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Article

Environmental Consequences of Shelf Life Extension: Conventional versus Active Packaging for Fresh-Cut Salads

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Abstract: The use of active coatings in fresh food packaging is an innovative technique that optimizes the functional properties of films, resulting in a longer product shelf life and reduced food waste. But, which is more sustainable, active packaging (AP) or conventional packaging (CP) for the packaging of fresh-cut products? To answer this research question, this study analyzes the environmental performance of AP during its life cycle for packaging a minimally processed fresh salad mix compared with CP, in terms of its manufacture and use. The AP is a bag that includes a bioactive component, oregano essential oil (OEO), which is an inhibitor of microbial growth, incorporated into an ethylene vinyl alcohol copolymer (EVOH) coating on a conventional polypropylene (PP) film. To this end, a Life Cycle Assessment (LCA) was carried out based on ISO 14040 and 14044, using the ReCiPe methodology. The results showed that using active packaging has a beneficial affect, reducing the amount of produced food by 30% compared with conventional packaging over the same period. The reductions in the studied impact categories were greater than 50% in most of them, with a 62% reduction in global warming. The proposed sensitivity analysis showed the difference between the disposal or treatment of waste generated by the packaging production process and the packaged product, indicating that this step is of great importance for the environmental impacts and sustainability of this process. In 80% of the scenarios analyzed, the AP achieved better results than the CP in terms of damage categories.

Keywords: active packaging; environmental performance; fresh product packaging; LCA; sustainable production

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1. Introduction

Fruits and vegetables are highly perishable foods that generate a high percentage of waste during their preparation, with significant losses incurred by the transportation, handling, and storage chain. It is estimated that approximately 40–50% of fruits and vegetables are wasted each year. Food loss and waste (FLW) are indicators of the inefficient functioning of agri-food systems. Significant levels of FLW occur throughout the food supply chain, from production to consumption. Up to 14% of global food production is lost between the post-harvest and retail stages, while 17% of total global food production may be wasted at the retail stage [1]. The use of appropriate and more sustainable packaging can help minimize these losses.

The carbon footprint of the entire food production chain accumulates as products move along the chain. When analyzing food waste, vegetables stand out as hotspots in terms of carbon footprint contribution due to the high percentage of lost or wasted products [2]. The 2019 FAO yearbook on the State of Food and Agriculture also considers that food packaging can help to prevent food loss by extending the shelf life and reducing waste. Although the production and disposal of packaging can also harm the environment, the overall impact depends on the environmental footprint of both the food (which varies by type of food and location) and the packaging materials used [3,4].

Regarding consumers, there exists a clear preference for products with transparent environmental credentials, which suggests that they are actively seeking packaging solutions that align with their sustainability expectations. This preference is particularly pronounced within the fresh fruit, vegetable, and produce categories [5]. In addition, a global trend is evident in the inclination towards the adoption of sustainable packaging, with up to 63% of consumers on a global scale expressing a decreased propensity to purchase products encased in environmentally detrimental packaging [6]. This trend is expected to persist, given that sustainability remains a prominent and enduring concern for consumers in the aftermath of the pandemic [7]. Consumers have exhibited a preference for bulk quantities of fresh produce or compact, sustainable packaging options [8]. This predilection is consistent with our overarching objective of minimizing packaging waste and seeking environmentally responsible alternatives.

Ready-to-eat vegetables have a stable position in the market because of consumers' convenience [9]. One of the problems with fresh-cut vegetables is that the microbial load is highly variable and complex and can be contaminated during processing [10]. The deterioration of this type of product is due to different molds such as *Penicillium*, *Alternaria*, *Aspergillus*, or *Botrytis* and bacteria of the genus *Pseudomonas*, *Bacillus*, *Escherichia*, *Yersinia*, *Listeria* or *Clostridium*, among others [11].

In general, the shelf life of fresh-cut vegetables is 7 days. One of the factors affecting the shelf life of fruits and vegetables is the continuity of the respiration process after harvesting [12]. At this point, the packaging material selection is very important since the package regulates the gas exchange between the external and internal atmosphere. [13].

In this sense, polypropylene (PP) is characterized by its good mechanical properties for food packaging, low water permeability, good thermal weldability, and low cost [14]. On the other hand, ethylene vinyl alcohol copolymer (EVOH) is a hydrophilic polyolefin which is highly water permeable and absorbs water; it provides a strong barrier against permanent gases and organic molecules when dry, but in humid conditions, this barrier is depleted [15]. This behavior has made EVOH a vehicle for incorporating substances in the development of active packaging, as it releases the active compounds through exposure to the food's water activity [16,17].

Nowadays, consumers demand natural antimicrobial food additives; for that, essential oils from plants with a high antimicrobial capacity can be a good choice. The use of these extracts in food preservation is a good way to prevent the growth of pathogens in cut fruits and vegetables [18]. In this specific study, oregano essential oil (OEO) was used; it contains a high percentage of carvacrol, which is a volatile phenolic compound with high antimicrobial activity. Different studies have shown the high antimicrobial capacity of this volatile compound in headspaces [19].

Nowadays, our excessive use of plastic means that its production is massive and has an impact on the economy. In 2019, the global production of plastics was 370 MT. In Europe, about 40% of plastic finds its use in packaging [20]. The separation of different plastics in recycling plants is usually carried out by the sink–float process. This process consists of separating different materials according to their different densities. Specifically, PP has a density of 0.90 g/cm3, so it floats on water, as does PE. The yield of the subsequent separation of these two materials is approximately 97% [21]. In the case of PP-EVOH packaging, recycling is possible as long as the EVOH does not exceed 5% of the total mass of the compound, as several studies show that further processing does not significantly affect the properties of the recycled PP [22].

A Life Cycle Assessment (LCA) is a method of analyzing the environmental impact arising over the entire value chain of a service or product. The environmental impact of food packaging should focus not only on the packaging but also on the food it contains [23].

The processes compared in a packaging LCA are usually the production of the packaging material and its end-of-life management. However, the food itself must also be considered in the LCA. The production, processing, and transportation of food also have a significant environmental impact on the LCA [24].

LCAs can identify critical points in a product's life cycle where environmental or eco-nomic issues may arise. This enables companies to anticipate and better manage the risks associated with their products. The data collected through LCAs allows companies to make more informed decisions at all stages of the product life cycle, from raw material acquisition to waste management, thereby enhancing efficiency and sustainability [25–27].

The increasing awareness of environmental concerns regarding new technologies for packaging fresh-cut products, like active packaging, has prompted a closer examination of the impact of each type of packaging [26]. The present work analyzes the environmental behavior of a new technology for packaging fresh-cut salads and the one which is currently found in the market, regarding their effects on global warming.

Some studies on food packaging highlight the significant environmental impact of vegetable and fruit production in LCAs considering the waste and loss it generates. This impact is significantly reduced when the shelf life of the food is extended through active coating packaging [28]. The study conducted by Vigil, M (2020) [29], which compares the LCA of conventional packaging with packaging coated with zinc oxide nanoparticles, an antimicrobial compound, shows a better environmental impact of the active packaging due to its waste reduction. Similarly, the study by Tousti, C (2023) [30], which analyzes conventional tomato packaging versus active packaging that extends the shelf life of tomatoes by three days, determined a 14% reduction in environmental impact in the LCA.

Through the Life Cycle Assessment (LCA) method, environmental aspects and potential impacts are evaluated throughout the life cycle of a product or activity (Singh et al., 2013). A comparison was conducted with corresponding stages of conventional packaging used for the same purpose, along with a sensitivity analysis that considered variations of the final disposal of the packaging, suggesting an additional environmental benefit. LCAs have been utilized to compare different types of packaging in terms of their environmental impact and their ability to reduce food waste [31]. Another advantage of using an LCA in such assessments is the optimization of the packaging design, which can assist manufacturers. For example, one study assessed fruit and vegetable packaging made from mulberry wood waste and found that this packaging had a lower environmental impact than conventional packaging [32].

The objective of this work is the analyses of the environmental behavior of a minimally processed fresh salad which has been lightly sanitized, cut, and packaged. The environmental assessment was conducted using Life Cycle Assessment (LCA) methodology and comparison of active packaging, made of PP and coated with EVOH and OEO, with a conventional PP packaging usually employed for minimally processed salads.

2. Materials and Methods

2.1. Description of Packaging and Materials

In this study, the packaging analyzed was used to pack a salad mix (containing grated carrot, iceberg lettuce, and red cabbage). For the conventional packaging (CP), the packaging material used was PP film. The active packaging (AP) was prepared by coating the same polypropylene (PP) film with ethylene vinyl alcohol copolymer (EVOH) incorporated with oregano essential oil (OEO) (Figure 1).

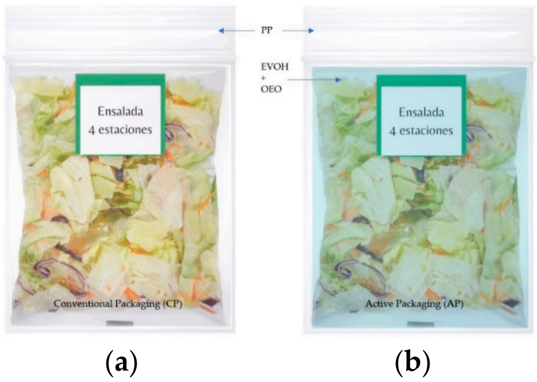

Figure 1. Packaging alternatives: (**a**) Conventional packaging (CP); (**b**) Active packaging (AP).

2.2. Preparation of the Active Film and Packaging of the Salad

To prepare the active packaging, the EVOH polymer was dissolved in a 1:1 (v/v) mixture of 1-propanol/water at 50 °C, and a concentration of 7.5% of OEO was added. A coating technology based on gravure printing was employed at Envaflex (Utebo, Spain) to produce the active material at a production speed of 60 m/min.

The salad packaging process was carried out in an industrial line with 250 g of product per bag at 60 units/minute during an 8 h working day, which represents 201,600 bags of AP and 288,000 bags of CP during the period of analysis, which was 70 days. The selected period was taken as a standard time for the analysis of the manufacturing of the two types of packaging based on the number of packages manufactured per day; within the 70 days, 10 manufacturing cycles were recorded for the CP and 7 cycles were recorded for the AP.

The bags had an area of 1115.04 cm^2 on each side and weighed 6.3 g. The coating ratio was 0.000133 g/cm^2 of EVOH + OEO and the coating covered 761.6 cm^2 on each side [15].

The difference in the number of packages for the two packaging types is due to the extension of the salad's shelf life provided by the AP in the same analysis period and the subsequent waste reduction, as explained below.

2.3. Life Cycle Assessment (LCA)

This LCA study was modeled in SimaPro$^{\circledR}$ 9.1.1.1 Ph.D. (PRé Consultants, Amersfoort, The Netherlands). The impact categories and the corresponding characterization models used for impact assessment are described below.

To assess the environmental impact of the packaging used, the ISO 14040 and 14044 standards (International Organization of Standardization, 2006a, 2006b) [33,34] were applied.

The ReCiPe 2016 Midpoint (H) V1.04 and method was applied for impact assessment and the ReCiPe 2016 Endpoint (H) V1.08/World (2010) H/A was used to analyze the damage.

ReCiPe is a method for the impact assessment of an LCA that translates emissions and resource extractions into a limited number of environmental impact scores by means of so-called characterization factors. There are two mainstream ways to derive characterization factors, i.e., at midpoint level and at endpoint level. ReCiPe calculated 18 midpoint indicators and 3 endpoint indicators. The midpoint indicators focus on single environmental problems, for example climate change, or acidification. The endpoint indicators show the environmental impact on three higher aggregation levels, which are: (1) effect on human health, (2) biodiversity, and (3) resource scarcity. Converting midpoints to endpoints simplifies the interpretation of the LCA results [35]. However, with each step of aggregation, uncertainty in the results increases.

2.3.1. Goal and Scope of the LCA

The goal of the LCA was to compare the environmental performance of a salad mix stored in a PP film with a coating of EVOH and oregano, denominated active packaging (AP), to that of a salad mix stored in a conventional PP film (CP).

2.3.2. Functional Unit

The purpose of the functional unit is to provide a reference unit according to which the inventory data is standardized [33,34]. The functional unit (FU) defined to describe and compare the function of the product in this study was "1 kg of packaging film to contain fresh-cut salad", considering that the individual packaging units have a 250 g containment capacity; according to this unit, the material and energy inputs to the system were considered.

In addition, it is important to indicate that for this analysis, the period of use for each package was taken into account, since, according to previously conducted studies [19], active packaging allows fresh product to have a longer shelf life (from 7 days with conventional packaging to 10 days with active packaging).

The number of bags considered for comparison was chosen during the use phase, which considers the extension of the shelf life of the packaged product in a specified time of 70 days, as mentioned above. In Figure 2, all processes considered in each phase can be seen.

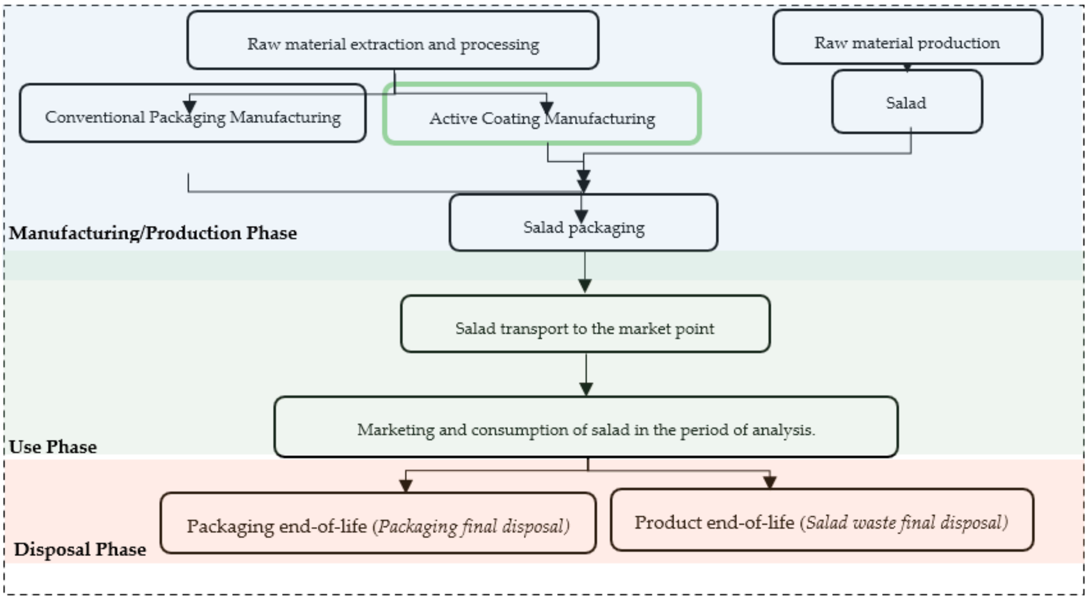

Figure 2. System boundaries of the packaged product with the analyzed packaging options.

2.3.3. Reference Flow

The reference flow for acquiring the FU in each case is shown in Figure 2. The main inputs and outputs of mass and energy in the packaging production system were considered. Since cut-off criteria were used to define flows that can be excluded due to not being considered relevant in the system [36], the processes that were contemplated had a 1% cut-off level for mass and energy. For the active packaging, the OEO constituted 0.02% of the total mass, so it was excluded from the boundaries of the system.

2.3.4. LCA Approach

An attributional LCA approach was applied to compare the environmental performance of the packaging, which provided an estimate of the environmental impacts of the processes involved in the production and disposal of the packaging. This allowed a comparison of the environmental profiles of the different packaging materials, providing the possibility to extrapolate the results to the fresh food industry. The attributional approach enabled an analysis of the real environmental advantages derived from the use of active packaging compared to conventional packaging because one of the main features of these new materials is their capacity to extend the product's shelf life and, therefore, reduce food loss. In addition, this approach made it possible to carry out a conscious and measured production.

The processes modeled in this attributional LCA involve operations related to vegetable production, but mainly to the production of packaging material (Figure 2).

2.3.5. System Boundaries

The system boundaries included the production of the package, its end of life, the production of the salad, and the transport of the materials to the packaging and sales points, as shown in Figure 2. The production and coating application process only took place if the EVOH coating was introduced. All the other stages were the same for the two analyzed systems, except the reference flows, which are different because they depend on the quantity produced. Thus, a common reference time was assumed for the two packaging systems.

The main factors considered in the assessment of the packaging were the shelf life of the packaged salad, assessed by measuring the antimicrobial activity of the film on the salad microflora, and the energy and mass used in the main manufacturing and processing processes of the packaging.

2.4. Life Cycle Inventory Analysis (LCIA)

2.4.1. Raw Materials Production

The values used in the LCA for the inventory were taken from measurements made in the laboratory, considering the quantities of materials used in the production of the packaging and in the packaging process.

A polypropylene film production process obtained from the Industry Data 2.0 database was used for the manufacture of the packages. Considering that there is not yet sufficient data on EVOH manufacturing in the literature or the databases, for the production of the coating, EVA production data were used as an approximation to EVOH [37,38], on the basis that EVA is a precursor of EVOH (Ecoinvent 3). The 1-Propanol was taken from the same database for the dissolution of the polymer and tap water, and the production of the salad was also considered from product data in the Ecoinvent 3 database. On the other hand, the electricity consumption of the salad packaging and the coating was considered.

The shelf life of the salad inside the packaging was considered to model the inputs and outputs within the boundaries of the system for the period analyzed, considering that in the conventional packaging, the average shelf life was 7 days, while in the active packaging, it was 10 days. The extension of shelf life was important to consider for the data introduced in the impact assessment software. To limit the analysis time, a common period was determined during which the fresh product would remain in good condition until the end of the analysis (70 days). In this period of time (70 days), 10 bags of CP and 7 bags of AP were used. The definition of this time is crucial to consider energy consumption and resource depletion in the processes according to the amount of packaging needed for this period. At the end of the 70 days, the raw material and energy consumption for the packaging manufacturing, packaging process, and salad products' production will have each been different, since the use of active packaging reduced the salad waste. The amount of packaging that can be produced from 1 kg of film is 159 pieces.

2.4.2. Transport

In the transportation stage, a 100 km distance was considered for the salad up to its packaging point, and then 50 km, once the salad was packaged, up to the point of sale (Table 1).

Table 1. Life Cycle Inventory.

Processes	Inputs/Outputs	Flows	Amounts	Units
Conventional Packaging Production	Inputs	PP film	1	kg
		Electricity	0.4	MJ
	Output	Conventional packaging	1 159	kg pcs
Active Packaging Production	Inputs	PP film	0.968	kg
		(EVA) Ethylene vinyl acetate copolymer	0.032	kg
		1-propanol	0.14	kg
		Tap water	0.06	kg
		Electricity	1.2	MJ
	Output	Active packaging	1 159	kg pcs
Product Production	Input	Salad	0.250	kg
		Transportation product	100	km
	Output	Minimally processed salad	1	kg
Transportation to Market Point	Input	Transport	50	km
	Output	Packaged salad	1	pcs

2.4.3. End of Life

Plastic film is recycled in a packaging classification plant within the mixed plastics section, where there is no distinction between the different types of polymers. Its main treatment in the European Union is incineration with energy recovery [39]. However, the end-of-life treatment analyzed in the case study was landfill disposal, mainly. The life cycle inventory used is representative of Spain for the period of 2020–2023 and includes the recovery of electricity, as well as corresponding credits regarding electricity that has not been produced using the average Spanish electricity production methods. However, other authors have conducted analyses of the variations in disposal and/or treatment scenarios for food packaging waste with similar characteristics (i.e., PLA packaging) [40], so a sensitivity analysis was conducted to visualize the effects of a different end-of-life process for food packaging.

3. Results

Figure 3 shows the global impact of salad packaging with the two packaging options considering all impact categories of the ReciPe Midpoint (H) method. The most significant impact is attributed to the production of the salad. However, it is possible to appreciate that by using AP, the salad production process proportion is lowered than it is with the use of CP; this is because by increasing the shelf life of the salad in AP, less salad has to be produced to obtain the same amount of product at the point of sale in the period analyzed (70 days).

In the Life Cycle Assessment of the two types of packaging, AP and CP, it became evident that in both cases, the impact categories with the highest scores are the same (global warming, GW; stratospheric ozone depletion, SOD; ozone formation (human health), OF (HH); fine particulate matter formation, FPMF; ozone formation (terrestrial ecosystems), OF (TE); terrestrial acidification, TA; freshwater eutrophication, FE; marine eutrophication, ME; land use, LU; fossil resource scarcity, FRS; and water consumption, WC), however, CP had higher values in all the impact categories (Table 2). CP had a higher overall impact in all categories, with an increase ranging from 42% to 64%.

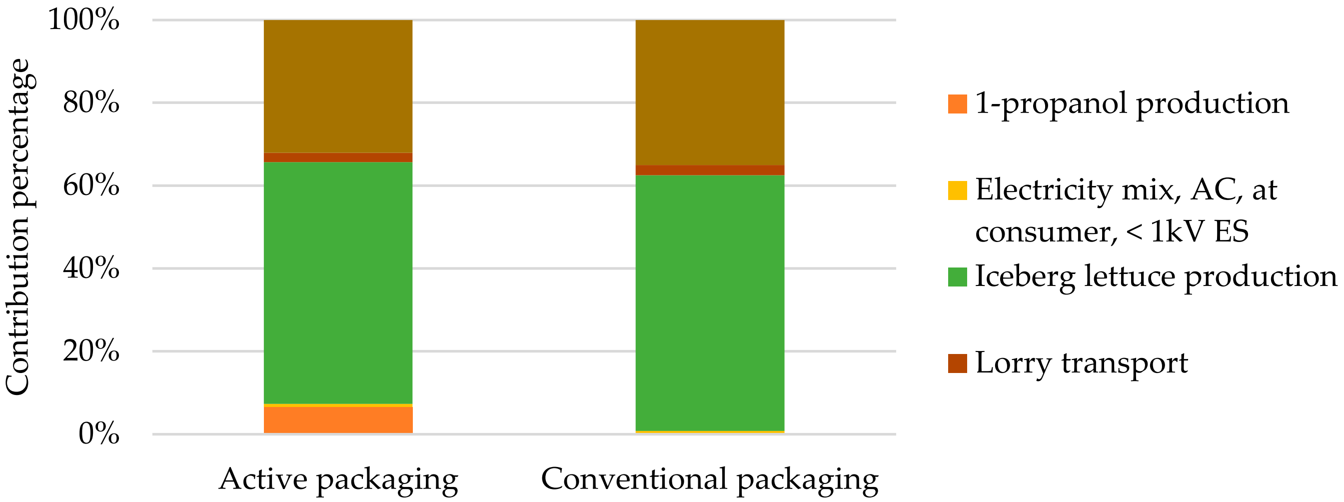

Figure 3. Standardization of damage category endpoint indicators for comparison between active packaging (AP) and conventional packaging (CP) in relation to the main processes in their manufacture.

Table 2. Indicator scores for the different midpoint impact categories.

Impact Category	**Units**	**CP**	**AP**	**Difference**
Global warming	kg CO_2 eq	24,576.137	9361.626	15,214.511
Stratospheric ozone depletion	kg CFC11 eq	0.155	0.055	0.099
Ionizing radiation	kBq Co-60 eq	81.650	32.492	49.158
Ozone formation (human health)	kg NO_x eq	88.124	33.502	54.621
Fine particulate matter formation	kg PM2.5 eq	37.638	14.531	23.107
Ozone formation (terrestrial ecosystems)	kg NO_x eq	88.191	33.993	54.198
Terrestrial acidification	kg SO_2 eq	110.117	41.592	68.525
Freshwater eutrophication	kg P eq	0.813	0.310	0.502
Marine eutrophication	kg N eq	31.991	11.432	20.559
Terrestrial ecotoxicity	kg 1,4-DCB	4740.788	1803.664	2937.123
Freshwater ecotoxicity	kg 1,4-DCB	12.661	4.561	8.100
Marine ecotoxicity	kg 1,4-DCB	24.177	8.744	15.432
Human carcinogenic toxicity	kg 1,4-DCB	2.651	1.027	1.623
Human non-carcinogenic toxicity	kg 1,4-DCB	76.912	30.297	46.615
Land use	m^2 a crop eq	41,323.206	14,839.179	26,484.027
Mineral resource scarcity	kg Cu eq	86.702	32.492	54.209
Fossil resource scarcity	kg oil eq	9359.688	3589.798	5769.890
Water consumption	m^3	1668.440	599.393	1069.047

A comparison of the two packaging LCAs concerning the damage category shows that the CP has a long-term damage rate of approximately 40% above that of the active packaging (Figure 4).

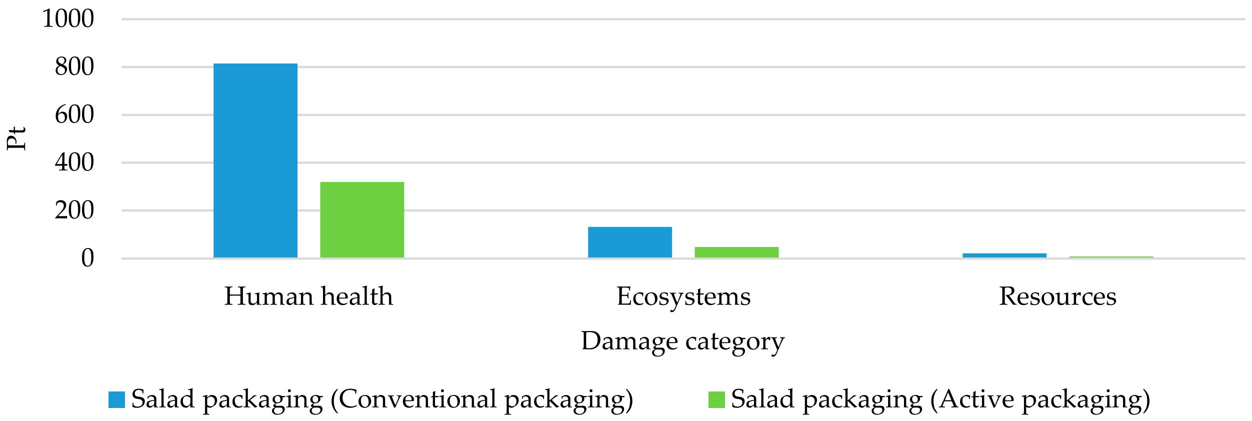

Figure 4. Normalization of damage category endpoint indicators for comparison between active packaging (AP) and conventional packaging (CP).

Figures 5 and 7 show the contributions of the salad packaging processes with the two alternatives (AC and CP) to the different impact categories, and Figures 6 and 8 illustrate in a schematic way the contribution of the processing of the products. In the comparison of the packaging, the AP, despite requiring more resources for its manufacturing, presents a better environmental performance due to its extension of the shelf life of the salad, a result also found by Settier-Ramirez, L et al. (2022) [41].

The analysis of the processes considered within the limits of the system for the two packaging types, CP and AP, showed that the most significant environmental load is caused by the salad production process, with a contribution of 67.4% for CP and 67.3% for AP, followed by the production process of the base raw material for the packaging (polypropylene), with 29.4% for CP and 27% for AP. In addition, another material that has a significant contribution in the AP is the 1-propanol used as coating solvent, with 5.81%.

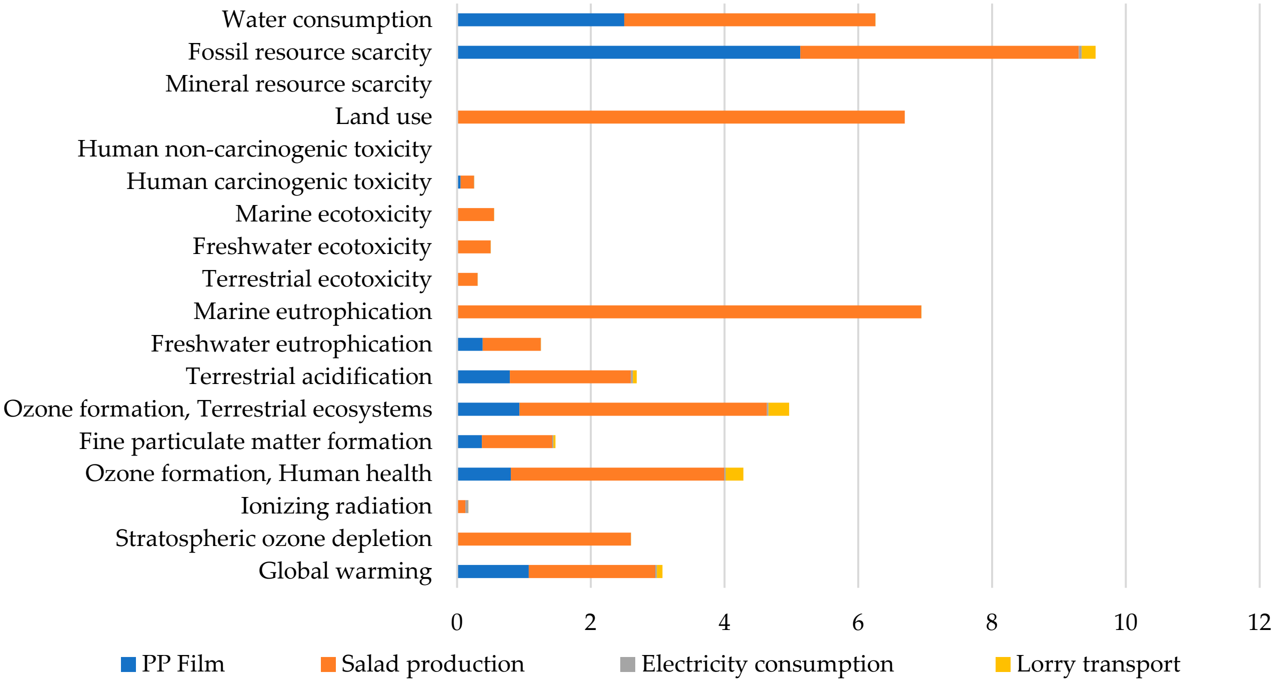

Figure 5. Midpoint category scores for conventional packaging (CP).

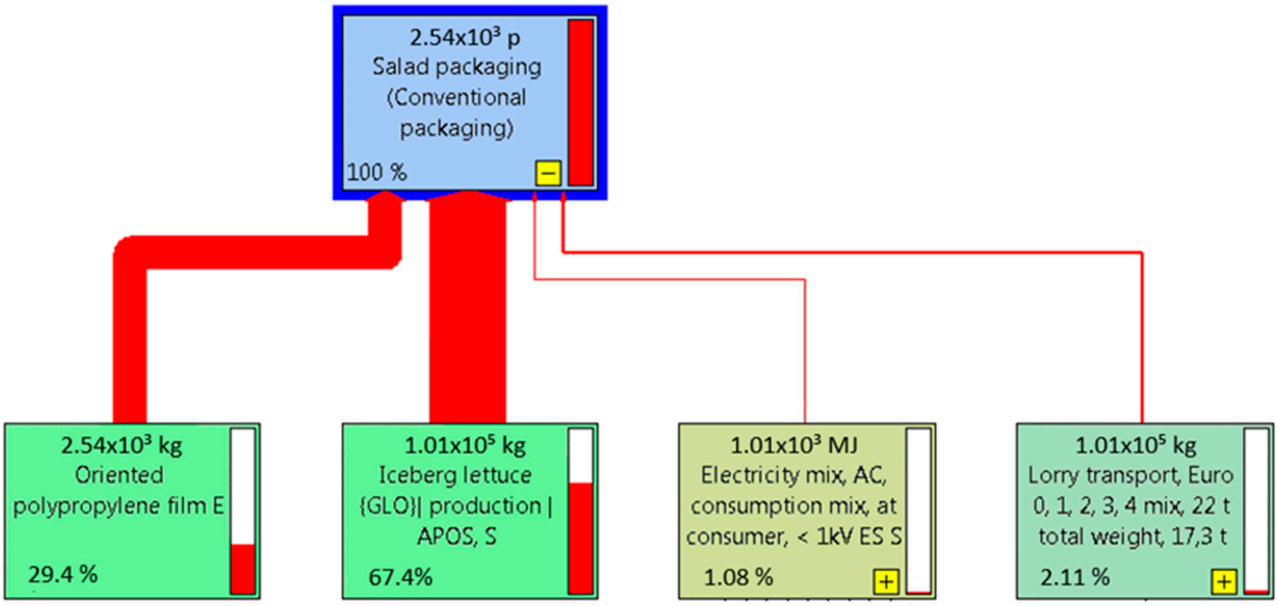

Figure 6. Main processes contributing to conventional packaging (CP).

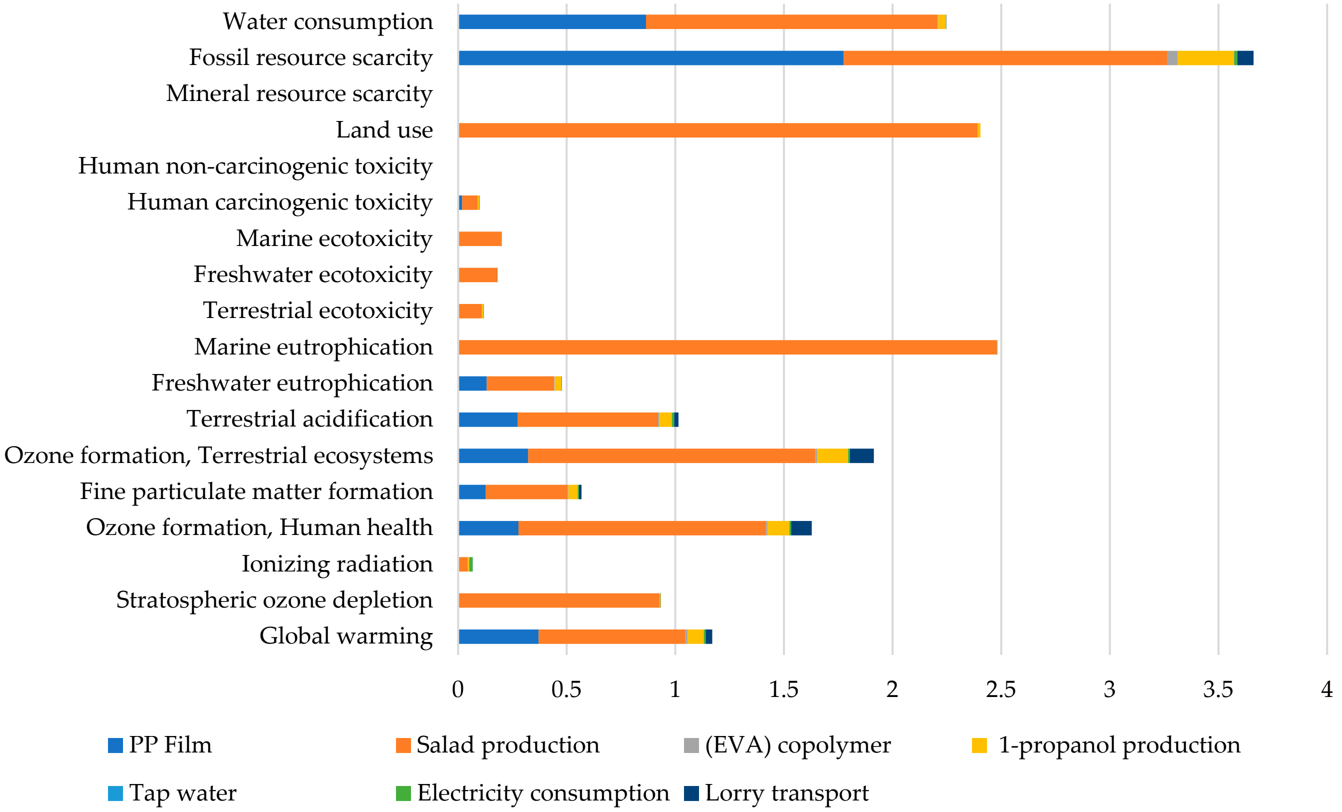

Figure 7. Midpoint category scores for active packaging (AP).

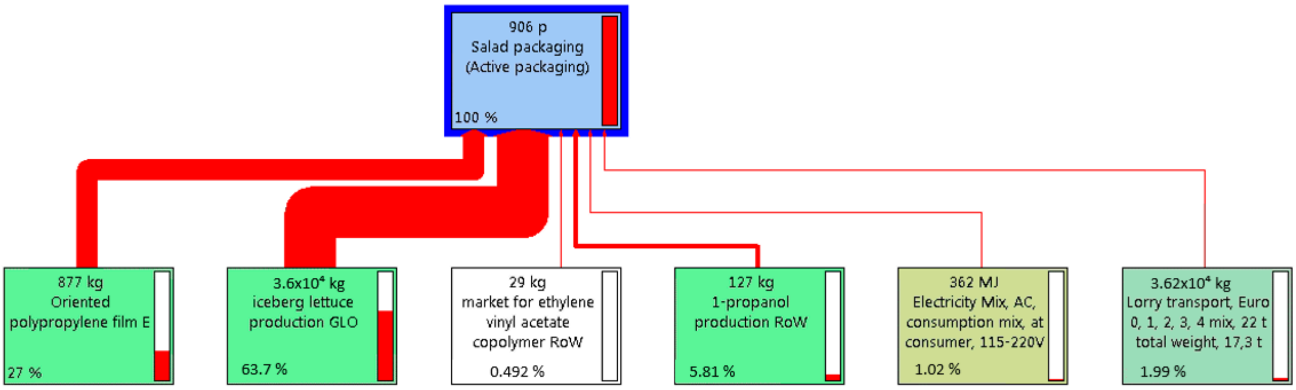

Figure 8. Main processes contributing to active packaging (AP).

The environmental performance of the AP was better in all impact categories, as expected. Evaluation of the indicators shows a reduction in impacts of between 40% and 60%. The use of AP has a lower environmental impact because fewer packaging units and less salad production require significantly fewer resources; furthermore, the reduction in food waste compensates for the additional steps in the manufacturing of the active packaging, e.g., the manufacture of the coating, which is similar to that found by Zhang et al. (2015) [37]. Regarding the production of the salad ingredients, it has a significant contribution in both the impact categories (midpoint) and the damage categories (endpoint), since the quantities of salad produced and the waste generated are more significant in the case of CP; the benefit of the extended shelf life with the AP is that it significantly reduces the amount of products that need to be produced and the damage incurred from the processes performed during the product's life cycle.

3.1. Sensitivity Analysis

A sensitivity analysis was performed to evaluate the environmental impact of material recycling and end-of-life incineration instead of landfill disposal. This study was carried out for different proportions of the three waste management alternatives according to the recycling and incineration rates of plastic waste in 2020 [39,42] (Table 3).

Table 3. Sensitivity analysis scenarios for packaging.

End-of-Life Treatment	Scenario 1	Scenario 2	Scenario 3
Landfill disposal	100%	36%	0%
Recycling	0%	46%	100%
Energy recovery	0%	21%	0%

The percentages assumed for the analysis were determined from those reported by Plastics Europe for Spain in relation to the final use of post-consumer plastics [39]. In addition, a case for the total recycling of the packaging was considered, since the percentage of non-PP materials in the packaging is less than 5% [22].

For the salad production, waste treatment data were obtained based on statistics, which can be assumed as follows: 8% of the waste goes to landfill, 70% to composting, and 22% to energy recovery/incineration [43,44] (Table 4). Figure 9 shows the configurations used to analyze the end-of-life treatment of the packaging and salad in order to combine the processes involved.

Table 4. Salad scenarios.

End-of-Life Treatment	End-of-Life Salad
Landfill disposal	8%
Energy recovery	22%
Composting	70%

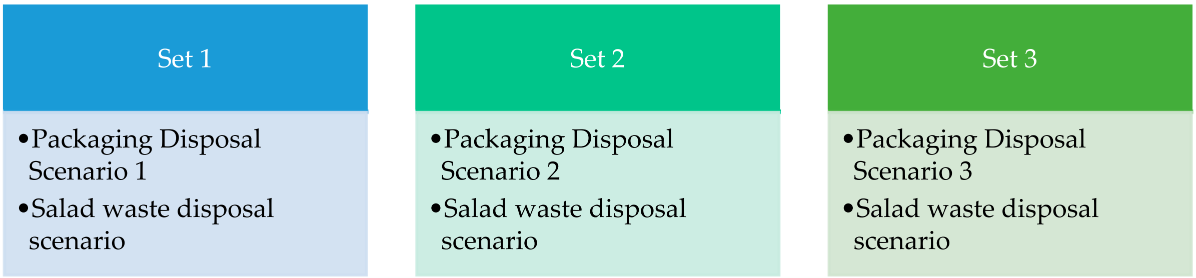

Figure 9. Scenarios analyzed.

3.2. Analysis of End-of-Life Packaging Scenarios

A comparison of the final disposal scenarios for the two alternatives (CP and AP) was performed with the damage categories; these categories consider their cumulative impact and reflect the damage caused to human health, ecosystems, and resources. The results showed that the AP performed better in all scenarios analyzed, as its scores had significantly lower values.

In the damage to Human health and damage to Ecosystems categories for each of the scenarios, the percentage of CP damage ranged between 63 and 65% above the AP values; however, in the Resources category, although for scenario 1, the damage was lower in the AP, in scenarios 2 and 3 there is an evident improvement. This is because in these scenarios, management practices such as recycling (46%) and incineration (21%) for scenario 1 and recycling (100%) for scenario 3 were considered to reduce the long-term damage associated with the amount of packaging produced (Figure 10).

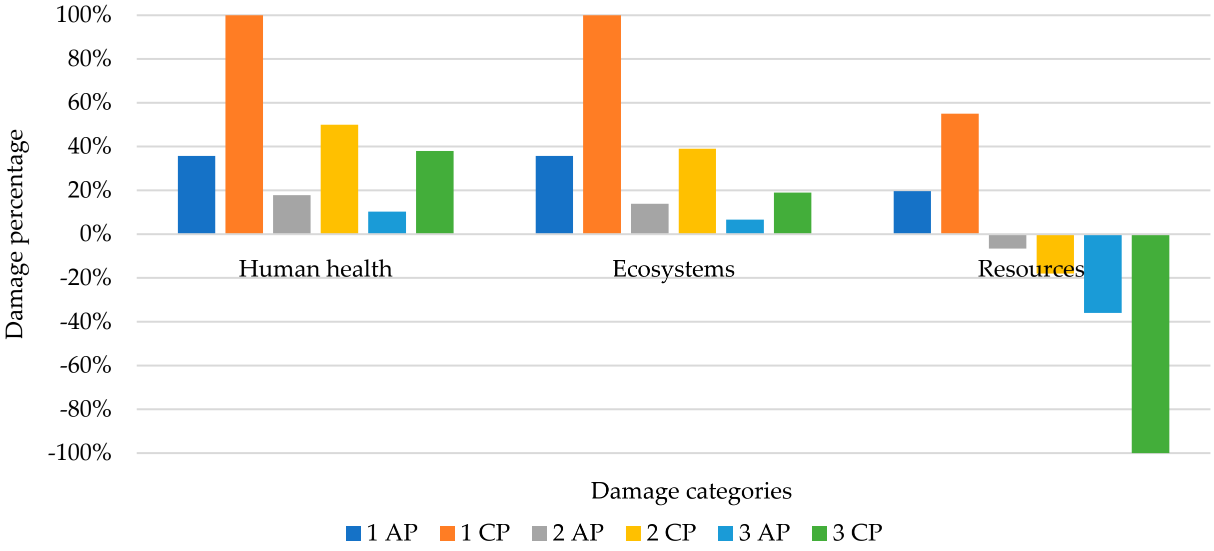

Figure 10. Comparison of active packaging (AP) vs. conventional packaging (CP) with disposal scenarios analysis, e.g., 1 AP (scenario 1 for AP), 1 CP (scenario 1 for CP). See Table 3.

When considering the whole product, i.e., the packaged salad, as mentioned above, the main benefit of using this packaging can be observed in the amount of packaged salad; its waste is still reduced when compared to the process of adding the coating to the packaging (Figure 11).

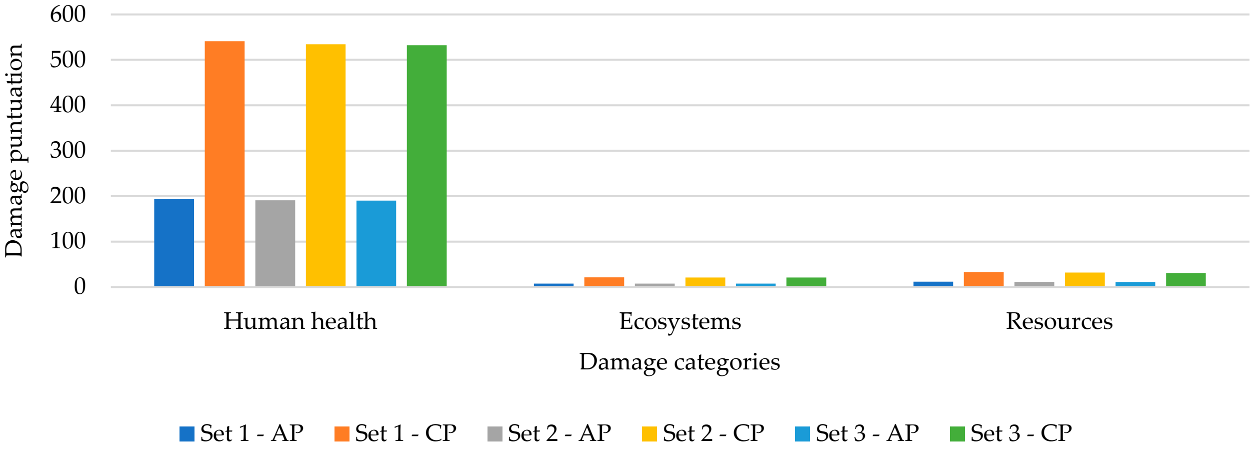

Figure 11. Comparison of AP vs. CP sets in terms of the main processes in the damage categories (endpoint indicators).

4. Discussion

The most critical impact categories with the highest values within the packaging LCA were analyzed. The category with the highest score was LU, which considers the land area necessary to produce salad products. In both cases, the packaging of the product mainly determines the increases in the impact categories.

In the case of GW, it can be observed that, although in the manufacture of AP, the addition of the coating is the process with the second-most significant impact after PP, if the complete product (product and package) is evaluated, due to the reduction in the amount of packaging necessary in the evaluated period, the impacts of the additional EVOH and propanol and their production processes are compensated and become irrelevant with respect to other processes during the use and end-of-life phases of the materials. The percentages in the GW category were 58% for the AP and 62% for the CP, which is within a similar range to that found by Zhang et al. (2015) [37], who had a result of approximately 63% for the analyzed packages. The production and disposal of PP and salad are the most significant processes in the two packaging alternatives. Europe is the fourth-largest producer of plastics in the world; its market share is about 15%, where PP production has a large share (16.6%) and its use in packaging corresponds to 39.1%. Moreover, the recycling rate is only 9.9% [39]. The improper disposal of packaging is responsible for adverse effects on global warming and particulate matter formation. Although conventional plastic packaging, such as PP [45], can be effectively recycled in developed countries, the accumulation of plastic in the environment due to landfill disposal is a significant issue [45,46].

The fossil resource scarcity (FRS) is mainly associated with the production of 1-propanol (AP), PP film manufacturing (AP and CP), and the production of salad products (AP and CP), as indicated by de la Caba et al. (2019) [46]. Regarding the importance of this category in the extraction of raw materials for the manufacture of packaging, the result obtained for CP was 9359.7 kg oil eq compared to 3676.7 kg oil eq for AP, which is evidence of an important improvement in this category that shows the toxicity effects of the processes that consume energy using fossil fuels [46]. Similarly, de la Caba et al. (2019) [46] indicated in their analysis that another category that has a significant impact on this type of process is the consumption of water (WC). In this case, however, it is essential to highlight that this WC reduction is due to the production phase of the inputs for the salad and packaging, so for this indicator, the result of the PA impact is lower due to a reduction in the number of resources used.

Terrestrial ecotoxicity and acidification are among the most critical impact categories [38] due to the processes they involve and the nature of materials used to manufacture the packaging. In terrestrial acidification and water eutrophication, the most relevant process of packaging manufacturing is the manufacture of PP (29% CP and 27% AP for TA, and 31% CP and 28% AP for FE), although in the overall process, the production of salad ingredients has the largest contribution (67% CP and 64% AP for TA, and 69% CP and 65% AP for FE).

The incorporation of the coating and the subsequent shelf-life extension of the packaged products contributes to the use phase if the life cycle of the packaging is also analyzed. Indeed, if we analyzed the same impact categories per packaging unit, we would not be able to assess the benefits of the AP without considering the use phase, since the coating preparation involves more resources and energy consumption, as reported by Stramarkou et al. (2022) [47]. Therefore, the advantages of active packaging with the active component are found in its use phase since its main objective is the extension of the shelf life of the packaged food, achieving a reduction in the impact categories of more than 50%.

The ozone formation (OF) has negative implications for human health and the environment, therefore the indicators OF and OF, HH exhibited similar behaviors, where the most representative processes for both AP and CP were the production of PP film and the production of salad ingredients, with a contribution of 17% and 70% for AP and 19% and 74% for CP.

Regarding the parameters, the Endpoint ReCiPe (Figure 10) score shows that the AP has a better environmental profile than the CP, equal to the results found by Vigil et al. (2020) [29].

When assigning the impacts of the different processes to each type of packaging within their life cycles, it was observed that the manufacturing phase is similar for both PP films, so in terms of quantity produced, the coating has a significantly lower impact (Figure 5). This can be explained by the fact that the coating is a very thin film on the inside surface of the package, and the quantity of materials used for its manufacture and application are much less than for PP film production.

The other significant difference between the scenarios is found in their end-of-life (EOL) processes. AP can undergo the same type of final treatment as CP, which means that the coating does not produce an additional environmental burden in its disposal scenario. In EOL waste treatment processes where recycling and incineration of the packaging are considered as an alternative, there is a methodological advantage over those that do not consider such processes [29].

In the packaging manufacturing process, the most significant environmental burden in most impact categories was due to the extraction or production of the raw material (in this case, the PP film and salad) due to the consumption of non-renewable and finite resources, respectively [48]. One way to reduce the impacts caused by packaging is to recycle these types of materials; however, recycling depends on the disposal practices of consumers, as mentioned by Gómez and Escobar (2022) [49].

With the above, it can be defined that using management practices such as recycling and energy recovery through incineration represents environmental benefits. Set 3 presents a better environmental profile since it considers scenario 3 of final packaging disposal (100% recycling) and salad waste treatments (8% landfill, 70% composting, and 22% energy recovery/incineration). However, this is an ideal scenario, which can only be achieved if waste management practices by consumers are improved. Set 1 has a more critical profile because it considers scenario 1 of the final disposal of the packaging (100% landfill) and the treatment of the salad waste (8% landfill, 70% composting, and 22% energy recovery/incineration). On the other hand, Set 2, which considers scenario 2 of final packaging disposal (36% landfill, 46% recycling, and 21% energy recovery) and salad waste treatments (8% landfill, 70% composting, and 22% energy recovery/incineration), could be considered closer to reality since it contains data based on waste management and treatment practices that are currently adopted.

Essential oil-coated packaging can be used for fresh products to extend their shelf life and inhibit pathogen growth, typically taking the form of films and coatings [37]. What follows is a review of the application of essential oils in packaging films for the preservation of fruits and vegetables: Some of the benefits of using essential oil-coated packaging for fresh products offer various advantages, including the effective prolongation of the shelf life of the food products. Vigil et al. (2020) [29] found similar results with ZnO, an inorganic compound; however, the introduction of coatings and their new processes generate additional environmental impacts which must be considered. Vigil et al. (2020) [29] used an LCA to analyze the sustainability of coated packaging for fresh products, and their study analyzed the sustainability of active packaging for the fresh-cut vegetable industry, considering biodegradable polylactic acid (PLA) and non-biodegradable polypropylene packages coated with zinc oxide nanoparticles (ZnO NP); however, they did not consider other package coatings, such as essential oils or LAE coatings. The existing studies have a limited scope, evaluating only the environmental implications of the production, use, and disposal of the packages themselves; therefore, a thorough analysis was conducted, encompassing the entirety of the packaging's life cycle, which extended to the upstream phases, such as the production of the coatings, as well as the downstream phases, including handling and end-of-life (EOL) recycling. Also, there is a need for comparative LCA studies that evaluate the sustainability of packaging with active coatings against conventional packaging alternatives. Other studies compared the environmental consequences of shelf life extension using conventional and active packaging for pastry cream [41], however, in the packaging LCA-related literature, there is a trend towards a more systematic consideration of the indirect environmental impact of packaging; so, it was important to include in the analysis the interrelationship between the different processes of the packaging manufacturing system, process, use, and final disposal [24]. To fill the gap in the literature, research should focus on conducting an LCA that considers the entire life cycle of packaging with active coatings for preserving fresh products. The studies should evaluate a wide range of materials and technologies, compare them to conventional packaging alternatives, and consider the environmental, social, and economic aspects of their sustainability.

5. Conclusions

The extension of shelf life is a fundamental factor when designing new packaging and LCA is a very valuable tool when assessing the sustainability of new packaging. Despite the added processes and increased energy consumption in the manufacturing of active packaging, the provided increase the shelf life of the salads is environmentally beneficial, reducing its impact on different indicators such as fossil resources and water consumption, and reducing its effect on global warming by 62%. Compared to conventional packaging, the use of active packaging is a better alternative from an environmental point of view. In the long term, active packaging has a 39% damage rate compared to CP in the human health sector, as well as 37% in ecosystems, and 39% in resources. The consumption, use, and disposal practices of both the packaging and packaged products are key factors in assessing the environmental impacts. The introduction of recycling as an end-of-life scenario could improve the performance of the analyzed system. The reduction in food loss derived from the use of active packaging is significant and leads to a conscious and measured management of food production; in this case, the use of AP reduced vegetable production by 30%. It is crucial to analyze the environmental behavior of new packaging materials and technologies in order to ensure that they present advantages for the environment. The Life Cycle Assessment (LCA) is a useful tool that has helped to identify critical areas in the life cycle of fresh-cut packaging. It enables the implementation of specific improvements aimed at reducing environmental impacts. This active packaging technology helps in reducing greenhouse gas emissions, optimizing resource usage, and minimizing waste, making the packaging more sustainable. The design of active packaging can also be optimized using this approach, which can enhance its sustainability efficiency. This encompasses aspects such as material selection, durability, recyclability, and energy efficiency.

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