

Article

Life Cycle Assessment of Fresh-Cut Salad Packaging: Evaluating Conventional vs. Bio-Based Films Under Current Waste Management Scenarios

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Abstract

This study presents a comparative Life Cycle Assessment (LCA) of packaging for 1000 kg of fresh-cut salad using conventional polypropylene (PP) and bio-based INZEA[®] FH05 bags. Using the Product Environmental Footprint (PEF) methodology, the analysis revealed weighted scores of 152 ± 14 mPt for PP and 158 ± 14 mPt for the bioplastic. To distinguish between statistical significance and practical relevance, a Monte Carlo Analysis (MCA) was performed. Statistical significance was defined by the probability $P(\text{PP} \geq \text{INZEA}^{\text{®}})$, representing the frequency of iterations where the PP impact was greater than or equal to the bioplastic, while practical relevance was assessed by the percentage difference (Δ) between mean values. The MCA demonstrates that the PP system is the environmentally preferable option in 91.5% of the simulated iterations; correspondingly, there is only an 8.5% probability (P) that PP results in a higher impact than the bioplastic. Despite this high frequency of preference, the overall tangible benefit remains modest, with a 4.1% reduction (Δ) in the total PEF score for PP. At the characterization level, bioplastic films showed a robust advantage in fossil resource depletion ($P = 96.2\%$; $\Delta = +4.7\%$ for PP); however, this was offset by significantly higher impacts in categories such as Acidification ($P = 0\%$; $\Delta = -11.0\%$) and Freshwater Ecotoxicity ($P = 0\%$; $\Delta = -29.7\%$). Conversely, the Climate Change category showed environmental parity with no tangible benefit ($\Delta = -0.5\%$) and a lack of statistical significance ($P = 43\%$). These findings indicate that the theoretical benefits of compostability are currently hindered by industrial infrastructural deficiencies. Under current scenarios, PP maintains a competitive environmental profile, highlighting that a successful transition to bioplastics requires both material innovation and systemic improvements in waste management infrastructure.

Keywords: Life Cycle Assessment (LCA); Product Environmental Footprint (PEF); polypropylene (PP); bioplastics; food packaging; waste management infrastructure; marine eutrophication; Monte Carlo Analysis (MCA); uncertainty analysis; circular economy; environmental trade-offs



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1. Introduction

Consumption of fresh-cut fruit and vegetable products—fresh, washed, and ready-to-eat—has steadily increased in Italy, the leading European market for these products. In 2024 alone, this sector generated sales of €1.085 billion, corresponding to approximately 157,000 tons of products and employing roughly 30,000 workers [1].

Despite a significantly higher price point compared to bulk produce—where a bag of lettuce can reach nearly €10/kg compared to less than €2/kg for loose heads—the

convenience factor remains the primary driver for modern consumers. Data compiled by NielsenIQ indicate that between January and May 2025 sales exceeded €440 million, with the vegetable segment growing by 2.3% and the smaller fruit segment surging by 7% [2].

The fresh-cut industry is increasingly defined by both its convenience and its commitment to environmental sustainability. Industry reports suggest that pre-washed and portioned products may help reduce household food waste; however, this benefit is contingent upon effective portion control and the shelf-life extension provided by specialized packaging [3]. Furthermore, production stages are increasingly adopting circular economy practices, such as photovoltaic integration, low-impact agricultural techniques, and the repurposing of processing waste for animal feed [4].

Within this framework, packaging plays a pivotal role by facilitating Modified Atmosphere Packaging (MAP) [5]. As established by Kader [6] and Sandhya [7], MAP can be achieved either actively via gas flushing or passively through the natural equilibrium between product respiration and film gas-transmission rates. For high-volume fresh-cut commodities like the lettuce varieties used in this study, passive MAP is the prevalent industry standard [8]. In this study, the choice of using standard bagging was specifically intended to evaluate the polymer's performance in creating this passive equilibrium without the confounding variable of initial gas injection.

While traditional petroleum-based plastics like polypropylene (PP) have dominated the market due to their mechanical performance and low cost, the industry is facing a massive environmental challenge. Based on current market volumes [2], it is estimated that approximately 84 million salad bags ($\pm 10\%$) are sold monthly in Italy. Based on a conservative average weight of 5 g per bag, this results in an annual consumption of approximately 5000 metric tons of single-use plastic packaging; this total is estimated to range between 4500 and 5500 metric tons when accounting for inherent variability in film thickness and market fluctuations.

To mitigate this impact, the industry is exploring bio-based and biodegradable alternatives, such as polylactic acid (PLA) and other biodegradable films [9]. However, the transition to bioplastics is not a straightforward solution and can sometimes result in *greenwashing* if not supported by rigorous data [10].

Scholarly research suggests a *green paradox*: while bioplastics aim to reduce fossil fuel dependency, their environmental superiority is strictly contingent upon production efficiency, material thickness, and the existence of robust industrial composting infrastructures [11]. Without a 100% efficient recovery system, biodegradable plastics land-filled in anaerobic conditions can release methane, a greenhouse gas (GHG) significantly more potent than CO₂, potentially making them more impactful than traditional inert plastics [12,13].

These technical challenges are well-documented within the broader Life Cycle Assessment (LCA) literature, which confirms that the environmental profile of biopolymers often exceeds that of conventional plastics like PP, depending heavily on methodological choices and system boundaries. Recent studies emphasize that comprehensive frameworks, such as the Product Environmental Footprint (PEF), as updated by Zampori and Pant [14], are essential to capture shifts in impact categories—specifically land-use change—which many *optimism-biased* LCAs overlook by assuming ideal biodegradation rates [11,15,16].

While bio-based materials can show a lower carbon footprint in specific applications [12], these benefits are frequently negated by energy-intensive synthesis and the environmental burden of agricultural production, which drives higher Acidification and Eutrophication scores compared to fossil-based PP [17–20]. Furthermore, functional requirements often necessitate greater material thickness for bioplastics to maintain structural integrity, leading to a higher mass per Functional Unit and thus a higher cradle-to-gate impact [21].

This study contributes to this state-of-the-art by providing a primary-data comparison within the Italian fresh-cut sector, evaluating whether the transition to bioplastics represents a standalone solution or one strictly contingent on regional waste management efficiency. Given this context, the objective of the present work was to conduct a streamlined cradle-to-grave Life Cycle Assessment (LCA) focused specifically on the primary packaging system for bagged salads. The study's boundaries were defined to quantify the environmental impacts associated with the entire life cycle of the packaging, including raw material extraction and film production (cradle), the distribution phase, and post-consumer disposal (grave). By comparing a traditional fossil-based plastic reference film with a biodegradable target film (INZEA® FH05), this research sought to provide a scientific basis for evaluating whether bioplastics can effectively balance environmental sustainability with the high-performance requirements of food preservation in the Italian fresh-cut sector.

2. Materials and Methods

2.1. Defining Objectives and Scope

A streamlined LCA was conducted to evaluate the environmental profile of primary packaging for fresh-cut salads, encompassing both the production and end-of-life (EoL) phases. The study was performed in accordance with ISO 14040:2006 [22] and ISO 14044:2006 [23], covering the four standard phases: goal and scope definition, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and interpretation of results.

2.2. Functional Unit and Material Characterization

The Primary Functional Unit (FU) for this study was defined as 1000 kg of fresh-cut salad leaves ready to be packed. This unit was selected to capture the total environmental burden of the packaging system required for a standard industrial batch. Two distinct materials were compared for the production of the 100 g retail packages of fresh-cut salad (e.g., baby lettuce, arugula, or mixed greens):

- (a) Polypropylene (PP) Film: The reference packaging consisted of a biaxially oriented PP film with a thickness of 40 μm and a grammage of 36.8 g m^{-2} ($\pm 9\%$ tolerance), manufactured by New Dimension Plastic Srl (Nocera Inferiore, Italy). This material is characterized by high mechanical strength and moisture barrier properties ($\text{WVTR} = 6 \text{ g m}^{-2} \text{ day}^{-1}$), relatively high oxygen permeability ($\text{OTR} = 1800 \text{ cm}^3 \text{ m}^{-2} \text{ day}^{-1}$), and a wide sealing range (115–140 $^{\circ}\text{C}$), ensuring hermetic closures during high-speed industrial packaging.
- (b) Biodegradable and Compostable Film: The target alternative was the INZEA® FH05 film, with a thickness of 35 μm and a density of 1210 kg m^{-3} , produced by Nurel S.A. (Zaragoza, Spain). It features a sealing range of 115–130 $^{\circ}\text{C}$ and is designed for disposal via organic waste streams in compliance with EN 13432 [24] (industrial composting) and EN 17033 [25] for biodegradation in soil.

To ensure methodological clarity, the assessment follows a two-tiered approach:

- Material-level analysis: Initial impacts were calculated per 1 kg of packaging film to compare the inherent environmental intensity of the fossil- and bio-based polymers.
- System-level analysis: Results were then scaled to the Primary FU. As detailed in Section 2.9, the model accounts for different industrial waste rates for the salad (5%) and the packaging films during the bagging process. Thus, the 1000 kg of input salad corresponds to the production and disposal of 9500 retail units (100 g each).

2.3. Composition and Inventory of the Bioplastic Film

To account for the proprietary nature of the INZEA® FH05 resin, a proxy recipe was developed based on manufacturer technical data and validated against established

literature for food-grade blown films [26–28], as reported in Table S1.1 in the electronic version of Supplementary Materials S1. Specifically, the primary polymer ratios and the use of acetyl tributyl citrate (ATBC) as a plasticizer follow the optimized formulations for high-performance biodegradable films described by Coltelli et al. [26] and Aliotta et al. [27], while the application-specific performance for food packaging aligns with the findings of Pietrosanto et al. [28].

The inherent compositional uncertainty was then integrated into the Monte Carlo Analysis (MCA). The ranges defined in Table S1.1—representing ± 10 –15% variations in the primary polymer ratios—were used as input probability distributions to calculate the environmental impacts. This methodological approach ensures that the estimated nature of the material composition is statistically quantified, providing a robust confidence interval for the final LCA results.

2.4. Life Cycle Inventory Data and Assumptions

Modeling data were sourced from the Ecoinvent database v. 3.9.1 using the *cut-off, S* system model [29]. The selection of the cut-off approach is based on the principle that the first user of a material should carry its full environmental burden, thus providing a clear and transparent distribution of responsibilities within the life cycle [30]. This choice is consistent with the general philosophy of the Product Environmental Footprint (PEF) methodology regarding the accountability of primary production impacts [31]. The use of the cut-off model is further justified by evidence from several life cycle studies on food systems, which indicate that the choice between cut-off and APOS (Allocation at the Point of Substitution) models often yields a negligible difference in the final results [32]. Specifically, sensitivity analyses conducted on food products have shown that switching from cut-off to APOS resulted in a minimal variation in the carbon footprint, often estimated at less than 2% [32]. This limited impact is particularly evident in lightweight primary packaging or energy-intensive food chains, where the environmental *credits* from material recovery are statistically secondary compared to the high-impact phases of cultivation, industrial processing, and refrigeration [33]. By adopting the cut-off model, the study provides a transparent and robust representation of the system's primary burdens, avoiding potential overestimation of recycling benefits in the early stages of the product's life cycle [30,34]. Additionally, while the cut-off model serves as the primary approach, a sensitivity analysis using the APOS model was performed specifically for the bioplastic end-of-life (Section 3.6) to evaluate how the distribution of burdens for secondary by-products (e.g., compost) affects the overall environmental profile.

The following proxy datasets were used for the INZEA® FH05 film:

- PLA: Polylactide, granulate {GLO} | market for polylactide, granulate | Cut-off, S.
- PBAT: Polyester-complexed starch biopolymer {GLO} | market for polyester-complexed starch biopolymer | Cut-off, S.
- ATBC: Acetyl tributyl citrate {GLO} | Technology mix | Production mix, at plant.
- Processing Additive: Estimated as a blend of Talc (50%), Silica (30%), and Glycerol Monostearate (20%) using respective Ecoinvent LCI results.

Manufacturing yield was assumed to be 97.6% for the PP film and 95.0% for the bioplastic film, reflecting the higher technical complexity involved in processing bio-based polymers.

2.5. System Boundaries

The industrial production of bagged salad involves several complex stages, including pre-washing, automated coring, cutting, washing (often using ozone as a disinfectant), de-watering, and final centrifugal drying. However, to isolate the environmental performance

of different material solutions, this LCA study adopted a *cradle-to-grave* approach focused specifically on the packaging system.

Consequently, the upstream agricultural phase (cultivation and harvesting) and the pre-packaging industrial steps (coring, cutting, washing, and centrifugal drying) are excluded from the system boundaries, as these remain identical across all scenarios. To neutralize the inherent variability associated with different salad varieties, a standardized matrix of pre-cut salad was assumed. Crucially, while the “Salad” node (Figure S1.4) is represented in the life cycle inventory, it serves as the functional carrier. The energy demand accounted for within this node is specifically defined to include the packaging operations (bagging, weighing, and sealing) and the energy requirements for the post-bagging cold chain storage, as detailed in the inventory for fresh-cut salad packaging and cold-refrigeration (Table S2.2). General facility overheads unrelated to these specific stages remain excluded.

As illustrated in Figure 1, the system boundaries examined in this study primarily include:

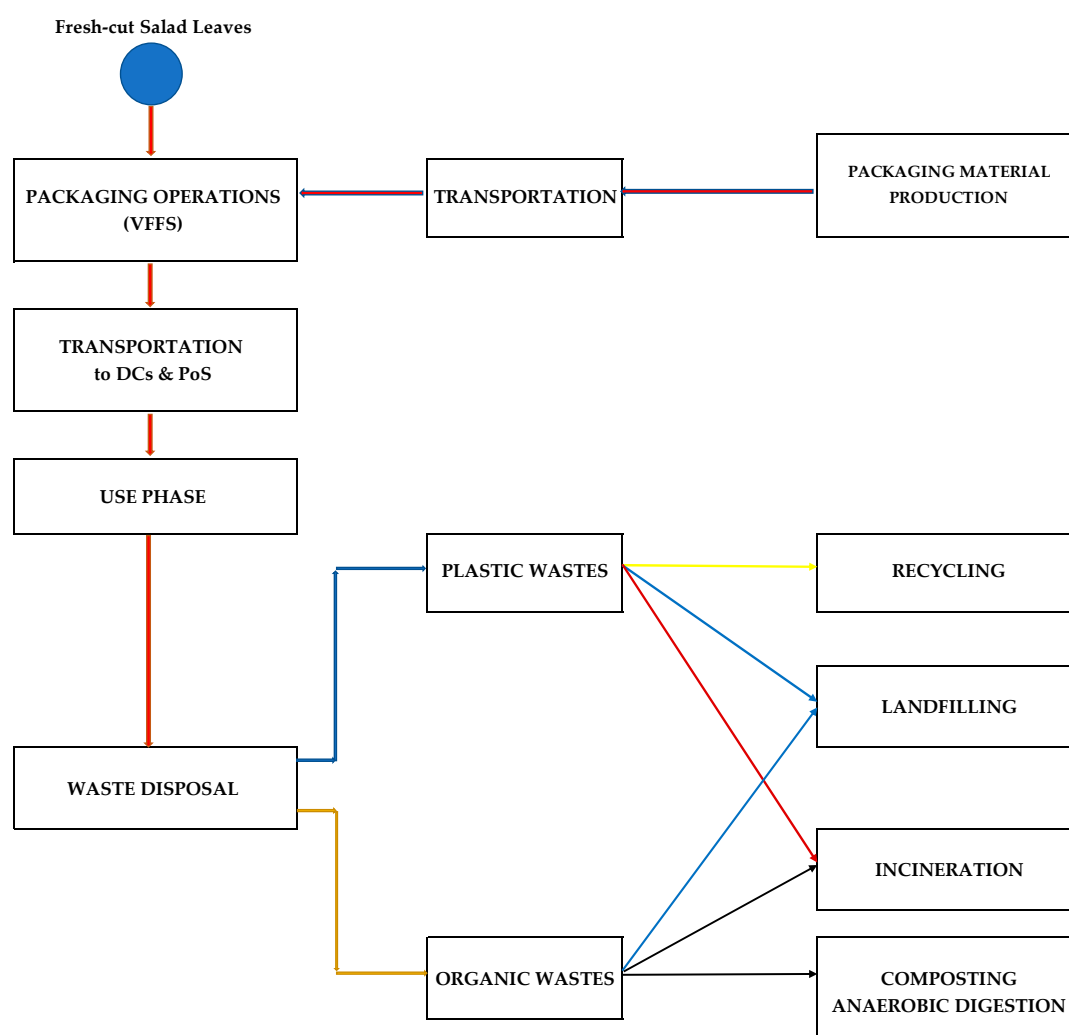


Figure 1. System boundaries for the cradle-to-grave LCA. The *Packaging Operations* stage specifically accounts for the VFFS machinery electricity, and secondary and tertiary packaging, while excluding identical upstream salad processing (washing/cutting). DC: Distribution Center; PoS: Point of Sale.

- Packaging Production and Logistics: The extraction of raw materials, manufacturing of the primary-tertiary packaging materials, and transport to the packaging facility.
- Packaging Operations (Bagging Phase): The electricity consumption is specifically associated with the Vertical Form-Fill-Seal (VFFS) process. This includes the energy required for the mechanical forming of the bag, the automated weighing/filling of the

salad, and—critically—the thermal sealing of the film. By isolating VFFS energy, the model accounts for potential variations in the “sealing window” (temperature and dwell time) required by the different polymer structures of PP versus the INZEA® FH05 bioplastic. Secondary casing and palletization energy are also included in this phase.

- Distribution Phase: The transport of the final packaged product from the facility to distribution centers (DC) and points of sale (PoS).
- Use Phase and End-of-Life: The management of post-consumer packaging waste and the organic waste generated during the product’s shelf life.

2.6. System Exclusions

Several elements were excluded from the system boundaries of this study to isolate the impact of the packaging configurations:

- Upstream Agricultural and Primary Processing: The cultivation, harvesting, transport, and primary processing of lettuce (coring, cutting, washing, and drying) were excluded, as these processes remain identical regardless of the packaging material used.
- Common Facility Energy and Refrigeration: General facility energy, including industrial refrigeration for the cold-chain and lighting, was excluded. As discussed by Manfredi and Vignali [33], these dominant loads can dilute packaging-related impacts; therefore, only machinery-specific energy for the bagging phase was considered.
- Capital Goods: The production, maintenance, and disposal of capital goods (e.g., machinery for film production, packaging lines, or domestic refrigerators), in accordance with Section 6.4.4 of PAS 2050 [35].
- Human Activity: Employee commuting, personnel travel, and administrative overhead.
- Consumer Logistics: Consumer transport to and from the Points of Sale (PoS), as detailed in Section 6.5 of PAS 2050 [35].

2.7. Geographical, Temporal, and Technological Boundaries

In accordance with Section 7.2 of PAS 2050 [35], the study considers typical process configurations and current technical and environmental standards for industrial-scale fresh-cut salad packaging lines in the year 2025.

2.8. Data Sources

Primary data regarding manufacturing yields and by-product generation (specifically post-consumer salad waste and packaging residue) were collected from the reference company—San Lidano Soc. Coop. Agr. (Sezze, Italy)—or sourced from specialized literature. San Lidano is a prominent Italian cooperative specializing in fresh-cut products, managing a direct supply chain of approximately 1000 hectares. With over 30,000 m² of processing space across three facilities and more than 25 automated packaging lines, the company has an annual capacity exceeding 100 million units, including bags, trays, and bowls of various formats and weights. This large-scale industrial context ensures that the LCI data—particularly regarding manufacturing efficiencies and waste fractions—are representative of contemporary European industrial standards.

Secondary data were sourced from the Ecoinvent v. 3.9.1 database, integrated into the SimaPro Craft 10.2.0.2 LCA software (Prè Consultants, Amersfoort, The Netherlands).

2.9. Packaging Phase

The primary packaging consists of a plastic or bioplastic bag (see Figure S1.1 in electronic Supplement S1), with main characteristics summarized in Table S1.2. The secondary packaging consists of an open recycled cardboard box (Figure S1.2 in electronic Supplement S1), with

characteristics detailed in Table S1.3. As shown in Figure S1.2, the tertiary packaging for the cardboard boxes consists of an EPAL wooden pallet (800 mm × 1200 mm) weighing 14 kg, a polyethylene (PE) stretch film and one adhesive paper label (3.1 g). The main characteristics of the tertiary packaging are reported in Table S1.4.

Table S1.5 summarizes the waste percentage for each packaging component during industrial-scale fresh-cut salad packaging, as collected at the reference processing plant.

Figure 2 illustrates the block diagram for the primary, secondary, and tertiary packaging processes of fresh-cut salad and the management of associated waste. It can be noted that the processing and packaging of fresh-cut salad generates several by-product and waste streams, each managed according to specific protocols:

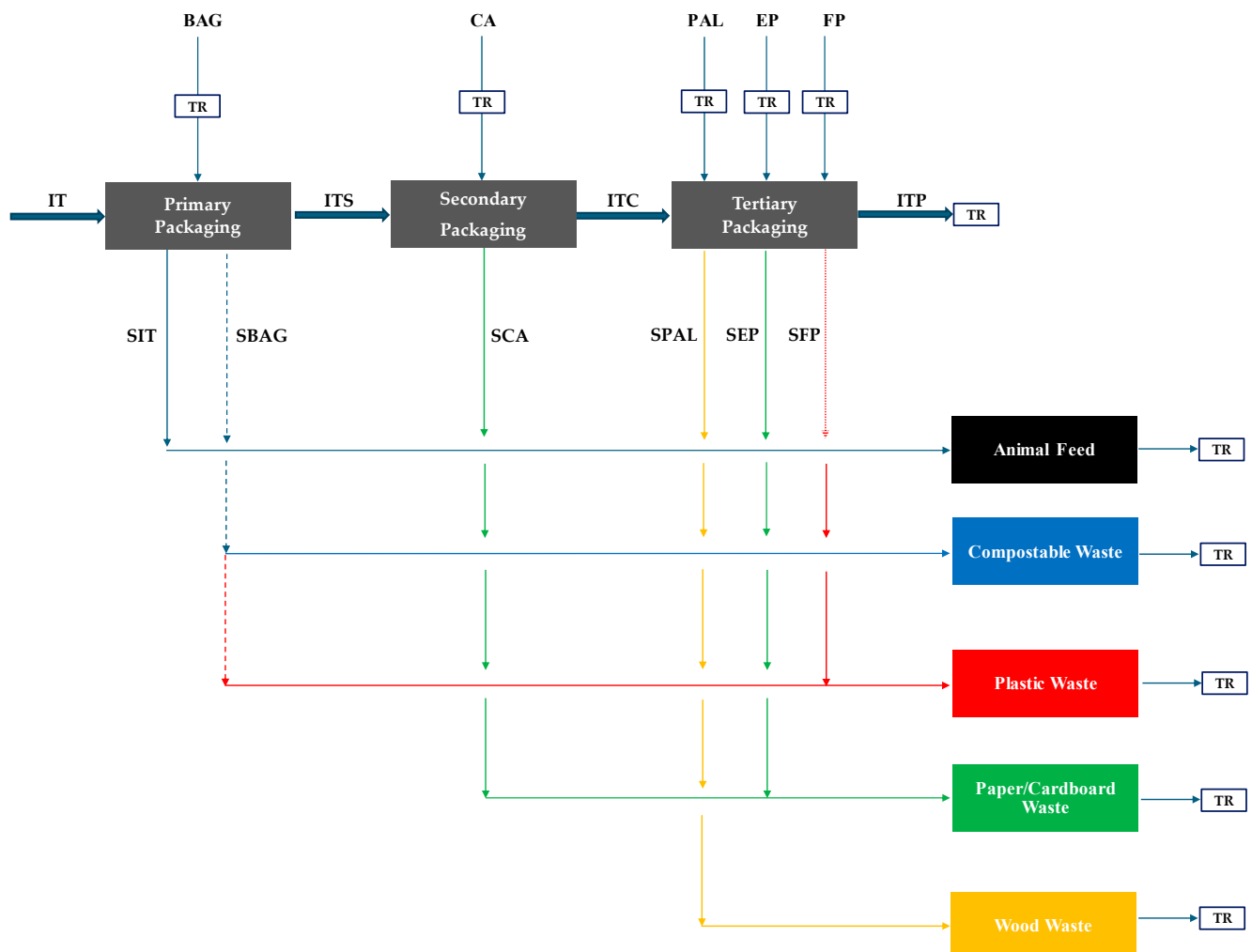


Figure 2. Flowchart of the primary, secondary, and tertiary packaging processes for fresh-cut salad and associated waste management. Refer to the Nomenclature for symbols. The dashed line indicates that bag waste is sorted as either plastic or compostable waste, depending on whether it is derived from polypropylene (PP) or bioplastic film.

- By-products (SIT): These consist of waste generated during the bagging phase of the washed and cut salad. These materials are collected and used for animal feed in local buffalo farms.
- Compostable Waste (RCO): Consists of primary packaging residues (SBAG) made of compostable and biodegradable bioplastics (e.g., INZEA®).
- Plastic Waste (RPL): Includes PP bags (SBAG) and polyethylene (PE) stretch film (SFP).
- Paper and Cardboard Waste (RCC): Includes non-compliant cardboard boxes (SCA) and labels (SEP).

- Wood Waste (RL): Wooden pallets managed primarily through repair and reuse; otherwise, they are disposed of as non-hazardous wood waste (SPAL).

Finally, Table S1.6 presents the mass balance associated with the primary, secondary, and tertiary packaging stages of fresh-cut salad, as well as the management of the corresponding process waste. The balance is calculated, assuming an input of 1000 kg of product ready for packaging in PP bags and accounts for the waste percentages specified in Table S1.5.

2.10. Energy Inventory and Assumptions

Electricity is the primary energy resource utilized in the packaging operations and cold-chain management of fresh-cut salad. In the absence of primary sub-metered data for specific machinery, this study adopted a standardized value of 8 MJ/kg for the packaging phase (comprising primary bagging, secondary casing, and tertiary palletization). This value is derived from industry benchmarks for fresh-cut processing facilities in Italy [36], corresponding to approximately 2.22 kWh per kg of film processed (or 222 kWh per 1000 packs of 100 g). Using the emission factor for the Italian medium-voltage electricity grid (0.1318 kg CO_{2e}/MJ, as derived from EcoInvent v. 3.9.1 database), the packaging operation contributes 1.054 kg CO_{2e} per kg of film. While thermal sealing requirements (sealing temperature and dwell time) may marginally differ between PP and INZEA[®] FH05, these operational variations are considered secondary within the cradle-to-grave context. According to the JRC methodological framework [37] and Siracusa et al. [38], environmental hotspots in food packaging are predominantly located in polymer synthesis and end-of-life management. Technical literature confirms that the energy associated with the mechanical conversion and sealing of lightweight films typically accounts for less than 5% of the total primary energy demand.

To validate the robustness of using a unified energy value, a sensitivity analysis was performed to identify the *decision threshold* (the break-even point). Given the Carbon Footprint results (3.75 kg CO_{2e}/kg for PP and 4.05 kg CO_{2e}/kg for INZEA[®]—see Section 3.2—and the specific electricity impact: 1.054 kg CO_{2e}/kg), the threshold for an inversion of the environmental preference is 28.5%. Since actual variations in heater-band demand between different polymers are typically under 5%, the potential for bias due to a lack of sub-metering is negligible. Furthermore, because bioplastics generally require lower sealing temperatures than PP, the use of a unified value represents a conservative estimate for the bioplastic scenario. This ensures that the comparative analysis remains rigorously focused on the primary environmental drivers: the feedstock origin of the packaging materials and the efficiency of the respective waste recovery systems.

2.11. Transport and Distribution Phases

The logistics network encompasses all inbound and outbound transport routes associated with the packaging life cycle and waste management. In alignment with modern environmental standards, all road transport was modeled using EURO 6 vehicles. Detailed logistics data, including specific vehicle types, load capacities, and transport distances, were provided by the reference company and are summarized in Table 1.

The transport inventory includes the following flows:

- Upstream Logistics: Transport of raw materials for packaging from primary production sites to the Packaging Factory Gate (PFG), based on a standardized distance of 250 km. This is followed by the delivery of converted packaging materials from the PFG to the salad processing facility (Factory Gate, FG).
- Distribution Network: Outbound transport of the final packaged salad. This includes the movement of palletized goods from the FG to Distribution Centers (DC) and

subsequent delivery in secondary cardboard packaging from DCs to various Points of Sale (PoS).

- Circular Logistics (Pallet Management): The transport of standardized EPAL wooden pallets between the Euro Pallet Management Center (EPMC), the processing facility (FG), and the DCs.
- Waste and By-product Logistics: Transport of industrial packaging scraps from the FG and post-consumer packaging waste from homes (CH) to the designated Waste Collection Center (WCC).
- Recovery of organic by-products, specifically bagging salad scraps, which are transported from the FG to local buffalo farms for use as animal feed.

Table 1. Inbound/Outbound logistics via EURO 6 road vehicles: transport routes, vehicle types, load capacity, distances for supply chain materials, and data sources.

Materials	Route Segment	Vehicle Type	Capacity [Mg]	Distance [km]	Data Source
Raw packaging materials	PS → PFG	Articulated truck	16–32	250	Assumption
Plastic/bioplastic film	PFG → FG	Heavy rigid truck	7.5–16	300	Company
Cardboard, labels	PFG → FG	Heavy rigid truck	7.5–16	50	Company
Pallets	EPMC → FG	Heavy rigid truck	7.5–16	50	Company
Pallets (Returns)	DC → EPMC	Heavy rigid truck	7.5–16	200	Company
Palletized salad	FG → DC	Articulated (Refr.) truck	16–32	150 (45–300)	Company
Salad in cardboard boxes	DC → PoS	Light truck	3.5–7.5	50	Company
Waste (organic & packaging)	FG, CH → WCC	Heavy rigid truck	7.5–16	50	Company
Salad scraps	FG → CaF	Heavy rigid truck	7.5–16	5	Company

CaF—Local Farm (Buffalo); CH—Consumer Homes; DC—Distribution Center; EPMC—EPAL Wood Pallet Management Center; FG—Factory Gate; PFG—Packaging Factory Gate; PoS—Points of Sale; PS—Production site; WCC—Waste Collection Center.

Regarding the upstream logistics of bioplastic granulates for INZEA film production, the supply routes may extend beyond the standardized 250km national average due to the international location of primary production sites. To account for this potential variability and ensure the robustness of the comparative analysis, a sensitivity analysis was integrated into the modeling process. Specifically, the transport distance for bioplastic raw materials was treated as a stochastic variable within the Monte Carlo Analysis (MCA), exploring a range from 200 km to 1250 km to simulate cross-European supply chains.

2.12. Economic Allocation and Multi-Functionality

To address the multi-functionality of the salad processing stage, an economic allocation approach was adopted. The industrial preparation of fresh-cut salad generates significant amounts of organic scraps during the preliminary cleaning, washing, and automated optical sorting phases. According to industry data and literature, these by-products account for an average of $36 \pm 6\%$ of the initial raw material mass [39]. In this study, a mass balance was modeled where 1000 kg of raw salad heads yield 640 kg of finished product and 360 kg of cleaning-sorting by-products. While the direct energy consumption of the facility and the upstream agricultural burdens of the raw salad were excluded to isolate the packaging comparison, the allocation is required to manage the flow of the organic scraps generated during cleaning and sorting. The allocation of environmental burdens was calculated based on current market values:

- Fresh-cut salad: 3.50 €/kg.
- By-products: 0.01 €/kg (based on a market price of 10 €/Mg for local buffalo farms).

As detailed in Table S1.7, the minimal commercial value of the scraps results in a negligible economic allocation factor (0.16%). This methodological choice effectively concentrates 99.84% of the studied environmental burdens on the primary product (the bagged salad), ensuring a robust and conservative assessment that reflects the commercial reality

of the product system and provides a functional unit that carries the full environmental weight of its biological origin.

2.13. Consumption Phase

Despite its convenience, fresh-cut salad is often not entirely consumed, contributing significantly to home food waste. While designed to minimize waste compared to whole heads, factors such as rapid spoilage after opening and oversized portions lead to high discard rates. In Italy, fresh vegetables are the most discarded food category; data from the Waste Watcher International Observatory indicate that vegetables represent approximately 25% of the total food waste by mass in Italian households [40]. Specifically, research shows that Italian consumers discard 19.4 g/day per capita of salads, ranking them among the top five most wasted foods [40]. This translates to approximately 7.1 kg/year per person, a figure that exceeds reported per capita consumption of 1.6 kg/year [41]. As noted, this discrepancy underscores the critical variance in statistical categorization and highlights an extremely high waste-to-purchase ratio in certain data streams. Rather than an error, this discrepancy highlights the extreme variability in collection methodologies—where waste figures often aggregate all leafy greens—and underscores the critical nature of waste relative to actual purchases. Supporting this, a survey by Legambiente [42] identified bagged salads and herbs as the most wasted items (30.8% of respondents). In the absence of a unified national percentage for bagged salad specifically, a meta-estimation procedure was applied to define the study's baseline. While general fresh vegetable waste in Italy is benchmarked at 15–20% [40], the fresh-cut format is pre-optimized to reduce unavoidable waste. Consequently, a conservative baseline waste rate of 10% was adopted for Italy to avoid overestimating the food-prevention benefits of the packaging. To account for high-waste consumer archetypes observed in international benchmarks—such as the UK, where 24% of consumers discard half of a salad bag [43]—a sensitivity range of 5–30% was applied. This interval ensures that the environmental trade-offs between packaging materials and food waste prevention are realistically evaluated under varying behavioral scenarios.

2.14. Waste Management and Disposal Scenarios

Waste management practices and recovery rates were modeled according to the Italian national guidelines [44–48]. The reference year 2022 was selected as it provides the most recent consolidated and validated statistical data available for Italy. The use of these benchmarks is consistent with the latest 2025 literature [44,45], reflecting the fact that national waste infrastructure does not undergo drastic shifts over short temporal horizons (2022–2025). The specific waste treatment scenarios for the reference year 2022 are detailed in Table S1.8 of the Supplementary Material S1.

These data reflect a robust recycling infrastructure for traditional materials, with high recovery rates for paper and cardboard (81.2%), aluminum (73.6%), and wood (62.7%), while plastic packaging shows a more moderate recycling rate of 48.9% [46]. Regarding organic waste management, which is particularly relevant for the disposal of food remains and biodegradable components, 2022 statistics indicate that 49.2% was recycled (with 44.0% undergoing composting and 5.2% treated via anaerobic digestion) [48]. The remaining fraction was managed through incineration with energy recovery (28.9%) or disposed of in landfills (21.9%) [44].

Within the landfill scenario, the impacts of biodegradable polymers were modeled using Ecoinvent 3.9.1 datasets that specifically account for the anaerobic degradation of bio-based materials. These datasets include the calculation of methane emissions generated from the fraction of degradable organic carbon, thereby capturing the GHG burden associated with bioplastics when they are not diverted to industrial composting facilities. These

recovery and disposal shares were integrated into the LCA model to accurately reflect the environmental credits and burdens associated with the post-consumer phase.

As detailed in Section 3.4 and Table A3, the EoL phase represents a minor contribution to the total life cycle impact (2.5% for PP and 1.3% for INZEA®). Consequently, the model is highly stable, and the comparative ranking of the materials is not sensitive to potential minor variations in prospective recycling or composting rates.

2.15. Environmental Impact Assessment

The environmental impact assessment was conducted according to the Product Environmental Footprint (PEF) methodology. While the general requirements followed the original PEF Guide [31], the characterization factors, normalization, and weighting were executed using the EF 3.1 method (v. 1.07) as integrated into the SimaPro Craft 10.2 software (PRé Consultants, Amersfoort, The Netherlands). This version incorporates the essential updates proposed by the Joint Research Centre (JRC) regarding improved models for land use, water scarcity, and toxicity [14]. The normalization and weighting factors applied follow the official JRC 2019/2021 sets, ensuring the results are representative of the current European environmental context. The PEF method considers 16 impact categories: Climate Change (CC); Ozone Depletion (OD); Ionizing Radiation-Human Health (IR); Photochemical Ozone Formation (PhOF); Particulate Matter (PM); Human Toxicity, non-carcinogenic (NC-HT); Human Toxicity, carcinogenic (C-HT); Acidification (AC); Freshwater Eutrophication (FWE); Marine Eutrophication (ME); Terrestrial Eutrophication (TE); Freshwater Ecotoxicity (FWET); Land Use (LU); Water Scarcity (WU); Resource Use-Fossils (RUF); Resource Use-Minerals and Metals (RUMM).

This methodology consolidates these environmental impacts into a single point score. This is achieved by normalizing each impact category against its corresponding global impact, as recommended by Sala et al. [49]. The normalized scores are then weighted according to Sala et al. [50] and summed to obtain an Overall Weighted Score (PEF).

2.16. Data Quality and Uncertainty Analysis

The reliability of the life cycle inventory was verified using a Data Quality Indicator (DQI) framework based on the Pedigree Matrix [51]. Primary data flows were categorized into *foreground data* (specific primary information for packaging and waste processes) and *background data* (generic secondary data, such as the Italian electricity grid mix). Critical flows, including factory electricity, packaging materials, and refrigerated transport, were identified via process network maps (Figure S1.4a,b). Each flow was evaluated across five dimensions: reliability (R), completeness (Co), and temporal (TiR), spatial (GeR), and technical (TeR) representativeness. These scores were aggregated into a final Data Quality Rating (DQR) according to the PEF methodology [17]. Furthermore, parameter uncertainty (PU) was quantified on a scale of 1 (highest quality) to 5 (lowest quality), correlating to specific geometric standard deviations (σ_g) ranging from 1.05 to 2.00. The overall standard uncertainty of the final PEF score (u_T) was calculated by combining individual uncertainties (u_i) using the Root Mean Square (RMS) method, assuming independent distributions [31,51].

2.17. Monte Carlo Analysis and Statistical Significance

To address uncertainties in primary data—specifically packaging waste percentages and resource consumption—a Monte Carlo Analysis (MCA) was conducted using SimaPro Craft 10.2. Uncertainty was modeled by assigning triangular or normal probability distributions to the relevant parameters within the LCA inventory. The analysis consisted of 2000 iterations to generate a robust probability distribution of potential environmental outcomes. Statistical significance was defined based on the probability of one packaging

system having a higher impact than the other [$P(PP \geq \text{INZEA}^{\text{®}})$]. A threshold of 95% was adopted to identify significant differences between the PP and INZEA[®] bags. To bridge the gap between statistical significance and *practical relevance*, the magnitude of the environmental benefit was quantified using two distinct metrics:

- The Weighted Single Score (PEF): Used to aggregate trade-offs across different impact categories and determine the overall environmental footprint.
- The Percentage Difference (Δ): Calculated between the mean values of the two systems to provide a clear indicator of the tangible advantage of one material over the other.

2.18. LCA Software Modeling and Network Structure

The life cycle of the fresh-cut salad packaging systems was modeled using SimaPro Craft 10.2.02 software (Prè Consultants, Amersfoort, The Netherlands). The model structure was organized into hierarchical product stages, including individual unit processes, assembly stages, and complex life cycle networks. To ensure methodological transparency, the end-of-life (EoL) scenarios for primary, secondary, and tertiary packaging materials were integrated into parallel life cycle modules. A detailed breakdown of the 36 distinct product stages (Processes, Assemblies, Waste Scenarios, End of Life Scenarios, Reuse, and Life Cycles) is provided in Electronic Supplement S2 (Table S2.1). Screenshots of the SimaPro modeling network and individual inventory stages are further detailed in Tables S2.2–S2.36 of the same Supplement.

3. Results

3.1. Data Quality Rating

The quantitative assessment of the LCI data quality, performed using the Pedigree matrix-based method described in Appendix A, yielded an overall Data Quality Rating (DQR) of 2.0 ± 0.5 for the PP bags and 2.1 ± 0.4 for the bioplastic bags. According to the PEF quality scale [31], these values classify the datasets as *Good* quality ($2.0 < \text{DQR} \leq 3.0$), bordering on the *Very Good* category. This confirms the reliability of the foreground data collected and the appropriateness of the background datasets selected for the environmental impact assessment.

3.2. Comparative Analysis of the Environmental Footprint of Plastic and Bioplastic Films

The material and energy flows for the production of 1 kg of film are illustrated via Sankey diagrams in Figure S1.3. These diagrams represent the total impact proportions, where the width of the arrows is proportional to the magnitude of the impact generated by each process.

For the PP film (Figure S1.3a), the cumulative environmental impact is 348.5 $\mu\text{Pt/kg}$. The primary contribution stems from raw material production: PP granulate (1.153 kg) contributes 262 $\mu\text{Pt/kg}$, while the extrusion process amounts to 58.9 $\mu\text{Pt/kg}$. Logistics (0.2882 t·km) and waste management of processing scraps (0.153 kg) account for 5 $\mu\text{Pt/kg}$ and 23 $\mu\text{Pt/kg}$, respectively.

The bioplastic film (Figure S1.3b) shows a total cumulative impact of 429 $\mu\text{Pt/kg}$. The supply chain involves a more complex variety of inputs: PLA granulate (0.71 kg) accounts for 242 $\mu\text{Pt/kg}$, while the polybutylene adipate terephthalate (PBAT) proxy (0.4145 kg) contributes 88.2 $\mu\text{Pt/kg}$. The film extrusion process (1.184 kg) adds 60.5 $\mu\text{Pt/kg}$. Minor additives (citric esters, glycerol monostearate, talc, and silica) and transport (0.2961 t·km) show lower individual impacts, while organic waste management entries reflect the handling of biodegradable processing scraps.

Table 2 presents the average environmental profiles and standard deviations ($m \pm sd$) for the production of 1 kg of either PP or INZEA[®] FH05 film.

Table 2. Environmental profiles for the production of 1 kg of PP or INZEA® FH05 film according to the standard PEF method: mean value and standard deviation for each environmental impact category (IC_j).

IC _j \Film	PP	INZEA® FH05	Unit
CC	$3.75 \pm 5.78 \times 10^{-2}$	$4.05 \pm 1.99 \times 10^{-1}$	kg CO _{2e}
OD	$1.96 \times 10^{-8} \pm 1.77 \times 10^{-10}$	$7.90 \times 10^{-8} \pm 4.78 \times 10^{-9}$	kg CFC11 _e
IR	$1.63 \times 10^{-1} \pm 1.47 \times 10^{-3}$	$3.66 \times 10^{-1} \pm 1.68 \times 10^{-2}$	kBq ²³⁵ U _e
PhOF	$1.23 \times 10^{-2} \pm 1.66 \times 10^{-4}$	$1.63 \times 10^{-2} \pm 8.17 \times 10^{-4}$	kg NMVOC _e
PM	$1.88 \times 10^{-7} \pm 3.75 \times 10^{-9}$	$2.25 \times 10^{-7} \pm 1.05 \times 10^{-8}$	disease inc.
AC	$1.43 \times 10^{-2} \pm 1.45 \times 10^{-4}$	$2.44 \times 10^{-2} \pm 1.22 \times 10^{-3}$	mol H ⁺ _e
FWE	$7.21 \times 10^{-4} \pm 6.50 \times 10^{-6}$	$1.49 \times 10^{-3} \pm 7.08 \times 10^{-5}$	kg P _e
ME	$2.87 \times 10^{-3} \pm 3.34 \times 10^{-5}$	$8.23 \times 10^{-3} \pm 4.49 \times 10^{-4}$	kg N _e
TE	$2.99 \times 10^{-2} \pm 3.52 \times 10^{-4}$	$6.90 \times 10^{-2} \pm 3.61 \times 10^{-3}$	mol N _e
ETFW	$1.21 \times 10^1 \pm 2.75 \times 10^{-1}$	$5.27 \times 10^1 \pm 2.88 \times 10^0$	CTU _e
C-HT	$3.06 \times 10^{-9} \pm 1.47 \times 10^{-10}$	$1.97 \times 10^{-9} \pm 8.97 \times 10^{-11}$	CTU _h
NC-HT	$2.75 \times 10^{-8} \pm 5.67 \times 10^{-10}$	$4.85 \times 10^{-8} \pm 2.54 \times 10^{-9}$	CTU _h
LU	$1.36 \times 10^1 \pm 1.22 \times 10^{-1}$	$4.63 \times 10^1 \pm 2.21 \times 10^0$	Pt
WU	$1.36 \pm 1.23 \times 10^{-2}$	$5.25 \pm 2.49 \times 10^{-1}$	m ³ depriv.
RUF	$9.64 \times 10^1 \pm 8.69 \times 10^{-1}$	$6.12 \times 10^1 \pm 3.34 \times 10^0$	MJ
RUMM	$1.16 \times 10^{-5} \pm 1.04 \times 10^{-7}$	$2.49 \times 10^{-5} \pm 1.36 \times 10^{-6}$	kg Sb _e

The characterization data show that PP presents lower absolute values in the majority of the indicators, including Ozone Depletion (OD), Ionizing Radiation (IR), and Acidification (AC). Notably, PP shows significantly lower values in Water Use (WU) and Land Use (LU). Conversely, the INZEA® FH05 bioplastic exhibits a lower impact in Carcinogenic Human Toxicity (C-HT) and Resource Use, Fossils (RUF).

Regarding Climate Change (CC), both materials show similar values (3.75 kg CO_{2e}/kg for PP vs. 4.05 kg CO_{2e}/kg for INZEA® FH05).

Using the standard PEF method, Table 3 reports the normalized and weighted values (IC_{NWj}) and the overall weighted score (PEF).

Analysis of the weighted data confirmed that:

- The production of 1 kg of PP film had a lower overall environmental footprint (349 µPt/kg) compared to the bioplastic material (429 µPt/kg).
- PP shows a lower weighted impact in almost all weighted categories, particularly in Water Use (10.1 µPt/kg vs. 39.0 µPt/kg) and Eutrophication.
- INZEA® FH05 demonstrates a specific advantage in Resource Use, Fossils (RUF), with an impact of 78.4 µPt/kg (18.3% of its total) compared to 123.3 µPt/kg for PP (35.4% of its total).

The robustness of the environmental profiles was further validated through Monte Carlo Analysis (MCA). For the PP film, the overall PEF score was 349 ± 4 µPt/kg. For the INZEA® bioplastic film, despite the high variability introduced in the transport distances (ranging from 200 to 1250 km to account for potential international supply chains), the PEF score remained remarkably stable at 437 ± 22 µPt/kg. The fact that the standard deviation remained low (~5.0%) despite a five-fold increase in potential transport distance confirmed that the environmental impact was heavily dominated by the material production phase rather than logistics. Consequently, the 250 km baseline assumption did not introduce significant bias into the comparative results.

Table 3. Mean values and standard deviations of the 16 normalized and weighted impact categories (IC_{NWj}) and the overall weighted score (PEF) for 1 kg of PP or INZEA® FH05 film according to the standard PEF method.

Film	PP		INZEA® FH05	
	IC _{NWj} [μPt]	m ± sd	m ± sd	%
CC		104.6 ± 1.6	113.0 ± 5.6	26.3
OD		0.024 ± 0.02	0.10 ± 0.01	0.02
IR		1.94 ± 0.02	4.3 ± 0.2	1.0
PhOF		14.4 ± 0.2	19.0 ± 1.0	4.4
PM		28.2 ± 0.6	33.8 ± 1.6	7.9
AC		15.9 ± 0.2	27.3 ± 1.4	6.4
FWE		12.6 ± 0.1	26.0 ± 1.2	6.1
ME		4.4 ± 0.1	12.5 ± 0.7	2.9
TE		6.3 ± 0.1	14.5 ± 0.8	3.4
FWET		4.1 ± 0.1	17.8 ± 1.0	4.2
C-HT		3.8 ± 0.2	2.4 ± 0.1	0.6
NC-HT		3.9 ± 0.1	6.9 ± 0.4	1.6
LU		1.31 ± 0.01	4.5 ± 0.2	1.0
WU		10.1 ± 0.1	39.0 ± 1.8	9.1
RUF		123.3 ± 1.1	78.4 ± 4.3	18.3
RUMM		13.7 ± 0.1	29.5 ± 1.6	6.9
PEF		349 ± 4	429 ± 21	100.0

3.3. Comparative Mass Balance and Waste Generation

Table 4 presents a detailed mass balance of the waste generated during the packaging phase of 1000 kg of washed and cut salad, using PP or bioplastic bags. The analysis also includes the packaging-to-raw-material ratio (P/RM).

Table 4. Mass balance of discarded packaging materials during the packaging of 1000 kg of washed and cut salad (RM) in PP or INZEA® FH05 bags, including packaging and overall waste, and the packaging-to-raw-material ratio (P/RM).

Parameters	PP Bags	INZEA® FH05 Bags	Unit
Fresh-cut Salad (Initial RM)	1000	1000	kg
Wood Waste	0.69	0.69	kg
Paper and Cardboard Waste	319.11	319.11	kg
Plastic Waste	67.73	14.24	kg
Salad Scraps (Cattle feed)	50.0	50.0	kg
Organic Waste (Bioplastic)	0	61.56	kg
Total Packaging Waste	387.54	395.60	kg
Total Waste	437.54	445.60	kg
Packaging/Raw Material Ratio (P/RM)	0.388	0.396	kg/kg

The following provides a concise description and comparison of the waste generated, based on the mass balances for packaging 1000 kg of fresh-cut salad in plastic and bioplastic bags:

1. Wood Waste: Wood waste was identical for both materials at 0.69 kg. This figure stems from the fraction of pallets damaged during the transport of the palletized product.
2. Paper and Cardboard Waste: Similarly, paper and cardboard waste was equal for both materials at 319.1 kg, as the secondary packaging remained the same regardless of the primary bag type.
3. Plastic Waste: This amounted to 67.7 kg for PP bags, whereas it was reduced to only 14.2 kg for bioplastic bags.

4. Salad Scrap: In both cases, salad scraps amounted to 50 kg, this being used as cattle feed.
5. Organic Waste: No organic waste was generated in the case of PP bags. For bioplastic bags—being compostable and biodegradable—organic waste amounted to 61.6 kg and was disposed of according to the national disposal scenario for organic waste.
6. Total Packaging Waste and P/RM Ratio: PP bags generated 387.5 kg of total packaging waste, while bioplastic bags produced a slightly higher amount (395.6 kg). This difference was attributable to the higher weight of each bioplastic bag (5.8 g vs. 5.0 g), which was reflected in a higher packaging-to-raw-material (P/RM) ratio: 0.396 kg/kg for bioplastic vs. 0.388 kg/kg for PP bags.

In summary, every kilogram of packaged salad required nearly 0.4 kg of packaging material, with bioplastics showing a slightly higher mass incidence. The primary advantage of bioplastic film was the qualitative nature of its waste; unlike traditional plastics, these scraps were theoretically compatible with industrial composting, mitigating long-term plastic accumulation. However, the realization of this potential is strictly contingent upon national waste management infrastructure. As shown in Table S1.8, only 49.2% of organic waste is currently diverted to recycling (composting or anaerobic digestion). Consequently, a significant portion of bioplastic ends up in less virtuous streams, such as incineration or landfill. Conversely, PP-related plastic waste faces similar limitations, with only 48.9% recycled, while the remainder (51.1%) is incinerated or landfilled. While both materials suffer from infrastructural inefficiencies, PP carries a higher environmental burden due to its lack of biodegradability. Despite generating a slightly higher mass of waste, bioplastic bags offer superior ecological potential through organic recycling, assuming future enhancements in disposal infrastructure.

3.4. Environmental Profile of Different Packaging Formats for Fresh-Cut Salad

To isolate the impact of packaging, a standardized functional unit of 1000 kg of washed and cut salad was used. This approach ensured that differences in the Product Environmental Footprint (PEF) were attributed to the production, transport, and end-of-life (EoL) of the PP and INZEA® FH05 bags, as well as the respective waste management flows.

Figure S1.4 illustrates the Sankey diagrams for the complete life cycle of both formats. For the PP packaging (Figure S1.4a), the cumulative impact was approximately 150 mPt. The primary flows included PP bag production (54.7 kg of granules contributing 16.5 mPt), the product use phase (including consumer waste generation), and salad production (65 mPt, representing electricity for packaging and cold storage).

The INZEA® FH05 packaging (Figure S1.4b) presented a total cumulative impact of approximately 156 mPt. The diagram identified the hotspots within the bio-based supply chain, where the intricate variety of constituents and the handling of biodegradable scraps defined the overall flow magnitude.

Table 5 presents the environmental characterization profiles according to the standard PEF method, integrated with the results of the Monte Carlo uncertainty analysis.

The combined evaluation of mean values, statistical significance (P), and percentage difference (Δ) provides the following insights:

- Climate Change (CC): While the mean values are identical (1.63×10^3 kg CO_{2e}), the MCA reveals a probability of 43% for $P(A \geq B)$, and a negligible percentage difference ($\Delta = -0.5\%$). This confirms that there is no statistically significant or tangible environmental benefit between the two packaging formats for this category.
- Categories with Higher Impact for INZEA® FH05: This film showed significantly higher impacts in 14 categories. Notable examples included Freshwater Ecotoxicity (ETFW), with a substantial reduction for PP of 29.7% ($P = 0\%$), and Land Use (LU),

where PP was 18.0% more efficient ($P = 0\%$). In these cases, the low probability values ($P < 5\%$) confirmed a robust environmental advantage for the PP system.

- Categories with Higher Impact for PP: The traditional fossil-based film showed a statistically significant higher impact on Resource Use, Fossils (RUF) (2.60×10^4 vs. 2.48×10^4 MJ), with a 4.7% increase and a probability $P(A \geq B)$ of 96.2%. Similarly, for Human Toxicity, Cancer (C-HT), the PP impact was 6.5% higher with a significance of 96.55%.
- Trade-off Analysis: These results highlighted a classic trade-off: while INZEA® FH05 provided a tangible benefit in reducing fossil resource dependency and specific toxicity scores, it incurred significant burdens in other categories like ecotoxicity and land use.

Table 6 reports the normalized and weighted values (IC_{NWj}) along with the overall weighted PEF score.

The aggregated results confirmed that the overall PEF score for PP (152 mPt) was lower than that of INZEA® FH05 (158 mPt), representing a total environmental saving of 4.1% (Δ).

The Monte Carlo analysis (MCA) provided high statistical robustness to this finding, with a probability $P(A \geq B)$ of only 8.5% for the single score. This indicates that the PP packaging system out-performed the bioplastic alternative in 91.5% of the simulated iterations. While the bioplastic film demonstrated a statistically significant lower weighted impact in Resource Use, Fossils (31.8 vs. 33.3 mPt; $P = 96.2\%$; $\Delta = +4.7\%$), this advantage was offset by higher scores in Water Use (33.1 vs. 31.5 mPt; $P = 13.85\%$) and significantly higher impacts across all other categories, most notably in Freshwater Ecotoxicity where PP showed a 29.6% reduction with absolute statistical certainty ($P = 0\%$).

Table 5. Environmental profiles (Characterization) for 1000 kg of salad packaged in PP (A) and INZEA® FH05 (B) bags according to the standard PEF method: mean value and standard deviation for each environmental impact category (IC_j), Monte Carlo probability $P(A \geq B)$, the mean difference with standard deviation, and the percentage difference (Δ).

IC_j	Unit	A	B	$P^{\#}(A \geq B)$ (%)	Difference Mean $m \pm sd$	$\Delta^{\S}$ (%)
CC	kg CO _{2e}	$1.63 \times 10^3 \pm 1.90 \times 10^2$	$1.63 \times 10^3 \pm 1.84 \times 10^2$	43	-7.89 ± 0.48	−0.5
OD	kg CFC11 _e	$2.58 \times 10^{-5} \pm 4.32 \times 10^{-6}$	$2.94 \times 10^{-5} \pm 4.23 \times 10^{-6}$	2.75	$-3.52 \times 10^{-6} \pm 1.83 \times 10^{-6}$	−12.0
IR	kBq ²³⁵ U _e	$1.58 \times 10^2 \pm 2.40 \times 10^1$	$1.72 \times 10^2 \pm 2.32 \times 10^1$	0	-12.51 ± 2.29	−7.3
PhOF	kg NMVOC _e	$4.92 \pm 5.64 \times 10^{-1}$	$5.23 \pm 5.48 \times 10^{-1}$	1.5	-0.316 ± 0.15	−6.0
PM	disease inc.	$7.10 \times 10^{-5} \pm 3.87 \times 10^{-6}$	$7.57 \times 10^{-5} \pm 3.83 \times 10^{-6}$	11.7	$-3.89 \times 10^{-6} \pm 3.18 \times 10^{-6}$	−5.1
AC	mol H ⁺ _e	$5.58 \pm 6.75 \times 10^{-1}$	$6.55 \pm 6.66 \times 10^{-1}$	0	-0.72 ± 0.16	−11.0
FWE	kg P _e	$2.00 \times 10^{-1} \pm 2.94 \times 10^{-2}$	$2.45 \times 10^{-1} \pm 2.89 \times 10^{-2}$	0	$-5.03 \times 10^{-2} \pm 6.67 \times 10^{-3}$	−20.5
ME	kg N _e	$1.71 \pm 1.23 \times 10^{-1}$	$1.99 \pm 1.20 \times 10^{-1}$	0	-0.33 ± 0.07	−16.7
TE	mol N _e	$1.31 \times 10^1 \pm 1.34 \times 10^0$	$1.68 \times 10^1 \pm 1.39 \times 10^0$	0	-2.60 ± 0.52	−15.5
ETFW	CTU _e	$5.60 \times 10^3 \pm 4.97 \times 10^2$	$8.84 \times 10^3 \pm 6.41 \times 10^2$	0	$-2.62 \times 10^3 \pm 5.14 \times 10^2$	−29.7
C-HT	CTU _h	$5.26 \times 10^{-7} \pm 5.14 \times 10^{-8}$	$5.34 \times 10^{-7} \pm 5.14 \times 10^{-8}$	96.55	$3.49 \times 10^{-8} \pm 1.98 \times 10^{-8}$	6.5
NC-HT	CTU _h	$9.16 \times 10^{-6} \pm 9.45 \times 10^{-7}$	$1.03 \times 10^{-5} \pm 9.28 \times 10^{-7}$	0	$-1.40 \times 10^{-6} \pm 4.12 \times 10^{-6}$	−13.6
LU	Pt	$8.78 \times 10^3 \pm 5.23 \times 10^2$	$1.08 \times 10^4 \pm 5.29 \times 10^2$	0	$-1.94 \times 10^3 \pm 4.13 \times 10^2$	−18.0
WU	m ³ depriv.	$4.24 \times 10^3 \pm 1.82 \times 10^2$	$4.46 \times 10^3 \pm 1.77 \times 10^2$	13.85	$-2.28 \times 10^2 \pm 1.98 \times 10^2$	−5.1
RUF	MJ	$2.60 \times 10^4 \pm 2.94 \times 10^3$	$2.48 \times 10^4 \pm 2.85 \times 10^3$	96.2	$1.16 \times 10^3 \pm 6.66 \times 10^2$	4.7
RUMM	kg Sb _e	$2.78 \times 10^{-3} \pm 3.40 \times 10^{-4}$	$3.62 \times 10^{-3} \pm 3.44 \times 10^{-4}$	0	$-8.29 \times 10^{-4} \pm 1.61 \times 10^{-4}$	−22.9

[#]—Probability $P(A \geq B)$ represents the frequency of iterations where the impact of PP is higher than or equal to INZEA®. Values $< 5\%$ indicate a statistically significant advantage for PP, while values $> 95\%$ indicate an advantage for INZEA®. Values around 50% suggest no significant difference between the two systems. [§]—The percentage difference (Δ) is calculated as (Difference Mean)/Mean B $\times 100$. A negative value indicates an environmental saving for the PP system.

Table 6. Normalized and weighted impact categories (IC_{NWj}) and overall weighted PEF score for 1000 kg of fresh-cut salad packaged in PP (A) and INZEA[®] FH05 (B) bags, Monte Carlo probability $P(A \geq B)$, mean difference with standard deviation ($m \pm sd$), and percentage difference (Δ).

IC_{NWj}	PP Bags		INZEA [®] FH05 Bags		$P^\# (A \geq B)$	Difference Mean [mPt] *	$\Delta^\S$
[mPt]	$m \pm sd$	%	$m \pm sd$	(%)	(%)	$m \pm sd$	(%)
CC	45.4 ± 5.3	29.9 ± 3.5	44.7 ± 5.1	28.3 ± 3.2	43	−0.22 ± 1.35	−0.5
OD	0.03 ± 0.01	0.021 ± 0.003	0.04 ± 0.01	0.022 ± 0.003	2.75	−0.004 ± 0.00	−10.6
IR	1.9 ± 0.3	1.2 ± 0.2	2.0 ± 0.3	1.3 ± 0.2	0	−0.15 ± 0.03	−7.4
PhOF	5.8 ± 0.7	3.8 ± 0.4	6.1 ± 0.6	3.9 ± 0.4	1.5	−0.37 ± 0.17	−6.1
PM	10.7 ± 0.6	7.0 ± 0.4	11.4 ± 0.6	7.2 ± 0.4	11.7	−0.58 ± 0.48	−5.1
AC	6.2 ± 0.8	4.1 ± 0.5	7.3 ± 0.7	4.6 ± 0.5	0	−0.81 ± 0.18	−11.1
FWE	3.5 ± 0.5	2.3 ± 0.3	4.3 ± 0.5	2.7 ± 0.3	0	−0.88 ± 0.12	−20.4
ME	2.6 ± 0.2	1.7 ± 0.1	3.0 ± 0.2	1.9 ± 0.1	0	−0.50 ± 0.10	−16.8
TE	2.8 ± 0.3	1.8 ± 0.2	3.5 ± 0.3	2.2 ± 0.2	0	−0.55 ± 0.11	−15.6
FWET	1.9 ± 0.2	1.3 ± 0.1	3.0 ± 0.2	1.9 ± 0.1	0	−0.89 ± 0.17	−29.6
C-HT	0.6 ± 0.1	0.43 ± 0.04	0.7 ± 0.1	0.42 ± 0.04	96.55	0.04 ± 0.02	6.2
NC-HT	1.3 ± 0.1	0.9 ± 0.1	1.5 ± 0.1	0.9 ± 0.1	0	−0.20 ± 0.06	−13.3
LU	0.9 ± 0.1	0.56 ± 0.03	1.0 ± 0.1	0.66 ± 0.03	0	−0.19 ± 0.04	−18.8
WU	31.5 ± 1.4	20.8 ± 0.9	33.1 ± 1.3	21.0 ± 0.8	13.85	−1.69 ± 1.47	−5.1
RUF	33.3 ± 3.8	21.9 ± 2.5	31.8 ± 3.6	20.1 ± 2.3	96.2	1.49 ± 0.85	4.7
RUMM	3.3 ± 0.4	2.2 ± 0.3	4.3 ± 0.4	2.7 ± 0.3	0	−0.98 ± 0.19	−22.9
PEF	152 ± 14	100 ± 9	158 ± 14	100 ± 9	8.5	−6.48 ± 4.62	−4.1

[#]—Probability that the environmental impact of PP (A) is higher than or equal to INZEA[®] (B). Values < 5% indicate a statistically significant advantage for A, while values > 95% indicate an advantage for B. *—Absolute difference between the weighted scores of the two systems ($m \pm sd$). [§]—Percentage difference calculated as (Difference Mean)/Mean B × 100. A negative value represents an environmental saving for the PP system.

3.5. Uncertainty Assessment of the Estimated Product Environmental Footprint

The quantitative uncertainty of the final Environmental Product Footprint (PEF) was estimated using the Data Quality Indicator (DQI)-based uncertainty propagation method detailed in Appendix A. The overall standard uncertainty (u_T) and the contributions of individual life cycle steps (u_i) are reported in Table A3 for both modeled scenarios.

A detailed analysis of the individual contributions identified that the overall uncertainty was primarily driven by the Processing and Cold-chain Electricity, which accounted for approximately 8.3–8.7% of the total 9.5% uncertainty. While this flow benefited from reliable background data, its dominant share of the total environmental impact made it the main source of absolute variance. Conversely, factors such as Primary Packaging and Transport contributed significantly less to the final uncertainty (ranging from 0.5% to 2.9%), reflecting the high precision of the foreground data collected ($PU = 2$) and the rigorous selection of secondary datasets. This qualitative robustness was further supported by the quantitative results, where the calculated $u_T \approx 9.5\%$ placed the study within the *Excellent* range according to the PEF quality thresholds ($u_T \leq 10\%$) [17]. This confirmed that the inventory data was highly representative and that the comparative results between PP and bioplastic bags were statistically robust, as the margin of uncertainty was significantly lower than the observed differences in environmental performance.

These analytical findings were in high agreement with the Monte Carlo simulation results (152 ± 14 mPt for PP and 158 ± 14 mPt for bioplastic), which independently yielded an uncertainty range of approximately 9%. The convergence of both the DQI-based propagation and the stochastic simulation reinforced the *Excellent* quality rating and confirmed the reliability of the comparative environmental profile.

3.6. Sensitivity Analysis: End-of-Life Modeling Using Cut-Off vs. APOS

To assess how the valuation of by-products influences the bioplastic's environmental profile, the EoL phase was modeled under the hypothesis that all organic residues (salad waste and INZEA[®] FH05 film) were directed to industrial composting. Beyond the baseline cut-off approach, the APOS model was employed to account for the shared responsibility

between waste producers and the users of recycled by-products [15]. This comparison evaluated whether the environmental *credits* or shared burdens inherent in the APOS framework significantly altered the competitiveness of the bioplastic scenario.

Table S1.9 reports the characterized (IC_j), normalized, and weighted (IC_{NWj}) values for 1000 kg of fresh-cut salad across the 16 PEF impact categories. The overall PEF scores for both system models were compared to identify if the recovery of valuable compost provided a sufficient offset to the bioplastic's upstream production impacts.

Table S1.9 reveals a critical finding: the total PEF score was identical for both the Cut-off and APOS scenarios (158 ± 14 mPt). All variations in individual impact categories remained within the model's uncertainty range, rendering the differences statistically insignificant. This near-perfect alignment stemmed from the fact that both models assumed 100% industrial composting for organic residues and bioplastic bags. In this specific scenario, the methodological divergence in by-product management was neutralized. The results confirmed that the environmental burdens associated with composting—namely collection, transport, and plant operation—were almost entirely offset by the environmental credits assigned to the resulting compost. These credits accounted for the avoided production of synthetic fertilizers, as compost serves as a direct nutrient substitute. Furthermore, the consistency between these scenarios and the national disposal baseline indicated that upstream packaging stages—specifically polymer synthesis, energy-intensive film conversion, and the refrigerated storage of the packaged product—exerted a far greater influence on the environmental profile than EoL management.

These findings align with PEFCR principles and Ecoinvent documentation, suggesting that different allocation models do not inherently dictate a *better* environmental outcome. Ultimately, the high impact of the initial life cycle stages renders the final disposal choice statistically secondary, highlighting the necessity of focusing on production efficiency rather than solely on EoL management.

4. Discussion

The environmental equivalence initially suggested by the absolute PEF scores—152 mPt for PP versus 158 mPt for INZEA[®] FH05—was further elucidated by the Monte Carlo Analysis (MCA). While these scores aligned with a growing body of literature challenging the inherent superiority of bioplastics, the MCA provided a robust statistical foundation for these findings. Notably, the results remained consistent under modeled scenarios, including sensitivity analyses for APOS and cut-off allocation models. As detailed in Section 3.6, even in a 100% composting scenario, the dominant cradle-to-gate industrial impacts consistently outweighed the potential variations introduced by different End-of-Life (EoL) logics.

4.1. The Trade-Off Between Bio-Based Origin and Environmental Impacts

The data obtained challenge the common perception that bioplastics are inherently more environmentally friendly in an absolute sense than conventional plastics. While the INZEA[®] FH05 film demonstrated a statistically significant advantage in Resource Use, Fossils (RUF) ($P = 96.2\%$; $\Delta = +4.7\%$ higher impact for PP), it presented higher environmental burdens in 14 other indicators. The MCA revealed that for categories such as Acidification (AC) and Freshwater Ecotoxicity (ETFW), the probability of PP having a higher impact was 0%, indicating a robust environmental saving for the fossil-based film of 11.0% and 29.7%, respectively. Conversely, for Climate Change (CC), the near-identical scores (1.63×10^3 kg CO_{2e}) and MCA results ($P = 43\%$; $\Delta = -0.5\%$) showed no *tangible benefit* between the two materials.

4.2. Analysis of Critical Categories: Water, Land Use, and Eutrophication

A significant finding was the high impact in Water Use (WU), Land Use (LU) and Eutrophication for the biopolymer compared to PP. The MCA provided a nuanced view: while Land Use showed absolute statistical certainty favoring PP ($P = 0\%$; $\Delta = -18.0\%$), Water Use exhibited lower statistical significance ($P = 13.85\%$; $\Delta = -5.1\%$). These results suggested that while PP was likely more efficient in water consumption, the practical advantage was less pronounced than in land occupancy. The resource intensities involved in converting biological feedstocks, detailed in the inventory for bioplastic film production (Table S2.24), currently exceed those of highly optimized fossil-based industrial chains (Table S2.3).

4.3. Infrastructure and the Circular Economy

The ecological potential of compostable materials is currently constrained by the limitations of regional organic waste management systems (Table S1.8). As shown in the comparative analysis of the 100g packaging formats, the virtuous life cycle of bioplastics depended heavily on the efficiency of waste separation and the availability of industrial composting infrastructure [37]. This aligned with the findings of Bishop et al. [11], who emphasized that the end-of-life (EoL) stage was a critical variable. Sensitivity analysis (Section 3.6) confirmed that, because PEF scores remained nearly identical between APOS and cut-off models even at 100% composting, the cradle-to-gate industrial production impacts of the polymers (Tables S2.3 and S2.24) were so dominant that they outweighed the benefits of any EoL accounting method (Tables S2.18 and S2.32). The environmental *cost* of synthesizing the biopolymer and converting it into film currently exceeds the potential *credits* gained at the end-of-life, regardless of the allocation logic applied.

4.4. Systemic Considerations and Climate Risks

The near-identical PEF scores found here demonstrated that bioplastics represent a systemic solution rather than a standalone one. Their benefit is entirely contingent on waste management efficiency. The overall Single Score MCA provided a definitive conclusion: PP is the preferable option in 91.5% of the simulated iterations ($P = 8.5\%$). Although the absolute magnitude of this benefit is modest ($\Delta = -4.1\%$), the statistical distribution confirmed that the PP format remains a more stable choice within the current infrastructure. If bioplastics reach landfills instead of industrial composting facilities, they can release methane—a greenhouse gas significantly more potent than CO_2 [12,13]. In such scenarios, traditional PP is climatically safer due to its inert nature, which prevents the release of sequestered carbon. Furthermore, the risk of bioplastics contaminating traditional mechanical recycling streams [10] suggests that improper disposal can actively degrade the existing circular economy.

4.5. Reflections on Systemic Sustainability

In summary, these results underscored the necessity of a weighted, multi-criteria LCA approach [22,23] to evaluate packaging materials. The data suggested that the transition to bioplastics requires a rigorous environmental basis rather than reliance on the bio-based origin alone.

For bioplastics to achieve a more favorable environmental profile over conventional polymers like PP, the following technical priorities must be addressed:

- **Feedstock Evolution:** Shifting toward second-generation, waste-based feedstocks (such as molasses or agricultural residues) is essential to minimize the high Land Use and Water Use impacts, as also observed by Ali et al. [52]. In this study, these categories showed a disadvantage for the biopolymer of $\Delta = -18.0\%$ and $\Delta = -5.1\%$, respectively, with the former supported by a $P = 0\%$ statistical certainty.

- Process Optimization: Reducing energy intensity and chemical demand during the synthesis of biopolymers and their conversion into film to lower the dominant cradle-to-gate footprint.
- Infrastructure Integration: Enhancing the efficiency of industrial composting collection to mitigate the climate risks (methane release) associated with the landfilling of biodegradable materials [12,13].
- Methodological Transparency: It is vital to implement assessments that account for real-world infrastructural constraints and the negative externalities associated with recycling contamination.

Within the current Italian waste infrastructure, PP maintained a competitive environmental profile for this specific application, being the preferable option in 91.5% of the Monte Carlo iterations. However, targeted improvements in biopolymer manufacturing and organic waste treatment could optimize the future role of bioplastics in the circular economy.

5. Conclusions

This study demonstrates that the environmental performance of bioplastics is a multi-dimensional outcome dictated by feedstock origin, production efficiency, and local waste infrastructure, rather than an inherent property of the material itself. The Product Environmental Footprint (PEF) analysis, supported by Monte Carlo Analysis (MCA), indicates that under the modeled technological and infrastructural conditions, the transition toward bio-based packaging for fresh-cut produce resulted in a state of practical environmental parity. While the PP system emerged as the environmentally preferable option in 91.5% of the simulated iterations, the total magnitude of this benefit remains modest at $\Delta = -4.1\%$. Consequently, the high statistical frequency of preference for PP does not translate into a substantial environmental advantage, as the overall scores remain within a narrow range of equivalence.

The results reveal a significant trade-off at the characterization level: while the bio-based origin offers a robust advantage in reducing fossil resource depletion ($P = 96.2\%$; $\Delta = +4.7\%$ for PP), it does not currently compensate for higher impacts in 14 other categories. Specifically, the MCA confirmed significant environmental savings for PP in Acidification ($\Delta = -11.0\%$) and Freshwater Ecotoxicity ($\Delta = -29.7\%$), both with a probability $P(\text{PP} \geq \text{INZEA}^{\text{®}})$ of 0%, indicating that PP impact was consistently lower in these categories. Conversely, the Climate Change category showed negligible differences ($\Delta = -0.5\%$) and a lack of statistical significance ($P = 43\%$).

Despite its rigor, the generalizability of this study is defined by several critical limitations:

- Geographical Constraints: The environmental profiles are representative of the Italian waste management infrastructure. Caution should be exercised when applying these results to other geographical contexts with different energy mixes or composting efficiencies.
- Processing Energy and Composition: The results are sensitive to the assumed energy intensity of the packaging conversion and refrigerated storage of the packaged product, as well as the specific proxy compositions used for the bio-blend. Reductions in facility energy use or optimized polymer synthesis would likely alter the comparative standing of the materials.
- Agricultural Data Scope: While this study focused on the industrial cradle-to-gate phase of the film, future research should integrate granular data on upstream agricultural variables to further refine the assessment of water and land use impacts, which currently show a disadvantage for the biopolymer of -5.1% and -18.0% , respectively.

- **Methodological Robustness:** The sensitivity analysis confirmed that the choice of EoL allocation (Cut-off vs. APOS) did not alter the total PEF scores. This reinforces that the environmental burden is heavily front-loaded in the upstream packaging stages—specifically polymer synthesis and energy-intensive film conversion—outweighing benefits gained from different waste accounting methods.
- **Real-world EoL Uncertainty:** This analysis assumed industrial-scale EoL handling. Future research should explore bioplastic behavior under non-ideal conditions, such as home composting or the accidental contamination of mechanical recycling streams, to provide a more holistic view of systemic impact.

In conclusion, for bioplastics to become a definitively sustainable alternative, future strategies must prioritize production-side energy efficiency and the minimization of industrial resource intensity during polymer synthesis.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18052198/s1>, *Supplementary Materials S1*: Figure S1.1: Photos of fresh-cut salad packaged in bioplastic bags; Figure S1.2: Photo of the secondary and tertiary packaging configuration; Figure S1.3: Sankey diagrams mapping the environmental footprint of plastic and bioplastic films; Figure S1.4: Sankey diagrams mapping the environmental footprint of a 1000 kg fresh-cut salad batch; Table S1.1: Detailed material composition of the bioplastic film; Table S1.2: Technical specifications for primary packaging; Table S1.3: Technical specifications for secondary packaging; Table S1.4: Technical specifications for tertiary packaging; Table S1.5: Industrial packaging waste percentages; Table S1.6: Material balances for the fresh-cut salad packaging process and associated waste; Table S1.7: Economic allocation parameters between the fresh-cut salad and by-products; Table S1.8: Italian waste management scenarios; Table S1.9: Environmental profile of the bioplastic system using the APOS and Cut-off system model. *Supplementary Materials S2*: Table S2.1: Summary of the product stages modeled in Simapro for the life cycle of fresh-cut salad (FCS) leaves packed in PP and INZEA® FH05 bags; Table S2.2: Inventory associated with fresh-cut salad packaging and cold-refrigeration; Table S2.3: Inventory associated with PP film production; Table S2.4: Inventory associated with carton production; Table S2.5: Inventory associated with paper label production; Table S2.6: Inventory associated with PE film production; Table S2.7: Inventory associated with wooden EPAL pallet production; Tables S2.8–S2.10: Assembly of primary, secondary, and tertiary packaging for PP-bagged FCS; Tables S2.11 and S2.12: Assembly of combined packaging (I + II and I + II + III) for PP-bagged FCS; Table S2.13: Assembly of 1 Functional Unit (1000 kg of FCS to be packed in PP bags); Table S2.14: Inventory associated with the PP-bagged FCS use phase; Tables S2.15–S2.17: Waste scenarios for plastic (RPL), cardboard/paper (RCC), and wood (RL) packaging wastes; Table S2.18: Disposal scenario for primary, secondary, and tertiary packaging material wastes (excluding wood pallets) for the PP system; Table S2.19: Disposal scenario for tertiary packaging material waste for the PP system; Table S2.20: Reuse phase of the wood pallet; Tables S2.21–S2.23: Life cycle data for the PP-bagged salad, its packaging materials, and the wood pallet; Table S2.24: Inventory associated with bioplastic film production; Table S2.25: Inventory associated with the INZEA®-bagged FCS use phase; Tables S2.26–S2.30: Assembly stages for the INZEA®-bagged system (primary through tertiary combinations); Table S2.31: Assembly of 1 Functional Unit (1000 kg of FCS to be packed in bioplastic bags); Table S2.32: Disposal scenario for packaging materials (excluding wood pallets) for the bioplastic system; Table S2.33: Disposal scenario for tertiary packaging material waste for the bioplastic system; Tables S2.34–S2.36: Life cycle data for the bioplastic-bagged salad, packaging materials, and wood pallets.

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Nomenclature

AC	Acidification [mol H ⁺ _e]
APOS	Allocation at the Point of Substitution
BAG	Plastic or bioplastic bags
Co	Completeness
CA	Cartons [kg]
CaF	Cattle farm
CC	Climate Change [kg CO _{2e}]
CFC ₁₁	Trichlorofluoromethane.
C-HT	Human Toxicity, carcinogenic [CTU _h]
CTU _e	Comparative Toxic Unit for ecosystems
CTU _h	Comparative Toxic Unit for humans
DC	Distribution center
DQI	Data quality indicator
DQR	Data quality rating
EoL	End of Life
EP	Pallet paper label [kg]
EPAL	European Pallet Association
EPMC	Euro pallet managing center
FCS	Fresh-cut salad
FG	Factory gate
FP	Shrink film for pallets [kg]
FU	Functional Unit
FWE	Freshwater Eutrophication [kg P _e]
FWET	Freshwater Ecotoxicity [CTU _e]
GeR	Geographical representativeness
GHG	Greenhouse Gas
IC _j	Generic j-th impact category
IC _{NWj}	Generic j-th normalized and weighted impact category
IPCC	Intergovernmental Panel on Climate Change
IR	Ionizing Radiation-Human Health [kBq ²³⁵ U _e]
IT	Washed and cut salad [kg]
ITC	Washed and cut salad in cardboard boxes [kg]
ITP	Bagged salad on pallets [kg]
ITS	Washed and cut salad in bags [kg]
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LCIA	Life-cycle impact assessment
LU	Land Use [Pt]
m	Mean value
MAP	Modified Atmosphere Packaging
ME	Marine Eutrophication [kg N _e]
MWCS	Municipal waste collection service
NC-HT	Human Toxicity, non-carcinogenic [CTU _h]

NM VOC	Non-Methane Volatile Organic Compounds
OD	Stratospheric Ozone Depletion [kg CFC _{11e}]
P(A ≥ B)	Monte Carlo probability (frequency of iterations where the impact of system A is higher than or equal to system B.
PAL	EPAL wooden pallet [kg]
PAS	Publicly Available Specification
PE	Polyethylene
PEF	Product Environmental Footprint [Pt]
PFG	Packaging Factory Gate
PhOF	Photochemical Ozone Formation [kg NMVOC _e]
PLA	Polylactic acid
PM	Particulate Matter [disease incidence]
PoS	Point of Sale
PP	Polypropylene
PS	Production site
P/RM	Packaging-to-raw material ratio [kg/kg]
PU	Parameter uncertainty/precision
R	Reliability
RCC	Paper and cardboard waste [kg]
RL	Wood waste [kg]
RM	Raw Material
RMS	Root mean square method
RPL	Plastic waste [kg]
RUF	Resource Use-Fossils [MJ]
RUMM	Resource Use-Minerals and Metals [kg Sb _e]
SBAG	Primary package residues
SCA	Carton waste [kg]
SEP	Pallet label waste [kg]
sd	Standard deviation
SFP	PE stretch film waste [kg]
SIT	Fresh-cut salad waste [kg]
SPAL	EPAL wooden pallet waste [kg]
SPC	Sandwich bread waste [kg]
SPE	PE bag waste [kg]
SSC	Scotch tape waste [kg]
TE	Terrestrial Eutrophication [mol N _e]
TeR	Technological representativeness
TiR	Time-related representativeness
TR	Transportation
u _i	Standard uncertainty contribution for each individual life cycle step
u _T	Overall standard uncertainty
VFFS	Vertical Form-Fill-Seal process
WCC	Waste Collection Center
WD	Waste disposal
WU	Water Scarcity [m ³ depriv.]
Δ	Percentage difference between mean environmental impacts [%]
σ _g	Geometric standard deviation.

Appendix A. Data Quality and Uncertainty Analysis

Appendix A.1. Identification of Significant Data Flows

Based on the process network maps (Figure S1.4), the primary contributors to the total Environmental Product Footprint (PEF) were identified. In this model, the electric energy for factory-level packaging and cold-chain preservation emerged as the dominant driver of

the *Salad* node impact, followed by the secondary and primary packaging, transport, and waste disposal (Table A1).

Table A1. Primary data flow contributions referred to a Functional Unit of 1000 kg of fresh-cut salad packed in PP or bioplastic bags.

Process Item	PP Bags (mPt)	Bioplastic Bags (mPt)	Data Type
Electricity (Packaging/Cold-chain)	65.08	65.08	Background
Primary Packaging (Film)	15.23	22.80	Foreground
Secondary Packaging (Cartons)	54.54	54.59	Foreground
Tertiary Packaging (Pallets)	3.55	3.55	Foreground
Transport	8.12	8.18	Foreground
Waste Disposal	3.75	2.00	Foreground

Appendix A.2. Pedigree Matrix Scoring

The data quality was assessed using the Pedigree matrix-based method [51], which includes five indicators: Reliability (R), Completeness (Co), Time-related representativeness (TiR), Geographical representativeness (GeR), and Technological representativeness (TeR). Each indicator is scored from 1 (excellent) to 5 (poor).

As shown in Table A2, the Data Quality Rating for each *i*-th item (DQR_i) was calculated as the arithmetic average of these five scores. The overall DQR for the dataset was then determined by averaging the individual DQR_i values. Following the PEF guidelines [31], the dataset is classified based on the following thresholds: *Excellent* ($DQR \leq 1.6$), *Very Good* ($1.6 < DQR < 2.0$), *Good* ($2.0 < DQR < 3.0$), *Fair* ($3.0 < DQR < 4.0$), or *Poor* ($DQR > 4.0$). Based on these results, the dataset for the PP bags (1.96) is classified as *Very Good*, while the bioplastic bags (2.08) fall into the *Good* quality category.

Table A2. Pedigree Matrix Scoring.

Data Flow Item	R	Co	TiR	GeR	TeR	Score (DQR_i)
Electricity	3	3	4	2	2	2.8
Primary Packaging (PP)	1	1	2	2	1	1.4
Primary Packaging (BIOPL)	2	2	2	2	2	2
Secondary Packaging	2	1	2	2	2	1.8
Tertiary Packaging	2	1	2	2	2	1.8
Transport	2	1	2	3	2	2
Waste Disposal	2	1	2	2	2	1.8
Overall DQR (PP bags)						1.96
Overall DQR (Bioplastic bags)						2.08

Appendix A.3. Uncertainty Propagation Methodology

The quantitative uncertainty of the final environmental footprint was estimated through the propagation of geometric standard deviations. To reflect the high reliability of the collected data, the standard uncertainty (u_i) for each life cycle step (PEF_i) was calculated using refined uncertainty factors:

$$u_i = PEF_i (\sigma_{gi} - 1) \quad (A1)$$

Specifically, a factor of 0.10 was assigned to verified primary data ($PU = 2$) and 0.20 to high-quality secondary data ($PU = 3$). The overall standard uncertainty (u_T) for the total PEF was then calculated using the Root Mean Square (RMS) method:

$$u_T = \sqrt{\sum_i u_i^2} \quad (A2)$$

The final uncertainty range is presented as $\pm(2 \times u_T)$, approximating a 95% confidence interval [33]. Table A3 provides P_i scores and resulting uncertainty propagation.

Table A3. Uncertainty analysis and calculated u_T values.

Scenario	PP Bags			Bioplastic Bags		
Life Cycle Step	PEF _i [%]	PU _i Score	u _i [%]	PEF _i [%]	PU _i Score	u _i [%]
Electricity	43.3	3	8.66	41.7	3	8.33
Primary Packaging	10.1	2	1.01	14.6	3	2.92
Secondary Packaging	36.3	2	3.63	34.9	2	3.49
Tertiary Packaging	2.4	2	0.24	2.3	2	0.23
Transport	5.4	2	0.54	5.2	2	0.52
Waste Disposal	2.5	2	0.25	1.3	2	0.13
u _T			9.47			9.51

Based on the calculated u_T values of approximately 9.5%, the dataset is classified as *Excellent* according to the PEF quality thresholds ($u_T \leq 10\%$). This high level of quantitative precision, combined with the *Very Good/Good* qualitative DQR scores, confirms that the life cycle inventory is highly robust and suitable for a rigorous comparative assessment.

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