–0.999 Tomato puree	[16]
1 kg of chopped tomato, peeled tomato, and tomato purée in glass, carton-based and can packaging	Italy	Cultivation Processing Packaging	CML 2001	Packaging agricultural	0.97–1.55	[9]
Tomato puree in glass jars (700 g)	Northern Italy	Cultivation Processing Packaging Transportation	CML 2001 and ReCiPe	Packaging agricultural	0.674	[15]
1 kg of tomato puree Without packaging	Northern Italy	Processing Waste management	Recipe	Processing	0.116	[34]

Table 2. Cont.

Functional Unit	Country	Considering Phase	Methodology	Environmental Hotspots	CO ₂ eq (kg)	R-Year
Tomato puree in carton (500 g)	Italy	Processing Packaging Transportation	IMPACT 2002+	Processing	0.172	[35]
1 kg of tomato juice in plastic bottle	Germany	Cultivation Processing Packaging	IMPACT 2002+	Packaging	1.83	[36]
Peeled tomato in tinplate (400 g)	Italy	Cultivation Processing Packaging Transportation End of life	ILCD 2011	Waste treatment	0.447	[37]
Tomato puree in carton (500 g)	Italy	Cultivation Processing Packaging Transportation End of life	ReCiPe 2016	Cultivation	0.774	[38]
1 kg peeled tomato in tinplate can (without juice)	Italy	Processing	ReCiPe	Packaging	1.50	[33]
Tomato puree In tinplate with plastic cap (500 g)	Iran	Cultivation Processing Packaging Transportation	CML-IA baseline	Packaging	0.338	[25]
1 kg tomato pasta sauce in glass and tin lid	USA	Cultivation Processing Packaging Transportation End of life	ReCiPe 2016	Processing agriculture	1.50	[18]
1 kg Diced tomato and tomato paste during (2005–2015)	USA	Cultivation Processing Transportation	CLM	Cultivation Processing	0.213–0.157 Diced tomato 0.945–0.827 Tomato paste	[17]
1 kg chopped tomatoes with juice in multi-layer plastic pouches, and tinplate can	Italy	Cultivation Processing Packaging	CML-IA baseline	Processing Appertization Ohmic heating	2.52–4.38	[6]
Tomato paste packaged in 220-L steel drums	China	Cultivation Processing Packaging Transport	CML 2002 and EI99	Cultivation Processing	490 for cold break, 516 for hot break	[19]

Manfredi and Vignali [15] reported that the production of tomato puree in glass bottles resulted in 0.47 kg CO₂eq emissions, from which 0.12 kg CO₂eq were attributed to cultivation, 0.077 kg CO₂eq to processing, 0.2 kg CO₂eq to packaging, and 0.079 kg CO₂eq to transportation, which closely align with the results of our work. Del Borghi et al. [9] also found that 500 g tomato puree packed in glass bottles generated 0.51 kg CO₂eq, with packaging contributing 0.23 kg CO₂eq. The findings of this study slightly differ from the results obtained by these authors, although the trends are similar. Furthermore, the study by Bacenetti et al. [34], specifically focusing on the processing phase of tomato puree production in Italy, reported 0.058 kg CO₂eq emissions. Similar results for the processing phase (0.074 kg CO₂eq) were obtained in our study, corroborating the outcomes presented in this paper.

It is important to note that LCAs are highly context-specific, and evaluating the environmental impacts of food production requires careful consideration of factors such as the location of the company where the study is conducted, inputs and outputs at each stage, and EoL stages for recycling or disposal. Slight variations in the system boundaries and

assumptions made in the surveys can significantly affect the results, potentially leading to different conclusions in the assessments of the environmental impact of food production.

3.2. Endpoint Level Contribution with Value Normalization

Value normalization is a technique in LCA that facilitates the interpretation and comparison of environmental impact assessment results. It involves dividing the impact indicator by a reference value to create a dimensionless indicator, which can be used to compare different products, processes, or scenarios, and also to communicate the environmental performance of products or services to stakeholders [27,28]. As illustrated in Figure 3, to provide a can of peeled tomatoes to the Italian market, packaging has the most significant adverse environmental impacts on human health, resources, and climate change, which is mainly attributed to tinplate cans used in the packaging phase. Similarly, to supply a bottle of tomato puree, human health is the category most affected by glass packaging compared to the others. The significant effect of packaging on the environmental footprint is driven by several factors. Glass and tinplate packaging production heavily relies on substantial amounts of natural resources such as sand, soda ash, limestone, and iron ore. These resources are finite, and their extraction can lead to adverse environmental consequences [39]. Moreover, the production of glass and tinplate packaging requires very energy-intensive processes as the materials must be melted at a high temperature of around 1200 °C [40]. In addition, during the production of glass and tinplate can packaging, the release of pollutants, such as sulfur dioxide, nitrogen oxides, and particulate matter, can lead to respiratory problems and various health issues. Similarly, the production of tinplate can also result in the release of volatile organic compounds (VOCs), which have detrimental effects on human health [40]. Consequently, the utilization of specific materials, along with the emissions linked to their manufacturing processes and their role in waste and pollution generation, positions them as primary contributors to environmental impacts across various categories [22,41]. However, the cultivation phase significantly impacts ecosystem quality and human health. The phase involves activities such as land use, irrigation, and applying fertilizers and pesticides, which can significantly impact the natural ecosystem. For example, the use of synthetic fertilizers and pesticides can lead to soil degradation and the pollution of nearby water sources, negatively affecting the health of local ecosystems [42].

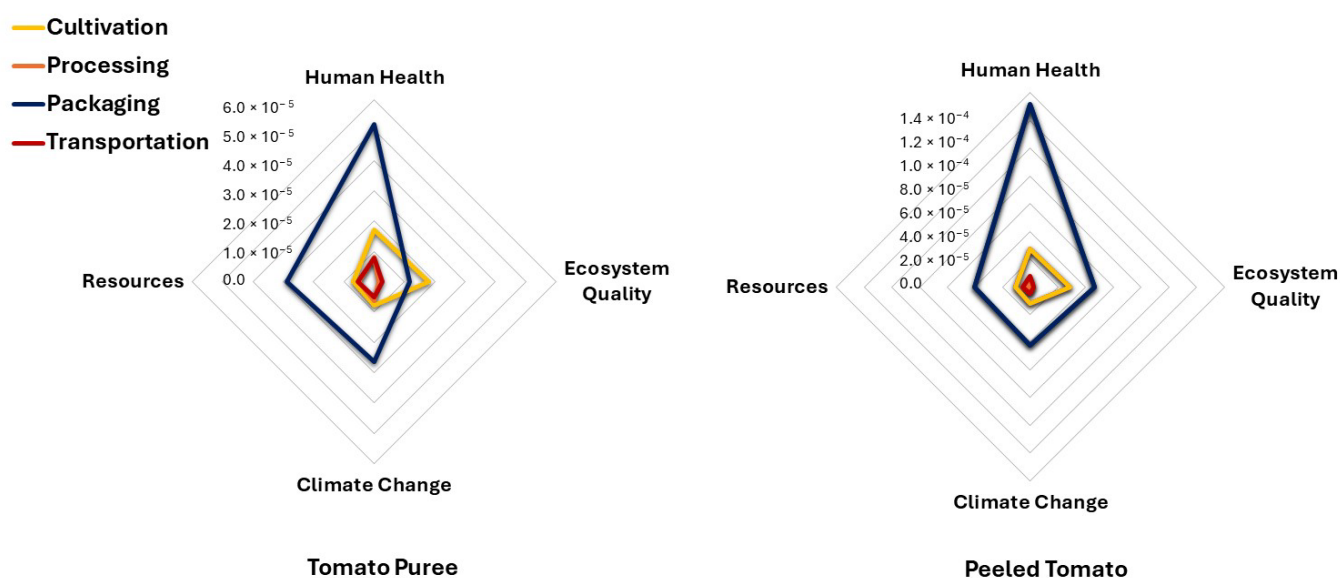


Figure 3. Normalized values at the endpoint level for a can of peeled tomato and a bottle of tomato puree (FU).

3.3. Contribution of the Packaging Phase to Environmental Impact at the Midpoint Level

Considering that the packaging phase has the highest impact at both the midpoint and endpoint levels, this study thoroughly examined the contributions to environmental footprint at a midpoint level of different packaging types (glass, metal, paper, plastic) applied in primary, secondary, and tertiary packaging. Figure 4 provides an overview of the impact categories and the corresponding contributions of various packaging materials in peeled tomato cans and tomato puree bottles.

In the case of peeled tomato production, the use of tinplate cans is identified as the primary contributor, accounting for over 92% of all impact categories in the packaging phase, followed by paper (0.6–4.9%) and plastic (0.02–3.9%), which have a relatively insignificant contribution. For tomato puree production, the metal used for bottle lids has the highest impact on human toxicity (80.1%), abiotic depletion (70.5%), terrestrial ecotoxicity (67.6%), freshwater ecotoxicity (65.5%), and glass, on the other hand, contributes to the remaining impact categories, with percentages ranging from 66.1% in eutrophication to 86.1% in ozone layer depletion, and paper packaging (0.6–5.4%) and plastic packaging (0.2–5.9%) have the lowest contributions in all categories.

These findings can be attributed to the extensive use of resources associated with glass and steel production. The manufacturing process for glass involves the utilization of materials such as silica sand, soda, limestone, and dolomite, while steel production requires the extraction of ferronickel, iron ore, and limestone. Additionally, the emission of SO₂ and hydrocarbons, which contribute to acidification and photo-oxidant formation, is mainly associated with electricity consumption and fuel use, particularly natural gas and heavy fuel oil, for glass and steel manufacturing [9,10].

Within the packaging subsystem, the manufacturing of chromium steel, including the pre-treatment of ore and its subsequent reduction to high-carbon for chromium, significantly contributes to human toxicity and terrestrial ecotoxicity in tinplate cans and metal lids for bottles [9].

Several studies have confirmed the significant environmental impact of tinplate and glass packaging materials used for peeled tomatoes. Shahvarooghi Farahani et al. [24], Arnal et al. [33], and Garofalo et al. [37] conducted studies on the environmental impact of peeled tomato packaging in tinplate cans. In these studies, it was found that tinplate cans were the primary contributor, accounting for 70% to 80% of the environmental impact across all impact categories.

Similarly, Manfredi and Vignali [15], in their LCA study on tomato puree production, highlighted the significant contribution to the environmental impact of glass bottles. They reported that glass bottles accounted for 66% to 82% of the overall packaging impact, followed by metal lids (11% to 20%), secondary packaging (6% to 21%), and paper labels (2%). The study emphasized that the weight of the glass bottles and the high energy requirements for glass production were the main factors driving their significant environmental effects.

These findings from multiple studies provide further evidence of the adverse influence on the environment of tinplate and glass packaging in the tomato processing industry. The weight, energy consumption, and resource utilization associated with these materials contribute significantly to the overall environmental impact. Considering alternative packaging materials or optimizing the production processes for tinplate and glass can help mitigate their environmental footprint in the tomato processing sector.

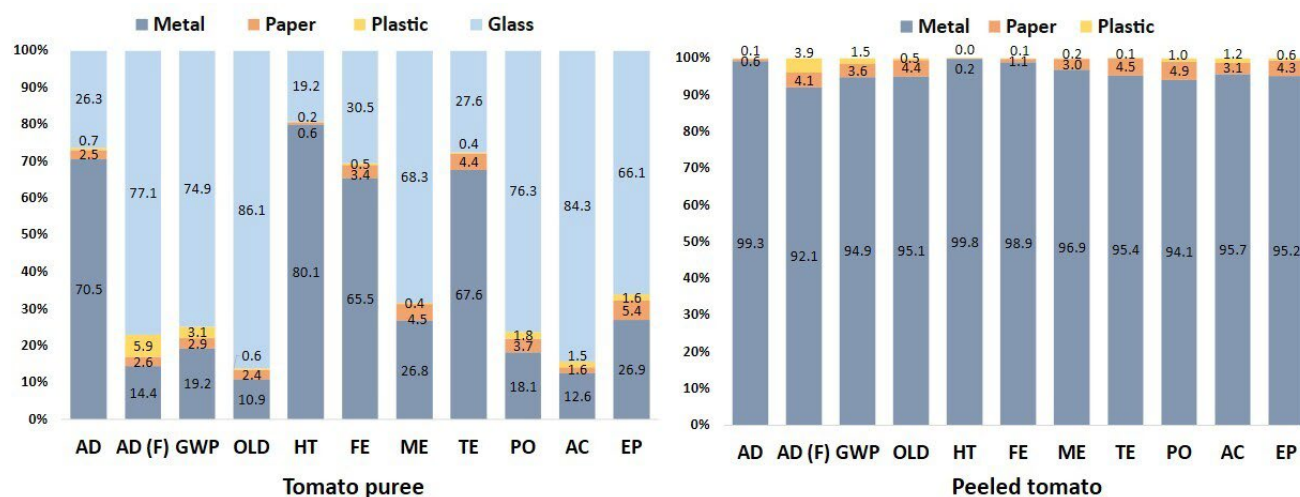


Figure 4. Contribution to the environmental impact in the packaging phase for peeled tomato (400 g) and tomato puree (500 g) production.

3.4. Development Scenarios and Sensitivity Analysis to Mitigate the Environmental Impact of the Packaging Phase in Tomato Processing

The primary objective of conducting an LCA study is to optimize the performance of the system analyzed through a sensitivity analysis. In this study, LCA results showed that the packaging stage is the main cause of environmental impact, with tinplate cans and glass bottles having significant environmental consequences.

Given the goal of selecting the best material for packaging tomato-based products with the least negative environmental effects, many studies concluded that metal and glass packaging have the highest environmental impacts among different types of packaging material [8–11,43]. However, the reduction in the environmental impact associated with packaging materials recycling in the EoL phase has been overlooked. Tinplate packaging is an example of how the application of circular economy practices can be beneficial to the environment. Its inherent recyclability (almost 100% recyclable) allows its usage in a continuous loop by recycling, reducing waste generation, and conserving valuable resources [43]. Through effective collection and recycling systems, tinplate packaging can be transformed into new steel products, ensuring the preservation of its protective properties and minimizing the need for the extraction of raw materials [44]. Similarly, glass packaging is 100% recyclable and can be recycled endlessly, ensuring that the recycled glass maintains the same level of quality and purity as the original material, making it a sustainable choice for packaging a wide range of products [45]. On the contrary, although multilayer packaging, including aseptic carton containers and pouches, has fewer environmental impacts [38,46], it poses challenges for recycling due to the complexity of separating the different layers [47]. Consequently, incineration is the most practical disposal method [48]. However, recent progress in recycling technologies has changed the perspectives on multiple uses of multilayer packaging, turning it into a potential candidate for recycling. However, the secondary materials produced by the recycling of multilayer packaging waste cannot replace the corresponding primary materials in a closed loop but can be only considered for open-loop recycling [49]. Moreover, since no official data on the percentage of recycling of multilayer packaging are available, the EoL stage of this kind of packaging material was not evaluated in this study.

To understand whether recycling the packaging material of current packaging types used in the company (tinplate cans and glass bottles) can compensate for their environmental impacts, the EoL scenarios of these materials have been evaluated by LCA. Since primary

packaging has the highest contribution to the environmental impact, and secondary and tertiary packaging have the lowest effects (less than 6%), only the EoL of primary packaging, including glass bottles with metal lids and tinplate cans, was considered in sensitivity analysis. Moreover, due to the complete recyclability of both materials and given that Italy exceeded the European target for 2030 for recycling rate for glass (75%) and metal (80%) packaging [50], a theoretical recycling rate of 100% of packaging materials can be a reachable goal in the close future [51,52], as evaluated in other scenarios. The inventory data in terms of the EoL of packaging material in Italy are presented in Table S2.

Additionally, alternative packaging options to replace glass containers for tomato puree were evaluated in different scenarios, focusing on materials with a lower environmental impact. Multilayer cardboard containers, commonly used as packaging materials for milk, juice, sauce, and fruit puree, as well as multilayer plastic and aluminum stand-up pouches, were considered, knowing that glass and tinplate containers are the most commonly used for packaging tomato puree rather than multilayer packaging materials. In this study, the cardboard container evaluated for tomato puree packaging (code C/PAP84) consists of poly laminated board (71% paper + 24% LDPE + 5% aluminum layer) and High-Density Polyethylene/Polypropylene (HDPE/PP) for closure and cap. The inventory data used for modeling the cardboard packaging for 500 g tomato puree, provided by the Tetra Pack company, were taken from the study of Ferrara and De Feo [42]. Moreover, flexible pouches of multilayer plastic and aluminum packaging (code C/LDPE90; 30% PET + 20% aluminum + 50% LDPE), which can be used also for tomato-based products packaging such as paste, puree, and sauce, were considered [53]. The inventory data to model this kind of packaging for a pack of tomato puree (500 g) were obtained from the LCA study performed by the organization [54]. The inventory data of both the cardboard and flexible pouch are presented in Table S3.

The only viable alternative to tinplate cans for peeled tomato packaging is the use of glass jars, which allow maintaining the integrity of tomato fruits. The foreground data regarding the glass jars was provided by the company in which this case study was conducted, where glass jars (202 g) with metal lids (8.4 g) were utilized for packaging 400 g of cherry tomatoes. Moreover, the background data for the production of glass jars and metal leads were obtained from the Ecoinvent database [30]. This study utilized eight scenarios for sensitivity analysis in the packaging stage of tomato puree and peeled tomato production.

- CS-1: Baseline scenario reflecting the current state of the primary packaging stage for peeled tomatoes with tinplate cans.
- SA-1: EoL scenario of tinplate packaging (current situation in Italy).
- SA-2: EoL scenario of tinplate packaging (100% recycling).
- SA-3: Replacement of tinplate packaging with glass packaging.
- SA-4: EoL scenario of glass packaging (current situation in Italy).
- CS-2: Baseline scenario reflecting the current state of the primary packaging stage for tomato puree with glass bottles.
- SA-5: EoL scenario of glass packaging (current situation in Italy).
- SA-6: EoL scenario of glass packaging (100% recycling).
- SA-7: Replacement of glass bottles with flexible pouch packaging.
- SA-8: Replacement of glass bottles with cardboard containers.
- SA-9: EoL scenario of glass packaging in Switzerland, which is the country with the lowest environmental impact in glass production.

Sensitivity Analysis to Identify Potentials for Improvement

The results presented in Figures 5 and 6 highlight the environmental impact of various peeled tomato and tomato puree packaging options. CS-1 and CS-2 refer to the existing packaging containers, considered as the reference point with 100% of the environmental impact. By comparing alternative scenarios to CS-1 and CS-2, improvements and/or challenges to reduce environmental impact can be easily identified.

According to Circular Economy Strategies of the European Union, steel recycling presents a compelling environmental benefit, as one ton of recycled steel saves considerable resources, namely 1.4 tons of iron ore, 0.8 tons of coal, 0.3 tons of limestone, and additives, and a reduction in CO₂eq emissions of 1.67 tons can be achieved. Additionally, substituting steel scrap for virgin ore results in a noteworthy 58% reduction in CO₂eq emissions in the production process of steel [55].

Considering the EoL scenario of the current situation in Italy, the recycling of tinplate cans yields substantial reductions in environmental impacts, as presented in Figure 5. Notably, global warming is reduced by 46%, and a significant decrease in other environmental impact categories occurs, ranging from 61% in human toxicity to 35% in ozone layer depletion. The scenario SA-2, involving 100% recycling, is the most promising, resulting in a 57% reduction in global warming. This highlights the environmental significance of steel recycling efforts. Furthermore, most environmental impact indicators show a potential reduction of over 50% through the complete recycling of tinplate cans.

The analysis of the development scenario SA-3 for peeled tomato packaging, replacing tinplate cans with glass jars, unveiled a substantial reduction in CO₂eq emissions from 0.417 to 0.284 kg CO₂eq, resulting in a decrease of 41% in global warming. Positive effects were found in all environmental impact categories, with the most significant improvements (more than 79%) observed in human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, and abiotic depletion. Moreover, when evaluating the EoL impact of both types of packaging, the results indicate that the EoL of glass packaging (SA-4) has a 34% reduction in global warming potential compared to the EoL of metal packaging (SA-1). Therefore, glass packaging emerges as a more sustainable option compared to tinplate cans.

The comprehensive evaluation of all scenarios for peeled tomato packaging indicates that recycling tinplate cans would lead to a substantial reduction in environmental impacts in all categories. However, the most favorable option is the substitution of tinplate containers with glass jars, considering the EoL scenario of glass (SA-4) and tinplate packaging (SA-1), or even scenario SA-2 with 100% recycling of tinplate cans. Thus, the proper management of the recycling and EoL of glass jars can contribute significantly to minimizing their overall environmental footprint. Nonetheless, due to their lower weight, tinplate packaging incurs reduced transportation costs and, consequently, lower carbon emissions. Furthermore, tinplate packaging is a more cost-effective alternative compared to glass packaging. Consequently, to determine the optimal choice of the packaging material, it is imperative to evaluate additional factors, including economic considerations.

Regarding glass recycling, the Federation of European manufacturers of glass containers [56] conducted a comprehensive LCA study, which covered 72% of European glass packaging producers to gain a complete picture of the CO₂ impact of glass manufacturing. The results showed that 1 ton of recycled glass (cullet) effectively substitutes 1.2 tons of virgin raw material, resulting in a reduction of 0.67 tons in CO₂eq emissions/ton of ready-to-use glass (EU average). Thus, replacing all virgin materials with recycled glass leads to a substantial reduction of approximately 58% in CO₂eq emissions.

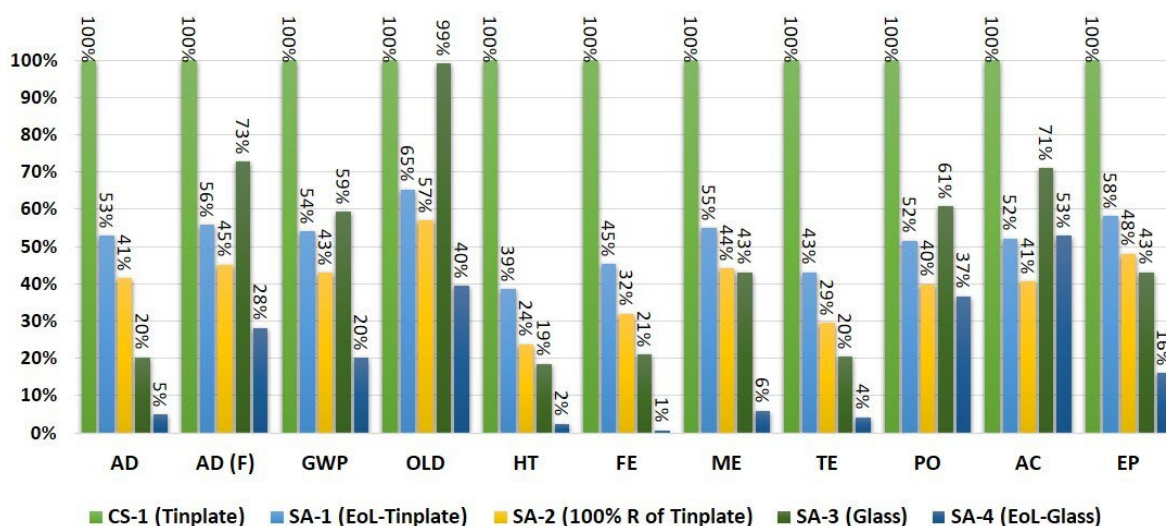


Figure 5. Sensitivity analysis for different scenarios of peeled tomato packaging.

For tomato puree, EoL scenarios related to glass packaging have provided valuable insights into its environmental impacts, as presented in Figure 6. Presently, recycling glass at 80.8% leads to a considerable reduction in environmental impacts across all categories, ranging from 26% in photochemical oxidation to 68% in freshwater aquatic ecotoxicity. Additionally, considering the recycling at 100%, photochemical oxidation is reduced by 32% and freshwater aquatic ecotoxicity by 85%. More importantly, recycling glass at 80.8% and 100% has shown the potential to reduce GWP of 48% (0.138 kg CO₂eq), and 60% (0.104 kg CO₂eq), respectively, compared to the base scenario (0.263 kg CO₂eq).

Replacing glass bottles with carton-based containers resulted in a remarkable reduction in GWP from 0.263 to 0.040 kg CO₂eq, with a decrease of 85% in CO₂eq emissions in the packaging phase. These results align with those presented in previous studies, such as Del Borghi et al. [9] and De Marco et al. [35,38], which also demonstrated that carton-based packaging for tomato puree generates lower CO₂eq emissions (0.05–0.07 kg CO₂eq) compared with glass containers. It should be noted that their studies also encompassed secondary and tertiary packaging, which may explain the discrepancy between their final results and those of our study.

Furthermore, the benefits associated with the utilization of carton-based containers for tomato puree packaging extend beyond GWP. In fact, this study reveals that the environmental impacts were reduced by more than 76% in all categories. These findings emphasize the potential of carton-based containers in providing a more sustainable packaging solution for tomato puree.

The LCA results revealed that the use of multilayer pouch packaging for tomato puree generated only 0.051 kg CO₂/500 g of product, which resulted in an 80% reduction in CO₂ emissions compared to glass packaging. Moreover, pouch packaging demonstrated a remarkable environmental advantage in other impact categories, with a reduction of 97% in human toxicity and 30% in abiotic depletion. It should be emphasized that this study exploring pouch packaging for tomato-based products was preceded by only one previous work, performed by the FPE organization, focusing on the LCA of pouch packaging for pasta sauce and comparing various packaging types, including tinplate, glass, and flexible multilayer pouch. The reported data allow us to conclude that pouch packaging generates approximately 0.055 kg CO₂eq per 500 g of pasta sauce, representing a substantial reduction of 63% and 69% when compared to glass and tinplate packaging, respectively [54].

The comprehensive analysis of all scenarios illustrated in this work enables us to highlight the significant environmental benefits of recycling in reducing the overall envi-

ronmental impact in all categories. Comparing all scenarios with the base scenario, the environmental footprint of carton-based and pouch packaging have a similar pattern in most categories and emerge as the best options for tomato-based product packaging. Even a 100% recycling rate of tinplate and glass containers is assumed, and the recycling of multilayer packaging is disregarded, carton-based and pouch packaging still outperform glass bottles in all categories, except abiotic depletion (AD), where pouch packaging showed a higher environmental impact. Nevertheless, it is worth emphasizing that glass packaging offers numerous advantages over carton-based and pouch packaging in the food industry, not only due to its reusability and recyclability but also to the intrinsic characteristics of glass, which is derived from natural compounds, is a nonporous, impermeable and durable material, has no or minimal chemical interactions with the products, and allows preserving food quality [56]. Moreover, in a pan-European survey commissioned by the FEVE [56], it was found that 74% of European consumers prefer glass packaging for their food and drinks. In addition, according to the InSites research in 13 European countries, 8 out of 10 consumers would recommend glass packaging over any other packaging materials due to its ability to preserve the taste of foods [57]. According to FEVE's recent study, 57% of European consumers affirmed that glass plays a prominent role in protecting their health and overall well-being (Federation of European manufacturers of glass containers) [58]. These findings emphasize the importance of using sustainable and eco-friendly packaging materials that meet consumer preferences and expectations. Consequently, when determining the optimal choice for tomato puree packaging, factors beyond environmental considerations, such as consumer preference, must be considered.

Examining the pivotal role of the glass packaging industry and consumer behavior in mitigating environmental consequences, an evaluation of glass production was conducted based on the Ecoinvent database in Switzerland [29] within scenario SA-9, incorporating the prevailing glass recycling rate of 94% [59]. This study unveiled that the manufacturing of a glass bottle (for 500 g tomato puree) incurred 0.185 kg CO₂eq emissions, marking a substantial reduction of 30% compared to the emission in the Italian case of 0.263 kg CO₂eq.

Assessing the EoL phase of glass packaging in Switzerland (CH), the findings demonstrated a remarkable environmental impact decrease ranging from 66% to 92% across diverse categories when juxtaposed with the baseline scenario. Notably, the GWP registered an 87% decrease with respect to the base scenario (CS-2) and a 27% decrease compared to the current situation in Italy (SA-5). This not only outperforms alternative multilayer packaging solutions, including carton-based containers and flexible pouches but also underscores the significance of implementing innovative industrial approaches in glass packaging and fostering the culture of recycling among consumers. The efforts made in finding breakthrough solutions for the production of glass packaging hold promise for a substantial reduction of the environmental footprint associated with their use in the food industry.

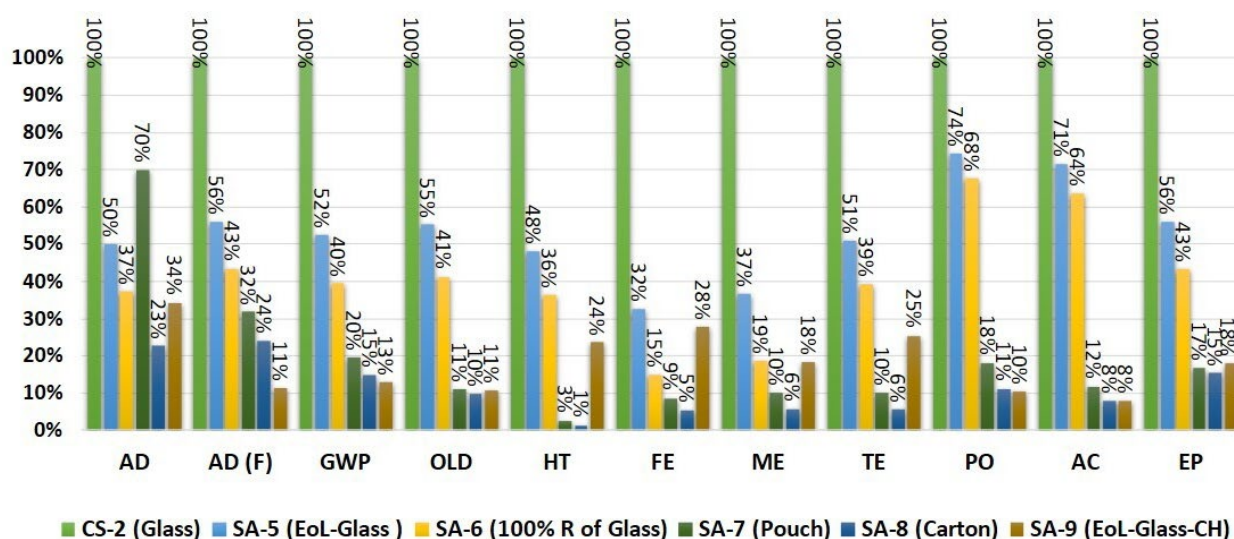


Figure 6. Sensitivity analysis for different scenarios of tomato puree packaging.

4. Conclusions

This study highlighted that the packaging phase of tomato products is the primary source of environmental burdens, accounting for more than 66% and 56.7% of CO₂eq emissions in peeled tomato and tomato puree production, respectively. Glass bottles and tinplate cans are the main contributors across all environmental impact categories.

To explore potential improvements, various development scenarios were evaluated, focusing on packaging material type and appropriateness for recycling. The results demonstrated that current end-of-life (EoL) practices for glass and metal packaging in Italy could reduce GWP by 48% and 46% in the packaging phase, respectively. Carton-based and pouch packaging for tomato puree exhibited the potential to decrease global warming impacts by 37% and 32%, respectively, considering the current recycling of glass packaging in Italy. However, considering consumer preferences and the potential for glass packaging to be produced more sustainably, it can serve as an environmentally friendly option. This underscores the crucial role of innovations in glass packaging production in reducing its environmental impact, reinforcing its position as a preferable choice. For peeled tomatoes, considering the EoL of tinplate and glass jars, the latter packaging, leading to a reduction of 34% of GWP, emerged as the preferable option. However, it is crucial to acknowledge that changing packaging materials may pose challenges, requiring alterations in production lines, especially packaging machines, with associated costs.

In line with SDG 13 (Climate Action), 100% recycling of packaging materials is a promising strategy, preventing disposal and reducing resource consumption, both in materials and energy. However, to select the most sustainable solution, a thorough assessment by Design for the Environment (DfE), Life Cycle Assessment (LCA), and Life Cycle Cost (LCC) for economic evaluation as well as consumer preference should be taken into the consideration. The new solution must be proven more suitable than the existing ones from environmental, social, and economic perspectives.

Future work should encompass all three pillars, namely sustainability, economy, and society, to understand the interconnections and impacts across various domains in selecting alternative solutions to reduce the environmental footprint of the food industry. Through such a holistic perspective, researchers can develop strategies that promote sustainable development, addressing the complex challenges and opportunities that arise at the nexus of these interconnected systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su17083648/s1>. Table S1: Life cycle inventory for a can of peeled tomato (400 gr) and a bottle of tomato puree (500 gr); Table S2: Inventory data regarding the end of life of packaging materials in Italy; Table S3: Inventory data regarding carton-based packaging and flexible pouch packaging for 500 gr tomato puree. References [51,52] have been cited in the Supplementary Materials.

Author Contributions: E.E.: Conceptualization, Methodology, Investigation, Data curation, Figure design, Writing—original draft. S.C.: Writing—review and editing, Formal analysis, Validation. G.P.: Conceptualization, Supervision. G.F.: Conceptualization, Supervision, Writing—review and editing, Funding acquisition, Project administration, Resources. All authors have read and agreed to the published version of the manuscript.

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