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Sustainability Analysis of Active Packaging for the Fresh Cut Vegetable Industry by Means of Attributional & Consequential Life Cycle Assessment

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Abstract: In order to enlarge the shelf life and avoid the waste of fresh-cut (FC) products, novel packaging techniques with antimicrobial properties have been proposed. In this work, we analyzed the potential environmental benefits of using films reinforced with bactericidal ZnO nanoparticles (NP) for FC produce packaging, when compared to the traditional polypropylene (PP) films. A biodegradable, polylactic acid (PLA) package and a non-biodegradable, polypropylene package, both coated with ZnO NP, were considered as novel technologies. The eco-profile of the considered alternatives was assessed via two life cycle assessments (LCAs). Firstly, an attributional LCA was performed in order to compare the materials in terms of their production and end of life (EOL) processes, allowing us to extend the conclusions to different food products. Secondly, a consequential LCA was performed taking into account the whole life cycle of the fresh vegetable, with special attention to the environmental implications of the produce losses among the chain. The uncertainties of the models were assessed via Monte Carlo approach. In both cases, the scenarios concerning the PLA and PP active packages with ZnO NP showed a better profile than the traditional techniques, specifically when considering the full supply chain of the FC vegetables in the consequential LCA. As agricultural production is the main contributor to the environmental impact of the cycle, the avoidance of wastes by extending the shelf life through the novel packages leads to the impact reduction of FC products.

Keywords: life cycle assessment; LCA; active packages; nanoparticles; fresh-cut produce; shelf life

1. Introduction

Fresh-cut (FC) products are defined as "those fruits and vegetables that may have undergone procedures such as washing, sorting, trimming, peeling, slicing, or chopping that do not affect their fresh life quality" [1]. Under this concept, we can find products such as sliced mushrooms, peeled and diced watermelon, packed baby leaves, and so forth. Due to their convenience and their ready-to-eat state, FC products have become an indispensable element of western society diets, and their use is in constant growth. The demand for these products is expected to represent 20% of the total food market in the near future [2].

Every step during the preparation of FC produce has a potential effect on nutrients and quality of prepared produce [3], and, as a result, this kind of product is much more susceptible to deterioration that the whole counterparts [4]. Maintaining produce quality for a longer time and enlarging its shelf life is one of the main challenges with which the FC industry has been confronted. Shelf-life extension entails a significant benefit from an environmental point of view, as longer expiring periods would lead to a decrease in food waste due to organoleptic traits loss. Food waste is a major concern in western society; the losses per capita reach 280 kg in the EU, of which 45% arise from households [5], and the derived impacts of this issue are incalculable.

Inactivating the metabolism of the microorganisms that may remain after produce washing and sanitizing is essential to reach an FC produce waste decrease, as they can promote surface browning and quality loss [6]. This aim has been addressed by the development of novel packaging techniques, which lead to an increase in the convenience, safety, and quality of food for customers while reducing the need for additives, washing water, and the incidence of food poisoning [7].

Polymeric films have been used to package fresh products for the last 50 years, due to their various draws compared with other materials, i.e., cardboard or paper packages. Films allow for the control of water loss, they protect from skin abrasion, reduce contamination during handling and among units, and are able to lower the circulation of respiratory gases [8]. However, for further protection against microorganisms, other technologies have arisen in recent times. In this context, active food packaging has emerged as an interesting alternative to traditional films. As stated in the EU regulations 1935/2004/EC and 450/2009/EC, active food packages are defined as those active materials in contact with food that can change the composition of food and/or its surrounding atmosphere [9]. A classification of the different kinds of active packages is shown in Figure 1. Among this kind of packaging techniques, we can find antimicrobial packaging, which aims to extend food shelf life by significantly reducing the microbial growth on food surfaces [10].

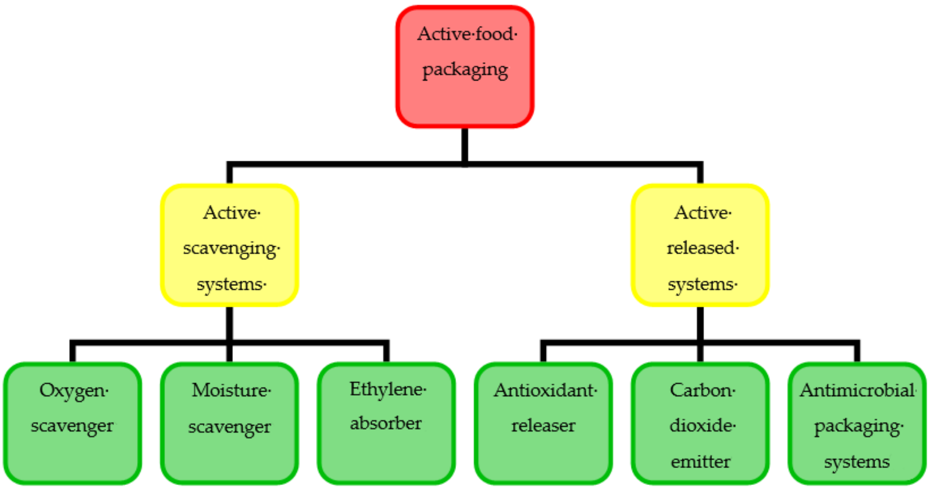

Figure 1. Classification of active packages according to the effects they promote in the FC produce surroundings. Adapted from [11].

Antimicrobial packaging can take several forms, from the addition of pads on the package surface containing volatile antimicrobial agents to the use of inherently antimicrobial polymers for film manufacturing [10]. Nanotechnology has also stepped into the world of active food packaging, as it can offer new materials and techniques with the ability to modify the physical and chemical properties of the packaging material. Indeed, several inorganic nanoparticles are broadly known for their antimicrobial properties, such as silver, copper oxide, or zinc oxide nanoparticles [12]. The latter are especially interesting due to their white appearance, ultraviolet light-blocking properties, and high versatility [13].

It has been proved that it is technically viable to combine ZnO nanoparticles (ZnO NP) with polypropylene films in order to promote an antimicrobial function to traditional packaging [14]. Furthermore, these nanomaterials can also be included in biopolymers in order to develop biodegradable packages with enhanced mechanical resistance while promoting limited microorganism growth [15]. This would entail an environmental gain derived not only from the aforementioned food waste decrease, but also from the displacement of single-use plastics from the current scenario.

The aim of this research is thus to establish the potential environmental benefits of using innovative polypropylene and biodegradable active packages, reinforced with ZnO nanoparticles, to pack FC fruits and vegetables. To do so, the Life Cycle Assessment (LCA) approach is used, as it allows us to consider the extraction and processing of raw materials, the manufacturing and distribution steps, the use and recycling by the consumer, and the final disposal [16].

LCA is a popular tool, and it has been therefore previously used to evaluate FC agricultural produce industry [17], but this article did not evaluate the use of different packaging alternatives. The use of active packaging for food preservation has also been addressed by means of LCA [18,19], but they considered other package coatings different to nanoparticles (LAE coating and essential oils). Indeed, they demonstrated that the use of active packages can significantly influence the decrease in the food waste generation, which is one of the main hypotheses of this paper. In our case, it is important to assess whether the combination of films with ZnO NP does not generate an impact that surpasses that avoided by the waste savings. The environmental burden of ZnO NP production has been previously evaluated in the field of material engineering [20] and chemical functionality [21], but never when it comes to its inclusion in films for the manufacturing of active films. In [21], the authors claim that one of the main environmental weaknesses of ZnO NP production is electricity consumption. Nevertheless, the small amounts of nanoparticles needed to produce novel packaging technologies may lead to a negligible effect of this issue. On the other hand, the use of active packages combining a biodegradable composite and nanoclays for FC produce has been evaluated from an environmental point of view [22]. These authors claim that nanoclays have the effect of improving technical and environmental performance, being some of the benefits due to the achieved extension of the produce shelf life. As the combination of different plastics (biodegradable and non-biodegradable) with the use of ZnO NP has not been previously studied, this article aims to fill this gap in active packages research in order to establish whether the environmental gains are maintained when nanoparticles are combined with packaging films.

2. Materials and Methods

Two different LCA approaches were conducted in order to compare the environmental performance of ZnO-reinforced packaging with the current packaging strategy. On the one hand, an attributional LCA was carried out, giving an isolated estimation of the environmental implications of the sole processes concerning the production, use, and disposal of the packages themselves. This allows for the comparison of the eco-profiles from the different packaging materials, independently from the product class they will contain, thus making it possible to extrapolate the results to different elements of the fresh food industry. On the other hand, it has been claimed that the packaging-related processes in the frame of FC produce life cycle entail a nearly insignificant environmental burden, since the agricultural phase accounts for the majority of the impacts [17]. The attributional approach, firstly considered, may thus not be representative of the actual environmental gain derived from the use of active packages, as a major draw of these novel materials is their ability to extend the product shelf life, and thus to decrease the food losses. Consequently, less FC vegetables need to be produced and purchased by a final customer in order to consume the same quantity of product. A consequential approach is thus regarded in a second LCA, which aims to describe how environmentally relevant flows will change in response to possible decisions and how they affect the production and use of the product [23]. The processes modeled in this consequential LCA also include the ones in the attributional LCA, but also those steps concerning the operations related to the vegetable production, processing, and consumption (Figure 2).

LCAs were performed according to ISO 14040 and 14044 [26,27], taking into consideration the following stages: (1) goal and scope definition; (2) life cycle inventory analysis (LCI); (3) life cycle impact assessment (LCIA); and finally, life cycle interpretation.

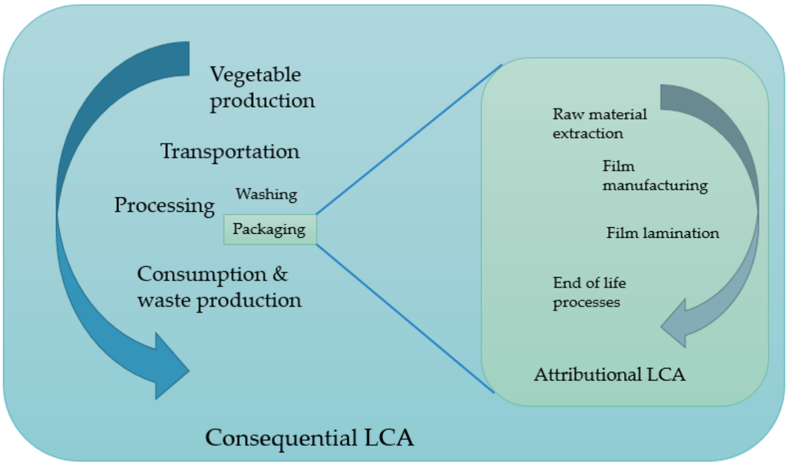

Figure 2. Distribution of the processes included in both the attributional (green) and the consequential (blue) LCAs. Note that the attributional LCA only considers the film manufacturing and disposal, which is also a part of the processes modeled in the consequential LCA. This consequential LCA, besides the film-related operations, also includes all the processes concerning the vegetable production, processing, and consumption [24,25].

2.1. Attributional LCA on the Packaging System

2.1.1. Goal and Scope Definition

The aim of this first LCA is to evaluate from an environmental point of view different packaging alternatives for FC produce, considering the different impacts of three alternative packaging materials. The active packages containing ZnO nanoparticles were compared to a reference package to assess whether their utilization entails a benefit. Therefore, the functional unit (FU) for this LCA was a packaging unit intended to contain a 130 g serving of FC lettuce, considering that this kind of fresh produce accounts for the majority of the sales market volume [28]. This quantity is obtained by dividing the total annual production of FC lettuce by the total amount of bags produced in 1 year by a given producer, as claimed in [17]. The weight of the package was the same across the different scenarios defined, as the mechanical properties of the employed materials are claimed to be equivalent, and it was set to 3.94 g according to [17].

To allow for the comparison, our analysis followed a cradle to grave focus, considering all the necessary inputs for the manufacturing of the different films, as well as the energy consumption, the needed transportations, and the end of life (EOL) processes of the different packages. The processes concerning bag manufacturing include film manufacturing and its lamination, as can be seen in Figure 2. The emissions involved in each process were also properly modeled.

Three alternative scenarios were defined in order to perform the comparison. Firstly, we set a reference scenario that aimed to represent the current trends in FC vegetable packaging. Polypropylene (PP) laminates were the materials conceived for this scenario, as their use is widely described in the literature [29–31]. Secondly, an active package in which PP films are coated with ZnO nanoparticles was considered. Third, a biodegradable alternative to the latter plastic was inspected, consisting of polylactic acid (PLA) composite, which was also reinforced with ZnO nanoparticles to promote the activity against pathogens. The biocomposite is manufactured using maize starch as a raw material, which is conceptualized as a waste from the agro-food industry.

Due to their particularities, the EOL of the three distinct packages is different, and it is considered that they are composted, recycled, landfill disposed, and/or incinerated in certain proportions according to the suitability of the materials.

2.1.2. Life Cycle Inventory

The different packages were modeled according to the material characteristics, taking into account both the film production and its lamination. Materials development and manufacturing viability assessment had been previously performed in the frame of the CEREAL project, which was carried out under the 7th Framework Program. All the experimental work corresponds to the aforementioned project and thus is not within the scope of this paper. However, details can be checked in [15,32]. Primary data to elaborate the Life Cycle Inventory (LCI) was extracted from the CEREAL works and consortium partners.

Besides these primary data, other sources were needed in order to complete the Life Cycle Inventory, corresponding to secondary data that was retrieved from two sources:

- Literature search. The data concerning the packages EOL processes, as well as some further details related to nanomaterial manufacturing, had been previously reported and were used here for the inventory elaboration.
- Background databases. In our work, Ecoinvent v3.2 was selected as the database to gather any possible missing data. Ecoinvent is a broadly used database for LCI completion due to its main three strengths: data reliability, transparency, and independence of host institutions [33].

Hence, polypropylene manufacturing was conceived basing on the data in the Ecoinvent v3.2 database. Lamination was modeled in terms of energy consumption with primary data from CEREAL project researchers. Raw material loss along the manufacturing process was set to 5%, according to [17].

Consortium partners used isotactic polypropylene in pellets, and zinc oxide coated with stearic acid for film manufacturing. ZnO NP were synthesized using a pyrolysis platform [32]. However, as no primary data or previous inventories concerning ZnO nanoparticle production were available, the modeling of this process on the two novel scenarios was limited to the production of the stoichiometric quantity of Zn, considering a 5% *w*/*w* coating, as described in [32]. These authors also claim that the coating of PP with the nanoparticles can be done by melt compounding without the addition of any compatibilizer.

The PLA nanocomposite is produced by a melt-blending process where ZnO NP are directly added to the PLA matrix [34]. Likewise, for the polypropylene scenario, the production of ZnO NP only includes the production of Zn.

Packaging end of life was modeled considering the several alternatives usually found in municipal waste management systems, specifically incineration, landfilling, recycling, and composting. The ratios assigned to each waste management option were modeled according to [35] and are summarized for each scenario in Table 1. It was assumed that composting can reach up to a 100% share on the ZnO NP–PLA scenario, as the presence of nanoparticles has been proven to have no negative effects on compostability [36,37].

Table 1. Alternatives for waste processing and their expected contribution to each of the technologies EOL step.

	Incineration	**Landfill Disposal**	**Recycling**	**Composting**
Reference PP scenario	36%	30%	34%	0%
ZnO–PP scenario	50%	50%	0%	0%
ZnO–PLA scenario	0%	0%	0%	100%

The inventory concerning the three scenarios is gathered in the Supplementary Materials.

2.2. Consequential LCA on Fresh-Cut Lettuce Production and Consumption

2.2.1. Goal and Scope Definition

The second LCA here performed aims to assess the environmental gain due to the shelf life extension that is achieved when utilizing active packages for FC products. Specifically, we compared the burden derived from the whole product life cycle when different packaging techniques are considered, including the produce losses owed to rapid quality deficiencies. Hence, the functional unit (FU) was set to a serving (130 g) of FC lettuce ingested by the final customer.

Since this LCA was conceived from a consequential perspective, the system needs to consider the full production chain of the FC lettuce, as well as the consumption and the disposal of the rests in order to quantify the upstream and downstream effects due to changes of consumption patterns.

The steps concerning the agricultural production of fresh lettuce and its processing need to be added to the three scenarios depicted in the first LCA, as well as the food waste generation. The production line of FC lettuce can be divided into three stages: greenhouse production under plastic tunnels, transport after harvest to the processing center, and produce processing (sanitation with sodium hypochlorite and packaging) [17]. The packaging step corresponds to the same processes considered within the attributional LCA, as noted in Figure 2. The distribution step was left out of the analysis since it was considered a highly context-dependent process, and results could not possibly be extrapolated to other situations.

2.2.2. Life Cycle Inventory

The agricultural production of fresh lettuce was modeled according to the Ecoinvent process *Lettuce {GLO}*. This item considers the emissions and intakes that are needed to produce the vegetable, as well as its transportation to the manufacturing plant. The inventory for the produce processing taking place there, namely its sanitation, was retrieved from the author's previous research [38]. These inventory items were common to the three scenarios. The distinct modeling of packaging production across scenarios was the same as in the attributional LCA, implying the same processes and considerations for the packages end of life as described in Section 2.1.2.

Switching into the consequential LCA implies the contemplation of the customers' trend changes when the novel active packages are introduced. In particular, the extension of salad shelf life implies that the food waste generated by the consumer is diminished, and thus less lettuce needs to be produced, processed, and packaged upstream in order to meet the FU of 130 g of FC vegetable to be ingested at the end of the chain. Furthermore, a decrease in fresh product consumption leads to less packaging materials to be produced and disposed of at the end of life.

To quantify the avoided food wastes in the active package scenario, a model for the food loss probability (FLP), reported by [39], was considered. In their studies, the authors claim that FLP can be calculated as a function of shelf life (SL). Here, we took into consideration two of the proposed models: a linear regression that directly relates the FLP to the SL through a line; and a first-order kinetic model, in which the natural logarithm of FLP holds a value directly proportional to the SL. For the calculation of the regression coefficients, we used the hypothesis retrieved from [39,40], which states that 8% of the packaged food is lost (FLP = 0.08), on average, when the SL is maximal (7 days for FC lettuce, as claimed by the CEREAL consortium); and the assumption that when we have a null shelf life, the whole product will be lost (i.e., FLP = 1 when SL = 0).

Using these regression models, it is possible to calculate the FLP as a function of the shelf life within the three scenarios. According to the investigations performed by the CEREAL consortium partners, it was estimated that the reference package promotes a shelf-life of 6 days for FC lettuce, while the novel active packages allow the product to reach the maximal shelf life, extending the expiration period up to 7 days. As a result, the FLP in the reference scenario is 21.2% when considering the linear model and 11.2% when applying the kinetic model. The inventory items concerning the produce agricultural production and processing were adjusted to fit the functional unit taking into account the respective food loss percentages. These new LCI data were used to analyze the environmental impacts of the proposed packaging alternatives from a consequential point of view.

The LCI tables can be seen in the Supplementary Materials.

2.3. Life Cycle Impact Assessment

In both LCAs, the modeling and evaluation of the different scenarios were performed using SimaPro v8. This is a software developed to collect, analyze, and monitor the sustainability performance of products and services. Using this software, it is possible to model complex life cycles in a systematic way, measure the environmental impact across the life cycle stages of a product, and identify hotspots in the supply chain [41].

We assessed the environmental impacts through ReCiPe indicators, utilized to transform the list of life cycle inventory results into a limited number of impact scores, categorized in 18 midpoint indicators [42]. These midpoint impact scores can be combined and coerced into 3 endpoint indicators, which measure three main concerns: damage to human health, damage to ecosystems, and damage to resource availability. Finally, the total impact can be summarized into a single-score endpoint indicator, and this was the measurement used for the final comparison of the alternatives. The final single-score indicator is calculated as a weighted sum of the normalized midpoint impact scores, depending on the relative importance of each category [43]. Since their development in 2008, ReCiPe scores have been broadly used to assess the life cycle impact [17,44–47], as this method encompasses both midpoint and endpoint indicators harmonizing previous popular approaches at each level, enabling the LCA to be flexible and more uniform [43].

2.4. Uncertainty Assessment

The LCA models depend on a variety of input parameters, in such a way that the final accuracy relies heavily on the fidelity of the data used in characterizing the inputs and emissions of the model and the assumptions taken over the scope definition [48]. Hence, there is an inherent uncertainty on the LCA results propagated from the LCI variables that can be due to factors such as variation in the physical quantity, measurement or parameter implementation inaccuracies, lack of information, and/or impossibility to retrieve high-quality data, and so forth [48].

In this particular case, the considered uncertain model parameters are:

- Inventory data retrieved from literature, which may have been measured under different conditions. The uncertainty of these data was evaluated through the pedigree matrix method [49].
- Processes modeled based on the Ecoinvent database. This database is one of a very few LCI databases that systematically includes explicit uncertainty data, captured by the geometric standard deviation [50].
- Percentages allocated to each of the packaging waste treatment. The EOL processes allocation presented in Table 1 heavily depends on the costumers' behaviors, which are undoubtedly uncertain. For instance, the total composting of the PLA packages will be possible only if the final users properly dispose the package into the suitable refuse container, which is known not to be always possible.
- Food loss probability within the reference scenario, which might be calculated through two different regression models. Primarily, LCI was constructed considering the linear model due to its simplicity. However, there is no proof that this could be more or less accurate than the kinetic model counterpart.

To treat the uncertainty on the LCA conclusions that is propagated by these parameters, a Monte Carlo analysis was performed. This method allows the establishment of an uncertainty range in the results by repeating the calculation runs with values that follow the probability distribution of the uncertain starting data [51], which needs to be priory defined. The pipeline to perform Monte Carlo simulation is as follows: (1) determine the parameter variables and their distribution functions involved in the model, (2) construct the model, (3) conduct multiple random sampling based on given parameter distributions, (4) obtain the distribution of the output variables (LCA impact assessment indicators) [52]. The third step is iteratively repeated a large number of times; in this case, 1000 simulations were performed, as suggested in the Simapro handbook [53]. The probability distributions of the input parameters are summarized in the Supplementary Materials.

By means of this analysis, it was possible to evaluate the environmental performance of the different alternatives in cases where LCI data are not deterministic, but they take a value according to the probability distribution. Therefore, it was considered that a novel package entailed a significant environmental gain if in at least 60% of the Monte Carlo iterations, it scores a lower burden than the reference scenario.

3. Results and Discussion

3.1. Attributional LCA

At midpoint level, novel packaging techniques initially promoted a decrease in 14 out of 18 impact categories when compared to the reference when just the packaging materials were considered (Figure 3A). The uncertainty propagation showed that active packages were clearly superior to the reference in most impact categories (Figure 3B). Indeed, ZnO–PLA films showed a decreased impact score in above 60% of the Monte Carlo iterations in 10 out of 18 categories, while ZnO–PP films entailed diminished impacts in 11 categories. The reference scenario showed an environmental draw in both cases for the "metal depletion" category, while it was also more beneficial than ZnO–PLA in terms of urban land occupation. The better profile in metal depletion may be explained due to the use of Zn for nanoparticle manufacturing. However, Zn is the 23rd most abundant element in the earth, and recycling accounts for about 36% of Zn consumption [54]. The expected increases in recycling rates are likely to compensate for the possible increases in metal consumption. As for the urban land occupation, composting of PLA in industrial facilities makes it necessary to destine a specific piece of land to the facilities, generating a significant impact [55]. In the remaining categories, none of the compared technologies showed a benefit in more than 60% of the iterations, and thus it was considered that the impacts were similar across the alternatives.

At endpoint level, the ReCiPe single score shows that novel packages have a better environmental profile than the reference package (Figure 4). When allocating the impacts to the different processes within the package life cycles, it could be noticed that the manufacturing step was similar for both polypropylene packages, whereas the PLA film production entailed a significantly decreased impact. This can be explained by the fact that PLA's raw material is corn starch, assumed to be an agro-food industry waste; therefore, its production entails no impacts. PLA is an aliphatic polyester, primarily produced by industrial polycondensation of lactic acid, derived from renewable sources such as corn sugar, potato, and sugar cane [56]. Since the starch is considered as a secondary product of the food industry, the only environmental burden derived from its use for PLA production comes from transportation to the processing plant. The results would be different, however, if the starch were not derived from wastes, and vegetable resources should be produced to meet the requirements for PLA film manufacturing. In such a case, the impact derived from this production would be clearly significant, and even some midpoint indicators, such as the agricultural land occupation, would be comparable or superior to the values obtained for the reference scenario.

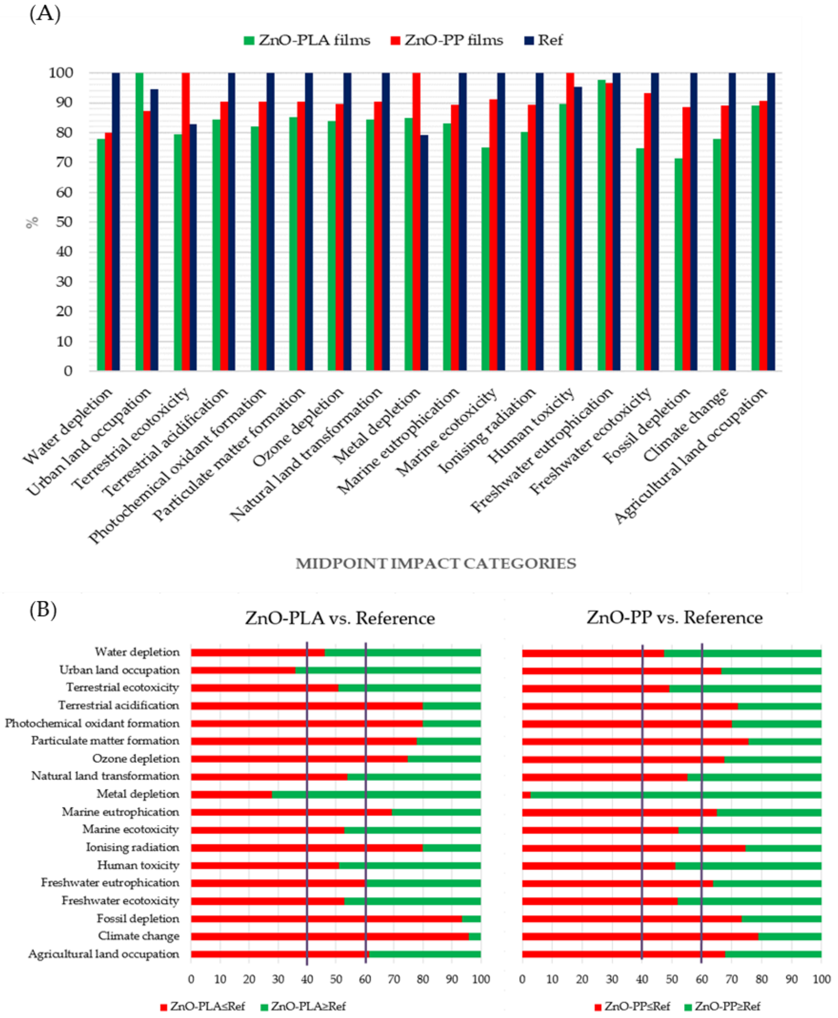

Figure 3. (**A**) Midpoint impact scores across the 18 categories, represented as % of the scenario where the score is maximal. (**B**) Uncertainty analysis results. In red, the share of iterations when active packages show a better environmental performance; green shows the share of iterations when reference packages had a lower environmental burden. In those categories where the boundary is between the blue lines, it is not possible to ensure which of the technologies shows better performance.

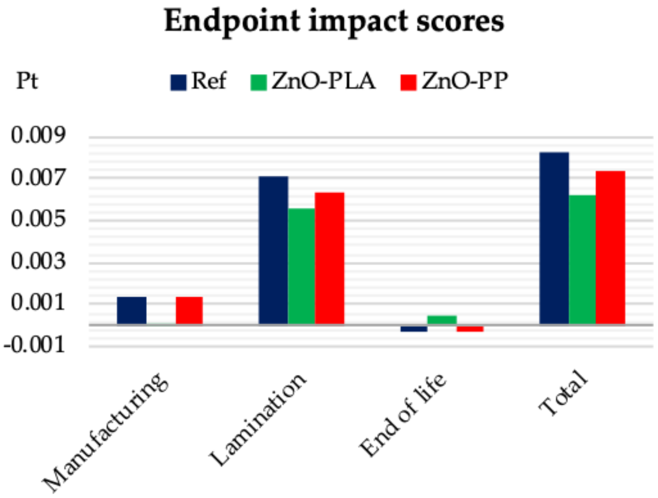

Figure 4. Endpoint impacts allocated to each of the steps concerning the package life cycle.

The other main difference amongst scenarios arises from the end of life (EOL) processes. PLA films are meant to be composted, which entails a null net impact, whereas PP packages' endpoint single-score held a negative value, decreasing the total burden. This can be explained considering two issues of LCA methodology. On the one hand, uncertainty concerning recycling processes is high, as there are some factors besides the plastic composition that clearly affect the recycling efficiency, such as its organic contamination [57]. Furthermore, there are some environmental concerns related to the utilization of single-use plastics, specifically due to marine littering, that are not properly addressed by LCA [58]. Microplastics persistence, which represents a major issue derived from plastics production, littering, and recycling processes, is not currently included in LCA studies [59,60]. Consequently, the EOL processes of those technologies where recycling is contemplated as an alternative have a methodological advantage towards those that do not consider such processes. On the other hand, recommendations for waste management of the PLA state that the material should be composted at industrial facilities, instead of the typical backyard compost piles, where the suitable degradation requirements cannot be fulfilled [55,61]. Industrial composting make this process more comparable to a landfilling scenario, and thus the impacts of the EOL result in a clear increase when compared to other alternatives [62].

By means of Monte Carlo analysis, we tackled the uncertainty issues related to the scenario modeling, leading to statistically significant conclusions. Thereby, the inferred probability distributions for the differences between the endpoint single scores showed a mean impact reduction of 17.8% in the case of ZnO–PLA packages and 7.2% for ZnO–PP packages, with respect to the reference (Figure 5).

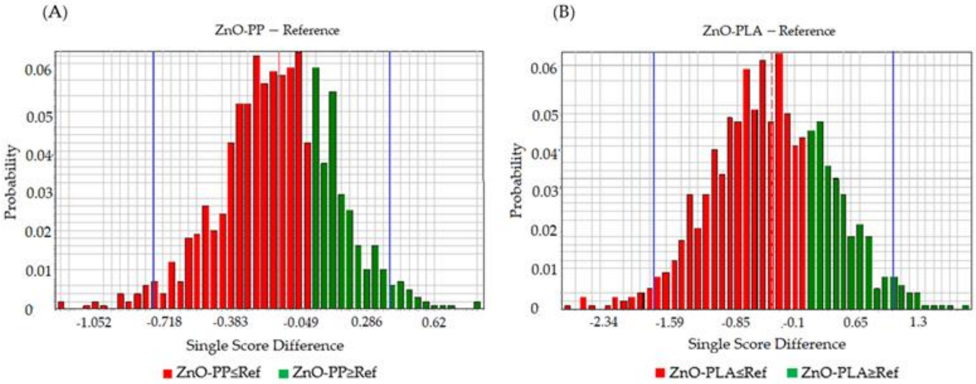

Figure 5. Monte Carlo analysis results on the Single Score Difference between the reference scenario and the ZnO–PP packages (**A**) and the ZnO–PLA packages (**B**) in the attributional LCA. In red, we represent the cases where novel active packages showed a decreased impact score when compared to the reference; in green, those cases where the reference package entailed an environmental gain at single score endpoint level. Blue lines delimit the 95% confidence intervals for the Single Score Difference.

Furthermore, a reduction in the single score was obtained in 70.2% and 70.8% of the Monte Carlo iterations for active PLA and PP packages, respectively, when different values of the input parameter within their probability distributions were considered. Hence, uncertainty evaluation showed that there is an environmental gain in active novel packages' life cycle when compared to traditional PP packages, which is especially important when biodegradable composites are used for manufacturing. The gain, however, might be different if the full life cycle of the lettuce inside is assessed. This issue is better addressed when considering a consequential LCA approach.

3.2. Consequential LCA

When analyzing the full life cycle for the fresh-cut lettuce by means of the consequential LCA, we were able to allocate the intensity of the impacts to each step of the cycle, both at midpoint and endpoint level. The results concerning the midpoint indicators within the reference scenario are shown in Figure 6. In 17 out of 18 categories, most of the impacts are derived from agricultural production.

This is consistent with the bibliography, where it has been previously stated that these processes are responsible for the greatest part of the environmental burden [17]. Following the agricultural production, packaging manufacturing also entails a significant load. The rest of the impacts are minor, including the package end-of-life (EOL) processes and the sanitation step, whose major concern has been claimed to be the energy consumption of the process [38].

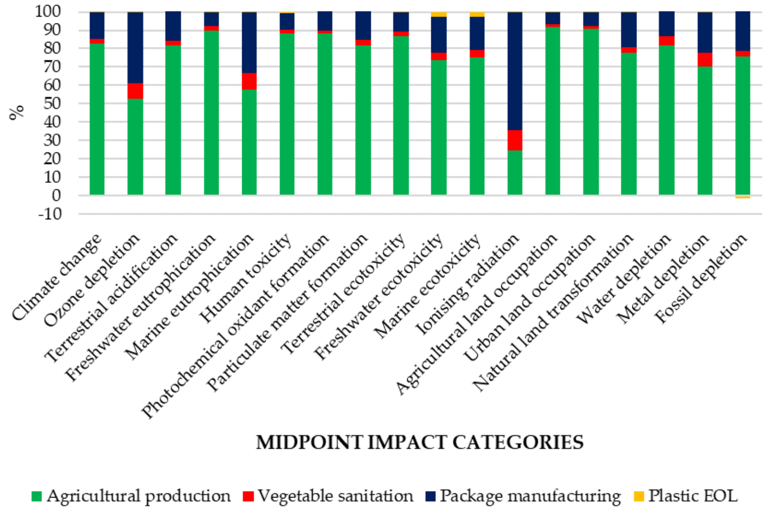

Figure 6. Relative contribution of the different life-cycle processes concerning the functional unit to the distinct ReCiPe midpoint impact categories. In green, it can be noticed that agricultural production accounts for most of the impacts in nearly every category.

The only category where package production showed a higher impact when compared to the lettuce production was the “potential in ionizing radiation”. This is explained, as package manufacture consumes a significant amount of electricity, of which around 20% comes from nuclear power stations in the considered Spanish mix [63].

The trends at the midpoint level are similar to the ones obtained when the endpoint single score was calculated (Figure 7). This indicator shows that agricultural production holds for the vast majority of the total impacts, followed by the package manufacturing. It is important to notice that, at the endpoint level, the EOL processes contribute to the total impact in a negative form, i.e., they avoid further impacts, due to the recyclability of PP.

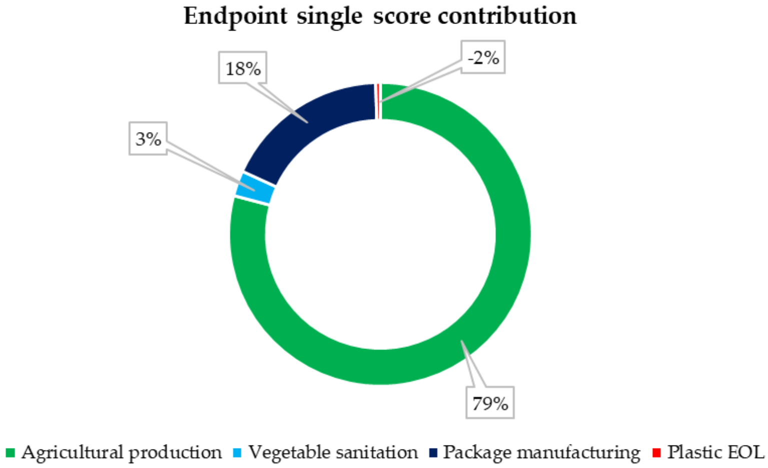

Figure 7. Relative contribution of the FC lettuce life cycle processes to the ReCiPe endpoint single score. Consistent with the results at midpoint level, the agricultural step is responsible for the greatest part of the impacts. Plastic EOL contribution sometimes holds a negative value as the recycling of polypropylene can be accounted for as an avoided impact.

When comparing those impacts to the ones concerning the novel active packages, the reference scenario showed increased scores in all the 18 categories (Figure 8A), although the differences were not acute, and the reduction of the impact was never greater than 20% compared to the reference. When uncertainty was considered by means of Monte Carlo analysis, we were able to conclude that active packages showed better environmental performance in at least 60% of the iterations in 13 categories when ZnO–PLA packages were considered and in 11 categories for the ZnO–PP packages (Figure 8B).

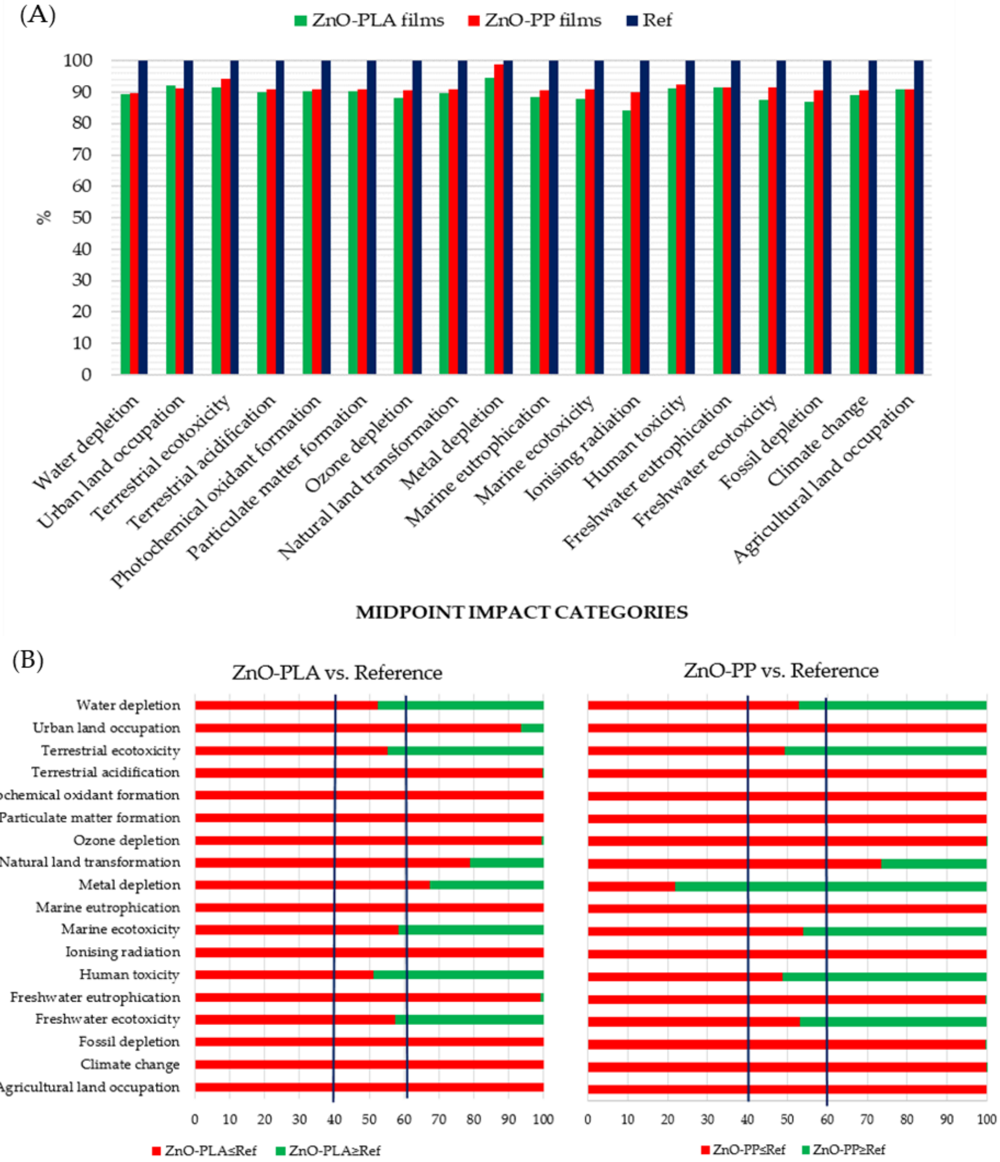

Figure 8. (**A**) Comparison of the midpoint impact scores across scenarios for the 18 ReCiPe categories. (**B**) Monte Carlo results for midpoint impact categories. In red, % of total Monte Carlo iterations in which active packages showed a decreased impact score when compared to the reference. In green, % of iterations in which an environmental gain was observed for the reference package when compared to the active package alternatives. The increased or decreased burden of some technology is considered if it is achieved in at least 60% of the iterations, i.e., the boundary does not lay between the blue lines.

The reference package only showed environmental benefits, measured as an impact reduction in over 60% of the iterations, in one category—metal depletion—when compared to the ZnO–PP package scenario. As was discussed in the attributional LCA (Section 3.1.), this is due to the use of Zn as a raw material for nanoparticle manufacturing. However, the mean decrease amongst iterations was about 2% of the ZnO–PP metal depletion score, which cannot be considered as significant. This fact enhances the idea that the impact derived from the use of Zn is negligible when all the FC product life cycle is considered.

Looking at endpoint impacts, the initial assessment showed that novel active packages entailed a diminished load when compared to the reference (Figure 9). As could be expected, compostable active packages showed an enhanced environmental benefit towards the reference when compared to the non-degradable active package option. The results obtained in this study regarding this topic are consistent with the existing literature, where it has been previously reported that biodegradable films in general, and PLA composites in particular, are able to decrease the environmental implications of food packages [22,64]. The environmental gain is, however, very similar to the one that can be obtained by the use of non-degradable active packages. Indeed, Monte Carlo analyses for the uncertainty of the models showed that ZnO–PP packages promote an impact reduction of 5.3% when compared to the reference package, while ZnO–PLA plastics can induce a mean reduction of 7.3%. This similarity in the results can be explained due to the impact distribution along the whole supply chain. As in the reference scenario, in the case of active packages, the agricultural production processes account for most of the total impact. Since both novel technologies promote the same shelf life extension, the upstream needs for the lettuce production are equal, and so they are the greatest part of the impacts. There is a substantial difference in the achieved gain when considering the consequential LCA versus its attributional counterpart. In this case, this is clearly explained by the relative importance of the processes concerning the package—its production and end-of-life—that have been clearly stated to be of little importance when compared to the upstream processes, namely the vegetable production and manipulation. When considering the whole vegetable product life cycle, packages play a minor role in the environmental profile. This issue had been previously described [17,38].

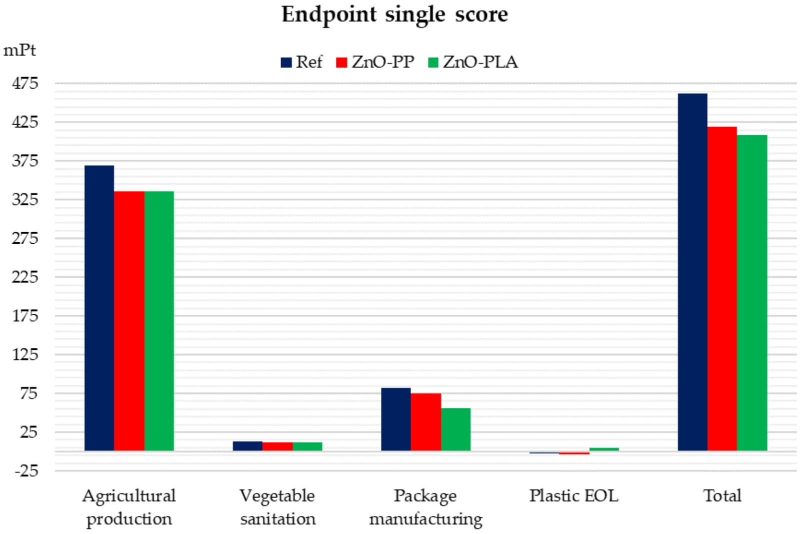

Figure 9. Comparison between the endpoint indicators within the three scenarios.

The minor role of packages production within the FC life cycle validates the simplifications assumed when modeling the ZnO nanoparticle production. Here, we just considered the production of the stoichiometric amount of Zn, and not the nanoparticle production itself. It has been claimed that nanoparticle production is an energy-intensive process [65], but nonetheless, the main contributor to the environmental loads from inorganic nanoparticles used for active packages production can be allocated to the manufacturing of the precursors [66], which is here considered. This, together with the fact that nanoparticles represent just 5% of the package's weight, and thus less than 0.2 g per FU is needed, reveals that any possible uncertainty derived from the model assumptions will entail a negligible deviation in the final results.

With Monte Carlo analysis, we also determined that the ZnO–PP package scenario promotes a decreased impact score in 67.1% of the iterations when compared to the reference, whereas the ZnO–PLA package scenario held lower single-score impact values in 71.7% of the iterations, greater than the 60% sensible cutoff (Figure 10). Hence, we can conclude that introducing novel active packages into the FC produce life-cycle promotes a benefit from the environmental profile thanks to the shelf-life extension. Indeed, these enlarged expiration periods are key to reaching the actual environmental benefits of introducing new packaging techniques in the FC product life cycle. In recent years, the focus has been set on those materials with optimized EOL processes, such as recycled and/or biodegradable packages [67]. However, focusing on increasing the shelf life could be more interesting for lowering the environmental burden from the FC industry plastics. When decreasing the food wastes, less quantity of produce and thus of plastics need to be used along the whole supply chain to ingest the same amount of vegetables. The employed plastics are not only derived from packages, but also other upstream processes (greenhouses, raw materials, and ready-to-use product delivery, and so forth). The complete substitution of these plastics with biodegradable alternatives is still not possible due to the mechanical specifications that they need to meet [68].

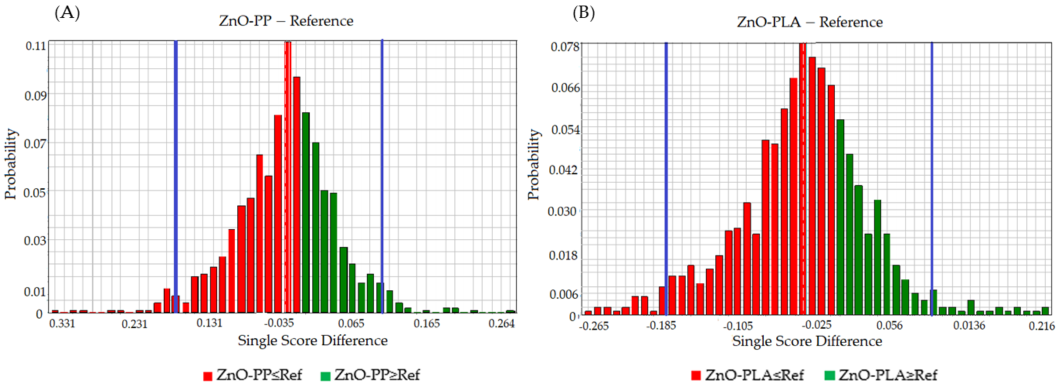

Figure 10. Probability distributions of the endpoint Single Score Difference for the consequential LCA, obtained by means of Monte Carlo analysis. In red, those cases where the impact in the reference scenario was superior to the novel active packages (**A**) ZnO–PLA scenario, (**B**) ZnO–PP scenario); in green, those iterations where these new technologies promoted a worse performance. Blue lines indicate the 95% confidence interval for the variable.

Here, it has been considered that due to the introduced technologies the shelf-life of the products is maximal, i.e., 7 days. However, some other factors affect the maximum shelf-life value. Leaving aside the internal factors, some environmental situations clearly influence the quality of FC produce, such as storage temperature, humidity, sharpness of cutting-knife, and chemical treatments [69]. Combining the optimal environmental conditions for these factors with the active packages could extend the maximal shelf life even more and thus decrease to a greater extent the amount of food wasted.

3.3. Uncertainty Analyses

LCA has been proved to be a useful tool in order to reach conclusions on behalf of the eco-profile of distinct solutions. However, this article highlights the importance of proper uncertainty evaluation to ensure the reliability of the results. In the case of the consequential LCA, the difference in single-score was not enough to be considered as statistically significant when ignoring the uncertainty of the results. Via Monte Carlo analysis, we estimated the probability distribution of the difference between the endpoint single scores for novel packages and the reference, being able to establish a confidence interval for that variable and a statistically significant estimation for the mean difference. It has been claimed that it is feasible to assess the cumulative effects of common uncertainty and variability sources by means of Monte Carlo tools included in the commercial LCA software [70], as we did here.

In this paper, Monte Carlo analysis was especially important to assess the uncertainty derived from the selection of the FLP model. In the paper from where the models were extracted [39], there is not any conclusion that makes it more preferable either the linear or the kinetic model for the FLP. Hence, it is not possible to exactly determine this parameter for the active packages. However, we can be confident that the deterministic value is within the range given by these two proposed models. By means of Monte Carlo, and as we determined the probability distribution of the FLP as a uniform distribution in the range of the values given by the two alternative models, in each iteration the LCA impact calculations are performed with an FLP value within that range, eliminating the issue derived from an improper model selection.

4. Conclusions

By utilizing LCA as a tool to establish the environmental profile of different technologies, we have been able to prove the better performance of active packages that include ZnO nanoparticles as biocidal agents when compared to the classical packaging technologies. The shelf-life extension has been proven to be key when optimizing the benefits of novel packages, and thus the efforts concerning the FC environmental burden avoidance should take into account this issue. Promoting longer expiration periods by the combination of different changes in the FC life cycle, including the introduction of the here presented packages, is a strong research field that should be addressed in the near future.

LCA has been also proved to be helpful to compare the burden of different scenarios, even if some primary data is lacking. Uncertainty analysis via Monte Carlo approach allowed for the determination of the effect of uncertain data that may generate inaccuracies in the final results. Together with an accurate definition of the deviations in the input data, the use of Monte Carlo has been key to reinforcing the value of the results reached in this work, and to establishing feasible conclusions regarding the high importance of shelf life extension in the FC industry.

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