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LIFE CYCLE ASSESSMENT OF FRESH FRUIT PACKAGING SYSTEMS: ENVIRONMENTAL BREAK-EVEN POINTS BETWEEN REUSABLE AND SINGLE-USE OPTIONS

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ABSTRACT

This study presents a comparative Life Cycle Assessment (LCA) of four packaging systems for fresh fruit distribution in the Italian retail supply chain: single-use rigid polypropylene (PP) crates, reusable foldable PP crates, single-use expanded polystyrene (EPS) crates, and single-use corrugated cardboard crates. The assessment follows ISO 14040 and ISO 14044 standards and adopts a multi-level packaging perspective, including primary, secondary and tertiary components. The functional unit is 1 kg of fresh fruit, while the system boundaries cover packaging production, transport to the packing facility, distribution, reverse logistics, washing operations and end-of-life management. Environmental impacts were quantified using the ReCiPe 2016 Midpoint and Endpoint (H) method. Results show that the reusable crate system achieves the best environmental performance under baseline conditions, namely 50 reuse cycles and a 200 km distribution distance. At endpoint level, this scenario reduces impacts by 73% for Human Health, 72% for Ecosystem Quality and 75% for Resource Scarcity compared with the worst-performing alternatives. Single-use PP crates exhibit the poorest performance due to the inability to amortize production burdens over multiple uses. EPS crates benefit from their low weight but remain constrained by fossil-based production and end-of-life limitations, whereas corrugated cardboard crates are penalised by higher material mass and lower pallet efficiency. Contribution analysis confirms that production dominates single-use systems, while logistics become more relevant in the reusable scenario. Sensitivity analysis demonstrates that reuse remains preferable even at 20 cycles and 500 km, although its advantage depends on efficient pooling, high return rates and controlled replacement losses.

1. INTRODUCTION

Global plastic production has increased exponentially, rising from 2 million tonnes in 1950 to approximately 415 million tonnes in 2023, with projections suggesting a potential increase to 0.9-1.1 billion tonnes by 2050 under business-as-usual trajectories (Geyer et al., 2017; Dokl et al., 2024; PlasticsEurope, 2024). Packaging represents the main driver of plastic consumption, accounting for approximately 44% of total global plastic use and about 40% of global plastic waste generation (OECD, 2022; Plastic Soup Foundation, 2025). In 2021, global plastic consumption for packaging applications reached approximately 172 million tonnes out of a total plastic consumption of 390.7 million tonnes, while packaging waste is expected to account for roughly 40% of all plastic waste by 2040 (PlasticsEurope, 2022). Despite substantial investments in recycling infrastructure, global plastic recycling rates remain disappointingly low, with less than 10% of plastic waste currently recycled worldwide; while landfilling and mismanagement continue to dominate end-of-life pathways (OECD, 2022).

Recognising the limitations of prevailing waste-management approaches, the European Union (EU) has adopted the waste hierarchy as a cornerstone of its waste policy and circular-economy transition, prioritising prevention and preparing for reuse over recycling, other recovery and disposal (European Parliament and Council of the European Union, 2008, 2018). This hierarchy challenges the linear economic model by promoting circular systems in which products and materials retain their value through multiple use cycles, thereby reducing dependence on virgin resource extraction and waste generation. Within this framework, reuse emerges as a key intervention strategy because it preserves product and material functionality be-

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fore the product enters waste-management routes, whereas recycling performance depends on the extent to which secondary materials retain their technical functionality and can substitute virgin resources (Tonini et al., 2022). A broad body of scientific literature has shown that reusable packaging systems can provide environmental benefits compared with single-use alternatives, although these benefits are highly context-dependent. In their systematic literature review of 91 comparative studies, Pålsson and Olsson (2023) show that Life Cycle Assessment (LCA) results depend strongly on transport settings, the number of reuse cycles, washing settings, packaging material and end-of-life assumptions. Their synthesis also indicates that reusable secondary packaging is environmentally preferable in many of the reviewed cases, particularly when reusable plastic systems are compared with disposable fibre-based or plastic alternatives.

In fruit and vegetable supply chains specifically, reusable plastic crates (RPCs) have been shown to outperform single-use corrugated cardboard boxes across several impact categories when food-loss reduction and energy optimisation are incorporated into the assessment. Gao et al. (2026) report that RPC use can reduce Global Warming (GW) by 32.36-50.38%, Freshwater Ecotoxicity (FEc) by 3.1-16.8%, eutrophication by 1.9-13.4%, and water consumption by 3.4-16.9% compared with cardboard-box packaging. These environmental advantages arise from multiple mechanisms: RPCs substantially reduce material consumption per functional unit (FU) due to their multi-use design; they can minimise food losses by providing greater product protection than single-use alternatives; and they enable system-level improvements in logistics and handling efficiency. Nevertheless, the environmental superiority of reusable systems is neither universal nor automatic. It requires careful system design, adequate return rates, efficient washing infrastructure, and geographical configurations that minimise empty return transport distances (Accorsi et al., 2022b; Gao et al., 2026).

Moving within this research direction, the present study applies LCA to compare four packaging alternatives commonly used in fresh-fruit distribution: (i) S1, a single-use polypropylene (PP) packaging system, representative of the dominant conventional disposable paradigm; although PP is technically recyclable, the effective use of PP recyclates remains constrained by contamination, insufficient sorting or cleaning, and inconsistent recyclate quality, which can limit their use in demanding applications or in large quantities (Geier et al., 2024); (ii) S2, a reusable PP packaging system designed for 50 reuse cycles, representing circular-economy principles through material longevity and multi-use optimisation; (iii) S3, a single-use expanded polystyrene (EPS) packaging system, widely used for its low weight and protective properties, but increasingly contested because of end-of-life and environmental-leakage concerns, since EPS foam is prone to weathering, surface cracking and fragmentation once released into the environment, thereby contributing to secondary microplastic formation (Polruang et al., 2025); and (iv) S4, a corrugated cardboard packaging system, representing a renewable fibre-based alternative with established recycling infrastructure, but also with potentially higher impacts during primary production.

To the best of the authors' knowledge, the main contribution of this research lies in the development of an integrated, multi-level LCA framework that simultaneously accounts for primary, secondary and tertiary packaging. This choice responds to the need, highlighted in packaging-logistics literature, to treat packaging as a system whose design affects not only product protection, but also logistics efficiency and environmental performance (Garcia-Arca et al., 2021). By applying this perspective to alternative fresh-fruit packaging systems, the study moves beyond isolated material comparisons and evaluates how single-use and reusable solutions perform under harmonised supply-chain and end-of-life conditions. The findings provide evidence relevant to the implementation of the Packaging and Packaging Waste Regulation (PPWR), Regulation (EU) 2025/40, particularly in relation to reuse targets and packaging-waste prevention policies, which are increasingly central to the EU circular-economy framework (European Parliament and Council of the European Union, 2025; Rodrigues and Esteves da Silva, 2024). Sensitivity analyses on transport distance and reuse cycles further identify the operational thresholds beyond which reusable packaging systems deliver genuine net environmental benefits, rather than merely shifting impacts across life-cycle stages.

2. METHODOLOGY: GOAL AND SCOPE DEFINITION AND LIFE CYCLE INVENTORY (LCI) ANALYSIS

This study applies an LCA approach to evaluate the environmental performance of alternative crate systems for fruit distribution, following the principles and requirements of ISO 14040 and ISO 14044 (ISO, 2006a, 2006b).

2.1 Goal and scope definition

The primary objective of this study was to comparatively assess alternative secondary and tertiary packaging systems for fresh fruit distribution, with the aim of identifying the environmentally preferable solution across selected impact categories.

The geographical scope is confined to Italy, reflecting the decision-making context of national fruit distribution. The FU, defined to ensure comparability and normalisation of all inflows and outflows among packaging systems with different unit masses and palletisation configurations, is 1 kg of fresh fruit delivered through the analysed packaging system. Inventory coefficients were derived from the investigated crate configuration, in which each crate accommodates 2.5 kg of fresh fruit, corresponding to approximately twelve apples. This reference crate load was determined through direct weighing trials performed by the authors and resulted in an average fruit mass of about 208 g per apple. According to United States Department of Agriculture (USDA) Foreign Agricultural Service data, apples weighing between 151 and 250 g fall within the medium-size class (USDA Foreign Agricultural Service, 2017). System boundaries were defined in accordance with the study goal and

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data availability, focusing on the operational performance of the packaging and distribution system, and include: (i) production of secondary and tertiary packaging components (standard and foldable PP crates, EPS crates, corrugated cardboard crates, PP trays, linear low-density polyethylene (LLDPE) stretch film, and high-density polyethylene (HDPE) pallets), (ii) transport of packaging components to the packing facility, (iii) packing operations and palletization, (iv) national distribution stages from the packaging plant to distribution centres and from distribution centres to retailers, (v) washing and sanitization processes in the reusable scenario, and (vi) end-of-life management of packaging materials through recycling, landfill, and energy recovery according to current Italian waste management practices. Internal logistics within distribution centres and retail stores, as well as logistics of the downstream end-of-life chain, are excluded from the system boundaries.

All packaging levels are included, from crates to trays, films, and pallets, with pallets modelled using an assumed service life consistent with reusable transport packaging practice (Coelho et al., 2020). Environmental impacts were quantified using the ReCiPe 2016 Midpoint and Endpoint (H) method implemented in SimaPro version 9.6.0.1 (PRé Sustainability B.V., 2024), with background life cycle inventory data primarily sourced from the ecoinvent 3.10 database using the allocation, cut-off by classification system model (Wernet et al., 2016).

2.1.1 Scenarios description

The analysis compares four packaging-and-transport configurations for fresh fruit, all sharing a common protective element: PP alveolar trays. These trays minimise direct fruit-to-fruit contact and reduce mechanically induced damage during handling and distribution. Although they may lower packing density, their inclusion reflects the protective role of packaging, which can be environmentally justified when it reduces product losses and food waste along the supply chain (Accorsi et al., 2014; Wikström et al., 2014). The scenarios are presented in Figure 1.

S1 adopts rigid, non-collapsible PP crates (30 × 40 × 8 cm) as secondary packaging, each loaded with a 30 × 40 cm PP alveolar tray accommodating 2.5 kg of fresh fruit. The crates are palletised as the tertiary unit in 25 layers of 8 crates, corresponding to 200 crates per pallet, and stabilised with LLDPE stretch film to withstand oscillatory and jolting motions during loading, unloading and transport. This configuration enables approximately 500 kg of fruit per pallet, with an overall pallet height of about 2.0 m. S2 preserves the same footprint and tray configuration but replaces the rigid crate with a collapsible PP crate (30 × 40 × 11.5 cm), designed to facilitate reverse logistics and reuse over 50 cycles. Due to the increased crate height, the pallet configuration is reduced to 20 layers of 8 crates, corresponding to 160 crates per pallet, approximately 400 kg of fruit and an overall pallet height of about 2.30 m. This scenario illustrates how packaging geometry, collapsibility and stacking configuration can influence pallet unitisation, fill rate and the amount of product transported per pallet, while load stability depends on proper pallet-unit formation and securing under transport conditions (Tkaczyk et al., 2021; Ahmad et al., 2022). S3 changes the secondary-packaging material to EPS while maintaining the same crate footprint as S1 (30 × 40 × 8 cm), the same PP alveolar trays, the same pallet pattern of 25 layers × 8 crates, and LLDPE stretch-film stabilisation. As a result, S3 also reaches 200 crates per pallet, corresponding to approximately 500 kg of fruit and an overall pallet height of about 2.0 m. S4 uses corrugated cardboard crates (30 × 40 × 14 cm)

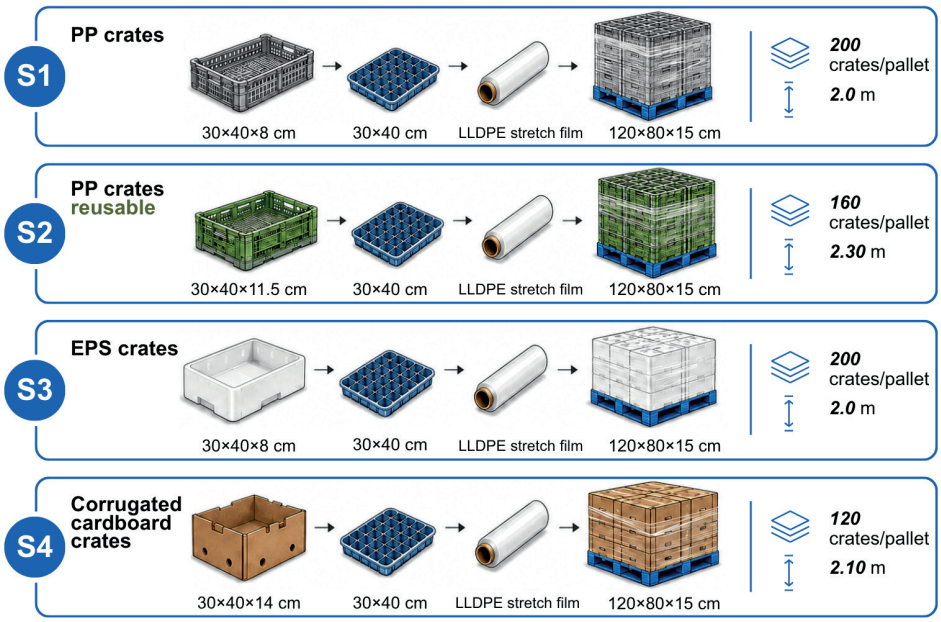


FIGURE 1: Packaging configurations analysed for fresh fruit distribution in the four scenarios: S1 = single-use rigid polypropylene (PP) crates; S2 = reusable foldable PP crates; S3 = single-use expanded polystyrene (EPS) crates; S4 = single-use corrugated cardboard crates. The figure also reports the common tray inserts, stretch film, pallet dimensions, number of crates per pallet and pallet height. LLDPE = linear low-density polyethylene; HDPE = high-density polyethylene.

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with equivalent PP alveolar trays. Because of the greater crate height, the pallet is limited to 15 layers of 8 crates, corresponding to 120 crates per pallet, and is stabilised with LLDPE stretch film. This configuration enables approximately 300 kg of fruit per pallet, with an overall pallet height of about 2.10 m.

2.1.2 Logistics configuration and distribution assumptions

The modelling framework adopts a process-based representation of the logistics system that distinguishes the forward logistics stages common to all scenarios and the additional closed-loop operations required only in S2, where reusable transport packaging is implemented (Figure 2).

Across S1-4, the shared forward chain starts downstream of Packaging Production, with secondary and tertiary packaging components transported to the Packing Facility, where filling and palletised unit-load formation occur; unitised product is then delivered to the Distribution Centre (DC) and subsequently dispatched to the retailer. The adopted modelling approach is based on the evidence that packaging design constraints shape logistics operations and network performance (Pålsson & Hellström, 2016; Accorsi et al., 2020). After retail use, single-use items (rigid PP crates, EPS crates, corrugated cardboard crates and PP trays) are assumed to enter municipal waste-management systems, where they are sorted by material and allocated to recycling, energy recovery, or landfill in accordance with local policy.

Conversely, S2 explicitly models a dedicated reverse-logistics loop for collapsible PP crates (and reusable pallets), whereby empty containers are returned from the retailer to the DC and then transferred to a Pooling Center for inspection, washing, and sanitisation prior to redistribution to the Packing Facility for subsequent cycles. This configuration parallels closed-loop reusable-container networks in food retail supply chains, where pooling, washing, inventory management and transportation are explicitly modelled, and where the pooler acts as the coordinating actor balancing the needs of suppliers and retailers (Accorsi et al., 2022). Strategic closed-loop network design studies further support the role of pooling structures in reusable packaging systems (Accorsi et al., 2020). In pooled reusable transport item (RTI) systems, the pooler commonly manages supply, collection and refurbishing activities (Accorsi et al., 2019).

TABLE 1: Technical characteristics of the packaging components used in the life cycle inventory (LCI), including dimensions, unit weight and data sources. PP = polypropylene; EPS = expanded polystyrene; LLDPE = linear low-density polyethylene; HDPE = high-density polyethylene.

Component	Dimensions (cm)	Unit weight (kg)	Source
Non-collapsible PP crates	30×40×8	0.195	Plastic Packaging S.r.l., 2023
Collapsible PP crates	30×40×11.5	0.850	CPR System, 2023
Expanded polystyrene crates	30×40×8	0.090	Direct measurement
Corrugated cardboard crates	30×40×14	0.500	Specialised suppliers
PP tray inserts	30×40	0.015	INFIA, 2014
LLDPE stretch film	60 m	0.635	Nolanplastica, 2023
HDPE pallet	120×80	14.5	CPR System, 2023

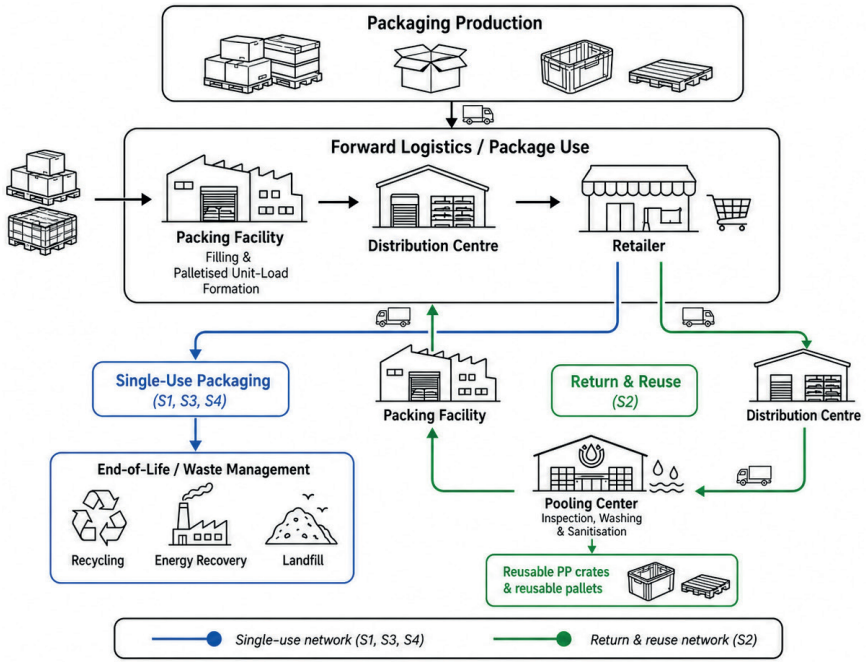


FIGURE 2: Logistics configuration and end-of-life pathways considered in the life cycle assessment (LCA) model. Single-use systems, namely S1, S3 and S4, are sent to waste management, including recycling, energy recovery and landfill, while S2 includes a return-and-reuse loop with pooling, washing, sanitisation and redistribution. PP = polypropylene.

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2.2 Life Cycle Inventory

2.2.1 Packaging data: scenario modelling and allocation to the FU

Table 1 synthesises the technical characteristics of all components employed, with data acquired from direct measurements, specialised catalogues, and sector-specific databases (Plastic Packaging S.r.l., 2023; CPR System, 2023; INFIA, 2014; Nolanplastica, 2023).

The different alternatives present pallet configurations with variable overall weight and height, depending on the amount of packaging used and the dimensional and mechanical characteristics of the packaging units. Pallet-loading studies show that pallet configuration and stability are influenced by unit dimensions, maximum allowable pallet height and weight, stacking pattern, and dynamic compression strength (Almasarwah et al., 2023). Table 2 summarises, for each scenario, the number of units per component, total packaging weight and overall pallet height.

For the reusable PP crates, 50 reuse cycles were assumed as a representative service life. This assumption is supported by the carbon footprint study conducted by Fraunhofer IBP, which sets the base-case scenario for RPCs at 50 rotations (Krieg et al., 2018). Similarly, the comparative LCA of food crates by Del Borghi et al. (2021) explicitly states that "50 recycle are considered during its lifetime" for multi-use crates. Further support is provided by Tua et al. (2019), who modelled the environmental performance of RPCs as a function of the number of deliveries/rotations, considering a range from 1 to 125 rotations. For HDPE pallets, a conservative service life of 20 cycles was assumed as a modelling proxy, using the service life commonly adopted for wooden pallets in LCA studies as a cautious benchmark. Khan et al. (2021), drawing on the review by Deviatkin et al. (2019), report an expected lifetime of 20 cycles for wooden pallets, with most reviewed studies ranging between 5 and 30 cycles.

For the sanitation process of reusable crates, a washing rate of 25% was adopted, meaning that, on average, one out of four returning crates requires washing, while the remaining three are considered suitable for reuse without specific interventions. Each washing operation was modelled as consuming 0.5 g of sodium percarbonate, 0.1 kg of water and 0.036 kWh of electricity, following Levi et al. (2011). Inventory data were normalised to the FU of 1 kg of fresh fruit. Since each crate contains the same amount of product, differences among scenarios arise from packaging material and mass, reuse allocation and pallet configuration, which is influenced by packaging dimensions, weight and mechanical characteristics. Crate and tray-insert weights were allocated directly per FU, while pallets and stretch film were allocated according to the total amount of fruit transportable per pallet. For S2, an additional allocation over 50 reuse cycles was applied. Following these allocation procedures, the packaging inventory inputs were normalised to the FU and are reported in Table 3.

Similarly, input consumption related to the inspection, washing and sanitisation of reusable crates was normalised by considering both the number of crates required per FU and the assumed 25% washing rate. Accordingly, S2 was modelled with 0.050 g of sodium percarbonate, 0.010 kg of water and 0.0036 kWh of electricity per FU, corresponding to 1 kg of fresh fruit.

TABLE 2: Unit-load configuration for the four packaging scenarios, including number of crates, tray inserts, stretch film requirement, pallet type, total packaging weight, stack height and fruit load capacity. S1 = single-use rigid PP crates; S2 = reusable foldable PP crates; S3 = single-use EPS crates; S4 = single-use corrugated cardboard crates. LLDPE = linear low-density polyethylene; HDPE = high-density polyethylene.

Scenario	Crates (n)	PP inserts (n)	LLDPE film (m)	Pallet	Total packaging weight (kg)	Total height (m)	Load capacity (kg apples)
S1	200 (non-coll. PP)	200	60	1 HDPE	57	2.0	500
S2	160 (coll. PP)	160	60	1 HDPE	154	2.3	400
S3	200 (EPS)	200	60	1 HDPE	36	2.0	500
S4	120 (cardboard)	120	60	1 HDPE	77	2.1	300

TABLE 3: Normalised inventory of packaging components per functional unit (FU = 1 kg of fresh fruit), expressed as kg of packaging per FU. S1 = single-use rigid PP crates; S2 = reusable foldable PP crates; S3 = single-use EPS crates; S4 = single-use corrugated cardboard crates. PP = polypropylene; EPS = expanded polystyrene; LLDPE = linear low-density polyethylene; HDPE = high-density polyethylene. *Value before allocation over 50 reuse cycles. **Value before allocation over 20 pallet reuse cycles.

Component	Unit weight (kg)	S1	S2	S3	S4
Non-collapsible PP crates	0.195	0.078	–	–	–
Collapsible PP crates	0.850	–	0.340*	–	–
Expanded polystyrene crates	0.090	–	–	0.036	–
Corrugated cardboard crates	0.500	–	–	–	0.200
PP tray inserts	0.015	0.006	0.006	0.006	0.006
LLDPE film	0.635	0.00127	0.00158	0.00127	0.00211
HDPE pallet	14.5	0.029**	0.03625**	0.029**	0.04833**

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2.2.2 Logistics data management in forward and reverse logistics systems

For the logistics micro-cycle, two Euro 5 road-transport vehicle classes were selected, reflecting the predominance of road haulage in Italian freight distribution (Comité National Routier, 2021) and the relevance of transport distance in reusable-packaging LCA modelling (Marmora et al., 2026). Euro 5 trucks in the 16–32 tonne class were assigned to motorway and extra-urban routes, whereas Euro 5 vehicles in the 3.5–7 tonne class were used for urban last-mile distribution. Fuel consumption and associated emissions were modelled using the corresponding SimaPro background datasets.

The forward logistics chain comprises three stages: (i) 150 km from the packaging manufacturing site to the packing facility, following Marmora et al. (2026); (ii) 200 km from the packing facility to the DC, in line with Abejón et al. (2020) and Marmora et al. (2026); and (iii) 30 km from the distribution centre to local retailers, following Ferrara et al. (2021) and Marmora et al. (2026). The first two stages were classified as motorway/extra-urban transport, whereas the final stage was classified as urban distribution.

For single-use systems, packaging components were transported directly to the packing facility and no return flow was modelled. For the reusable scenario (S2), the pooling, sorting and washing centre was assumed to be co-located with the packing facility. Empty crates therefore followed a reverse route of 30 km from the retailer to the DC and 200 km from the DC to the washing/pooling centre. The subsequent transfer from washing to packing was treated as internal handling and was not modelled as a dedicated transport process. All transport activities were expressed in kg·km per FU.

2.2.3 End-of-Life (EoL) data: waste scenarios and related logistics

The end-of-life stage was modelled through three treatment routes: recycling, energy recovery and landfilling. Collection and transfer to treatment facilities were represented by a single average distance of 30 km, modelled with Euro 5 trucks in the 3.5-7 tonne class and applied consistently across all EoL routes (Mondello et al., 2017; Marmora et al., 2026). Transport was expressed in kg·km/FU, while treatment processes were modelled using ecoinvent 3.10 datasets (Wernet et al., 2016).

In Italy, packaging-waste management is organised within an Extended Producer Responsibility (EPR) framework, under which producers contribute to the management and financing of post-consumer packaging collection, recycling and recovery activities (Rigamonti et al., 2015). This institutional framework influences the effective distribution of packaging waste among the available end-of-life routes and is therefore reflected in the national management shares adopted in the present model. Accordingly, the EoL scenarios were parameterised using operational data reported by the relevant material-specific consortia.

For plastic packaging, allocation factors were derived from the 2022 Management Report of COREPLA (Italian National Consortium for the Collection, Recycling and Recovery of Plastic Packaging), resulting in 55.4% recycling, 33.0% energy recovery and 11.6% landfilling (COREPLA, 2023). For paper and cardboard packaging, the 2022 Annual Report of COMIECO (Italian National Consortium for the Recovery and Recycling of Cellulose-based Packaging) provided the corresponding allocation factors of 85.1% recycling, 6.4% energy recovery and 8.5% landfilling (COMIECO, 2023).

3. RESULTS AND DISCUSSION: LIFE CYCLE IMPACT ASSESSMENT (LCIA) AND INTERPRETATION

3.1 Life Cycle Impact Assessment: Midpoint-Oriented analysis and Interpretation of results

Figure 3 reports midpoint-level results. For each impact category, scenario values are expressed as percentages relative to the scenario showing the highest impact in that category.

S2 confirms the most favourable overall environmental profile, exhibiting lower values than the other scenarios across most categories. This systematic reduction aligns with LCA evidence on pooled RPCs, where a higher number of rotations distributes manufacturing burdens over many uses, provided that reverse logistics and reconditioning (collection, inspection, washing and sanitisation) are efficient and well controlled (Tua et al., 2019; Abejón et al., 2020; Albrecht et al., 2022; Lupi et al., 2024). The graph demonstrates that S2 exhibits comparatively low levels across GW, FEc, Human Carcinogenic Toxicity (HcT), Human Non-Carcinogenic Toxicity (HncT), and Water Consumption (WC).

This points to the ability of reusable plastic crates to deliver environmental benefits across multiple impact categories, namely climate, toxicity, energy, and water. This interpretation is corroborated by Abejón et al. (2020), who found that reusable plastic crates outperform single-use cardboard boxes in all the impact categories considered, driven by lower primary energy consumption and substantially reduced freshwater use.

S1 approaches 100% in several impact categories, including GW, Ionizing Radiation (IR), Terrestrial Acidification (TA), and Fossil Resource Scarcity (FRS), mainly because the upstream burdens associated with polymer production and crate manufacturing are assigned to a single use. Although the crate-to-product ratio in S1 (78 g/FU) indicates relatively favourable logistical efficiency, also reflected in the limited amount of tertiary packaging required (0.00127 kg LLDPE/FU and 0.029 kg HDPE pallet/FU before allocation over 20 pallet reuse cycles) these downstream advantages are not sufficient to offset the structural limitation of a linear packaging system. This interpretation is supported by system-level LCA evidence showing that single-use PP container networks tend to have higher impacts than reusable PP crate systems, since production and end-of-life burdens cannot be distributed over repeated use cycles (Albrecht et al., 2013; Accorsi et al., 2022a).

S3 shows an intermediate profile: it does not systematically reach the highest impacts, but it does not achieve the

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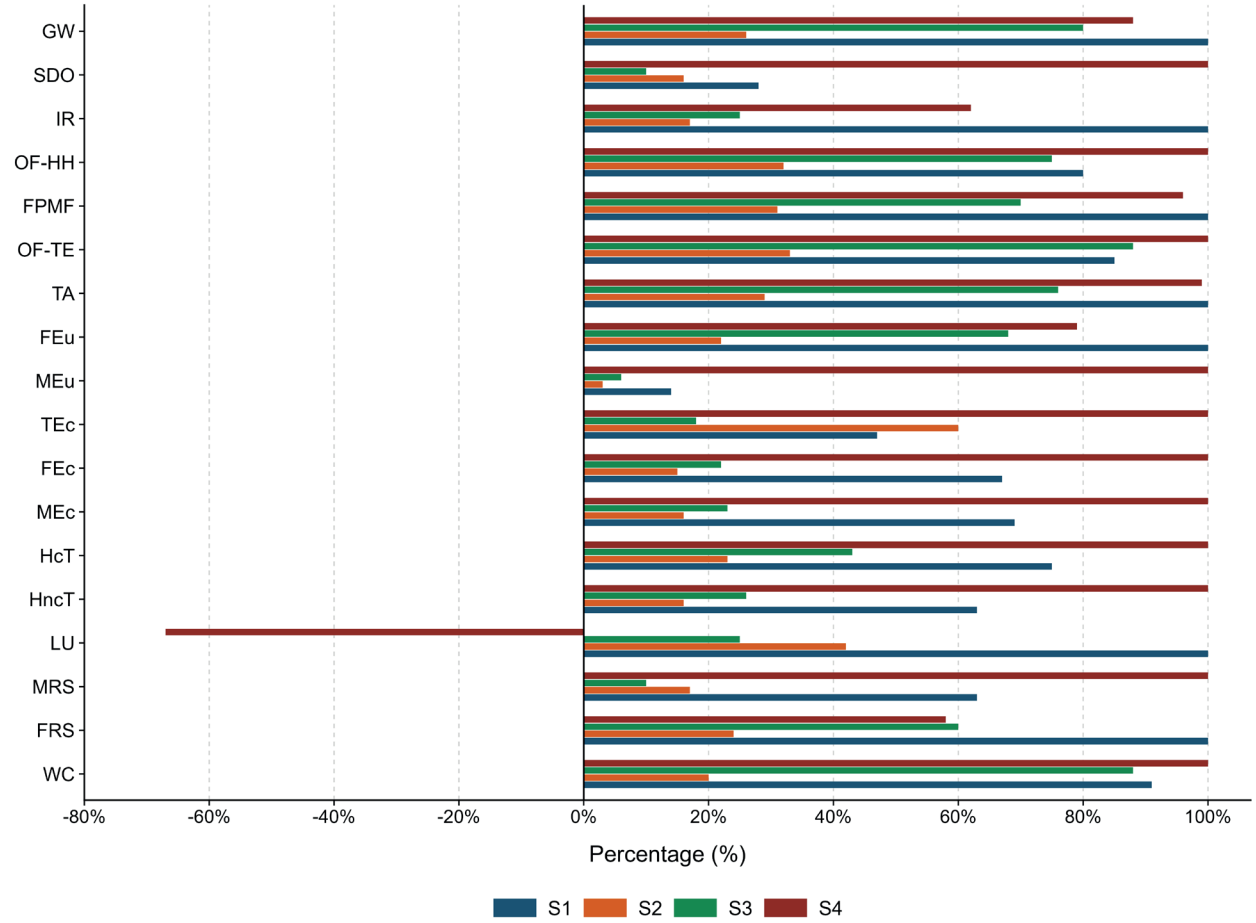


FIGURE 3: Midpoint impact assessment results obtained using the ReCiPe 2016 method, Hierarchist perspective, expressed as relative percentages normalised to the worst-performing scenario in each impact category (100%). S1 = single-use rigid PP crates; S2 = reusable foldable PP crates; S3 = single-use EPS crates; S4 = single-use corrugated cardboard crates. GW = Global Warming; SOD = Stratospheric Ozone Depletion; IR = Ionizing Radiation; OF-HH = Ozone Formation, Human Health; FPMF = Fine Particulate Matter Formation; OF-TE = Ozone Formation, Terrestrial Ecosystems; TA = Terrestrial Acidification; FEu = Freshwater Eutrophication; MEu = Marine Eutrophication; TEc = Terrestrial Ecotoxicity; FEc = Freshwater Ecotoxicity; MEc = Marine Ecotoxicity; HcT = Human Carcinogenic Toxicity; HncT = Human Non-Carcinogenic Toxicity; LU = Land Use; MRS = Mineral Resource Scarcity; FRS = Fossil Resource Scarcity; WC = Water Consumption.

lowest values either. Its main advantage lies in lightweighting, since the low crate-mass allocation (36 g/FU) reduces burdens related to transport, handling and tertiary packaging. However, this benefit is partly offset by the impacts associated with EPS production and by the sensitivity of its end-of-life modelling. EPS is particularly affected by upstream fossil-based production and disposal processes such as landfill and incineration (Desole et al., 2024), while LCA evidence specifically addressing industrial EPS packaging shows that recycling and incineration scenarios can lead to substantially different climate-change results, with closed-loop recycling performing best and incineration worst (Hallberg et al., 2023). Although the favourable mass and palletisation efficiency of S3 reduces the requirements for LLDPE stretch film and pallets, the system remains a single-use option and its production burdens cannot be amortised over repeated cycles.

S4 exhibits the poorest performance in several categories, including Stratospheric Ozone Depletion (SOD), Ozone Formation-Human Health (OF-HH), Ozone Formation-Terrestrial Ecosystems (OF-TE), Marine Eutrophication (MEu), Terrestrial Ecotoxicity (TEc), FEc, Marine Ecotoxicity (MEc), HcT, HncT, Mineral Resource Scarcity (MRS), and WC, mainly due to its high crate-mass allocation, equal to 200 g/FU. Moreover, since fewer FUs fit on each pallet, S4 requires the largest physical pallet mass per FU (0.04833 kg/FU before allocation over 20 pallet reuse cycles) and the highest stretch-film demand per FU, increasing upstream burdens from both pallet and film production. Beyond these logistics-driven mechanisms, paperboard-based systems involve relevant trade-offs in water- and energy-related burdens. The pulp and paper sector is widely recognised as water-intensive, with reported water use ranging from 10 to 300 m³ per tonne of product and highly polluted wastewater corresponding to approximately 75% of the freshwater used (Esmaeeli & Sarrafzadeh, 2023). Moreover, corrugated-cardboard recycling still requires relevant process inputs: recycling one tonne of corrugated cardboard requires 7 m³ of water, 600 kg of steam and 700 kWh of electricity (Accorsi et al., 2014). Comparative LCAs of fresh-produce distribution report trade-offs between corrugated containers and reusable plastic containers, with RPCs showing

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advantages in categories such as acidification, respiratory effects and ozone depletion, while corrugated containers may perform better in global warming and non-renewable energy use (Corrugated Packaging Alliance & Quantis, 2019).

Attention should be given to the Land Use category, in which S4 displays a negative result, i.e. the lowest value among the scenarios. This outcome is best interpreted as a modelling effect of recycling credits attributed to corrugated board under a substitution/system-expansion logic. In this approach, the burdens of the substituted system are subtracted from the analysed product system; the ILCD Handbook explicitly describes this as a "crediting" or "avoided burden" approach and notes that substitution may lead to negative inventory flows (European Commission, 2010). Therefore, when recycling benefits are modelled as avoided primary material production, negative contributions can arise in those impact categories where the avoided system carries relevant burdens, such as land-use-related impacts associated with virgin fibre supply.

3.2 Life Cycle Impact Assessment: EndPoint-Oriented analysis and Interpretation of results

Figure 4 reports the endpoint results, expressed as percentages by normalising each scenario to the worst-performing one within each damage category. This endpoint perspective complements midpoint results by aggregating impacts into the three ReCiPe 2016 (H) damage indicators through cause-effect modelling (Huijbregts et al., 2017).

Across all three damage areas, S1 remains the worst-performing option (Human Health: 99%; Ecosystem Quality: 100%; Resource Scarcity: 100%). This confirms that the burdens associated with a linear single-use configuration are not confined to isolated midpoint dimensions but rather combine into consistently high damage scores once impacts are aggregated. The endpoint convergence on S1 as the worst scenario indicates that upstream processes characteristic of single-use fossil-based polymer packaging contribute simultaneously to climate- and emission-driven damage pathways and to long-term scarcity metrics, producing a robust ranking at damage level.

In contrast, S2 confirms the most favourable profile across all damage indicators (Human Health: 27%; Ecosystem Quality: 28%; Resource Scarcity: 25%). Importantly, the endpoint results show that the benefits associated with pooled reuse persist after aggregation into damage categories, implying that the advantage is not attributable to a single midpoint driver but is reflected across the broader ReCiPe 2016 damage model structure (Huijbregts et al., 2017).

The most consequential shift under endpoint aggregation concerns the comparison between S3 and S4. Although midpoint results tend to penalise S4 because of its higher material intensity and associated logistics burdens, endpoint aggregation narrows the gap between the two scenarios and even reverses their ranking for Resource Scarcity (S4: 57% vs S3: 61%). This behaviour can be interpreted in light of the ReCiPe 2016 resource-scarcity framework, where the endpoint indicator is expressed in monetary terms as the extra future costs associated with mineral and fossil resource extraction (Huijbregts et al., 2017). Fossil resource scarcity is characterised through Surplus Cost Potential, which represents the future cost increase caused by marginal fossil resource use (Ponsioen et al., 2014; Huijbregts et al., 2017). Within this modelling logic, lightweight packaging configurations based on fossil-derived polymers may remain disadvantaged in the Resources damage area despite favourable mass-based logistics, because their dependence on fossil feedstocks directly contributes to the scarcity mechanism embedded in the endpoint model.

This material-level interpretation helps explain the S3-S4 reversal in the Resource Scarcity endpoint. S3 is based on EPS, whose production begins with styrene, a petrochemical monomer that is polymerised into solid polystyrene before being expanded (Desole et al., 2024). There-

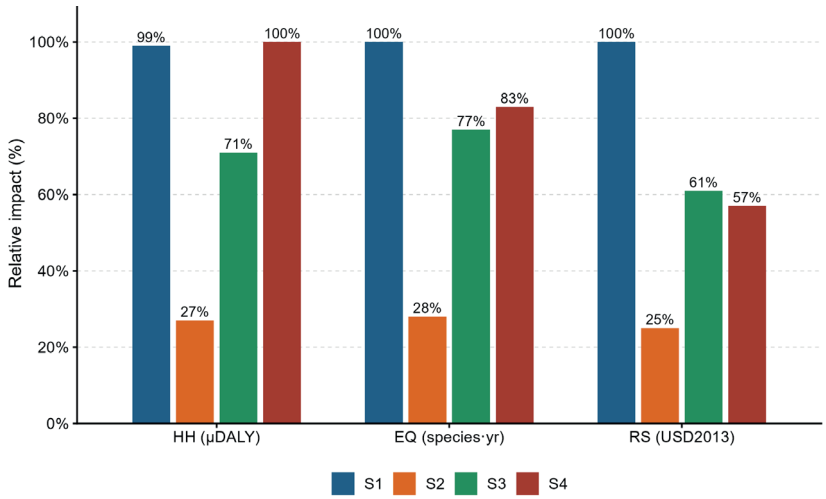


FIGURE 4: Endpoint damage assessment results obtained using the ReCiPe 2016 method, Hierarchist perspective, expressed as relative percentages normalised to the worst-performing scenario within each area of protection (100%). HH = Human Health; EQ = Ecosystem Quality; RS = Resource Scarcity. S1 = single-use rigid PP crates; S2 = reusable foldable PP crates; S3 = single-use EPS crates; S4 = single-use corrugated cardboard crates.

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fore, although EPS is lightweight, its upstream material chain remains directly linked to fossil-derived inputs. This is further supported by cradle-to-gate inventory data for general-purpose polystyrene resin, used here only to document the upstream polystyrene value chain: the system boundary explicitly includes petroleum and natural-gas extraction as feedstocks through styrene production, while most of the total energy demand is associated with incoming materials and their raw materials rather than with final resin production itself (Franklin Associates, 2022). By contrast, S4 is based on corrugated board, a material of biological origin typically composed of paper liners and a corrugated paper flute (Desole et al., 2024), and more generally derived from renewable wood and wood-fibre feedstocks (Albrecht et al., 2013). This difference in feedstock origin helps explain why S4, despite its higher mass and logistics burden, can show a slightly lower Resource Scarcity endpoint score than S3. At the same time, this result does not imply that corrugated board is preferable in all endpoint dimensions. Desole et al. (2024) show that corrugated-board-based packaging may be penalised in Ecosystem Quality because the raw materials involved are almost entirely of biological origin, with damages associated with paper production and land-use-related pressures. Conversely, the same study reports that polystyrene production does not cause significant damage to Ecosystem Quality because no significant emissions to groundwater and soil are generated. This consideration corroborates the present endpoint results, where S4 performs worse than S3 in Ecosystem Quality (83% vs 77%) suggesting that lower fossil-resource dependence does not automatically translate into lower ecosystem-related damage.

3.3 Analysis and discussion of environmental impacts along the life cycle

Figure 5 presents the midpoint results disaggregated by life-cycle stage, packaging production, distribution, end-of-life and, where applicable, reverse logistics, for the following impact categories: GW (g CO_2 eq), Fine Particulate Matter Formation (FPMF) (mg $PM_{2.5}$ eq), TA (mg SO_2 eq), and FRS (g oil eq). Stage-specific contribution analysis allows the identification of environmental hotspots and facilitates interpretation of the physical drivers underlying inter-scenario differences.

Across scenarios, GW results show that production is systematically the dominant hotspot, in line with comparative studies on fruit and vegetable transport packaging, where polymer manufacturing and conversion as well as pulp-and-paper processing are identified as the most impact-intensive life-cycle stages due to their energy demand and associated greenhouse gas emissions (Albrecht et al., 2013; Accorsi et al., 2014).

The EoL stage remains non-negligible even when recycling is assumed, because recycling still involves CO_2-relevant operations such as collection, transport, sorting and reprocessing. For waste-paper systems, Merrild et al. (2008) show that the GW of paper reprocessing is strongly connected to energy consumption, especially electricity use, and varies substantially according to the reprocessing technology adopted and the system boundaries selected. This is relevant for S4, where fibre recovery and reprocessing can still contribute to the climate profile despite the assumed recycling pathway. Similarly, plastic recycling is not a passive recovery process: mechanical recycling is affected by contamination and inefficiencies in sorting and

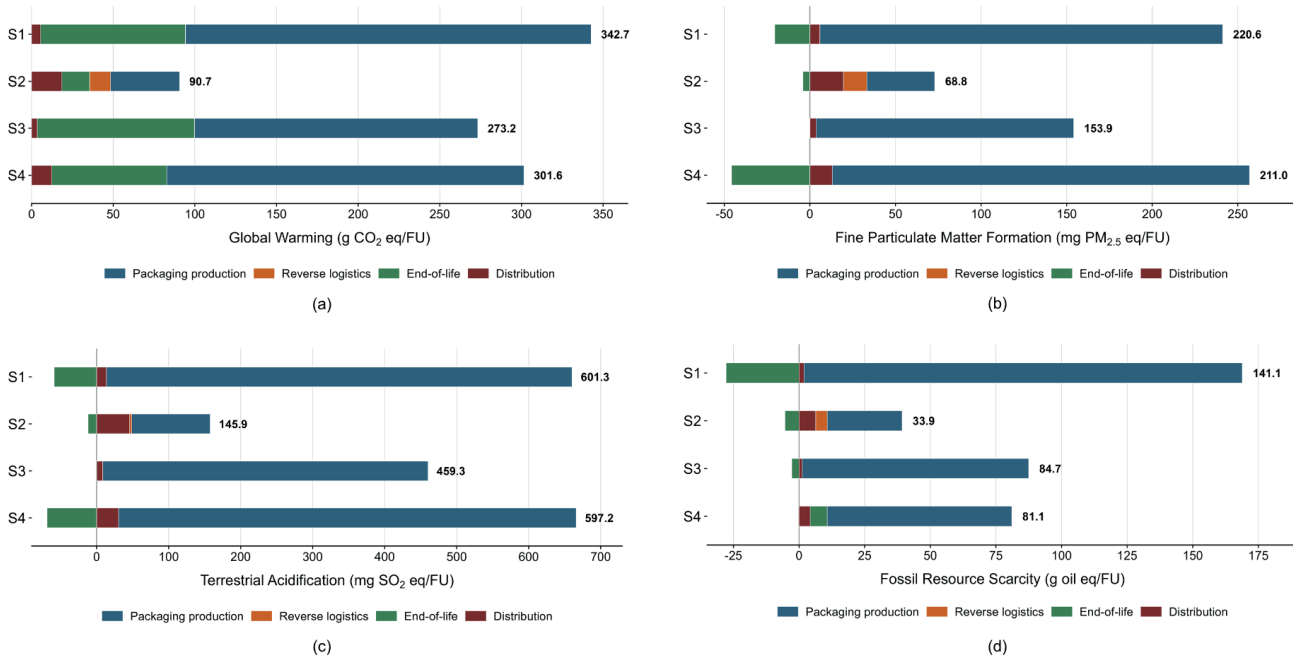


FIGURE 5: Contribution analysis by life-cycle stage for selected midpoint impact categories, expressed per functional unit (FU = 1 kg of fresh fruit). Results are disaggregated into packaging production, reverse logistics, distribution and end-of-life. GW = Global Warming; FPMF = Fine Particulate Matter Formation; TA = Terrestrial Acidification; FRS = Fossil Resource Scarcity. Negative end-of-life values are shown as credits and plotted to the left of the zero axis.

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cleaning, with implications for processing requirements and energy-related emissions (Jiang & Bateer, 2025). These factors contribute to the emission profile observed in S1 and S3. The reusable PP system (S2) exhibits the most favourable climate profile. Nevertheless, Figure 5 (a) indicates a structural trade-off for S2 whereby distribution and reverse logistics become comparatively more influential, since higher unit mass and the need to retrieve empty crates increase transport work and fuel consumption.

Similar stage-based interpretations apply to FPMF and TA (Figure 5 (b) - Figure 5 (c)), where production remains a major driver for single-use scenarios, but logistics can become decisive for heavier or return-loop systems. This is because FPMF and TA are affected by airborne precursors such as NO_x, SO_2 and primary $PM_{2.5}$, and transport-related emissions are sensitive to distance, shipment mass, vehicle load and fuel consumption (Kellner & Otto, 2012; Huijbregts et al., 2017). Negative contributions in selected EoL stage-impact category combinations can instead be interpreted as avoided-burden credits associated with energy recovery or material substitution, whereby recovered energy or recycled material offsets conventional production processes (European Commission, 2010).

FRS (Figure 5 (d)) highlights the material dependence of results. For plastic-based systems, production-stage contributions are notably high, since the supply chains for PP and EPS draw on fossil resources in two ways, both to fuel the processes themselves and to provide the actual chemical building blocks for the polymers. At the end of their life, however, these contributions may actually turn net negative: recycling or energy recovery can generate avoided burdens by offsetting the need for virgin plastics, petrochemical products, or electricity from conventional sources. This is precisely what Perugini et al. (2005) observed in their work, namely, that recycling plastic packaging not only avoids environmental impacts but also saves crude oil compared with simply landfilling or incinerating it without recovery. The picture changes noticeably when we look at corrugated cardboard. Here, recycling mainly replaces virgin fibre and paper production, rather than fossil-based polymer feedstocks. As a consequence, the benefits in terms of FRS are structurally less immediate and tend to hinge quite heavily on the specific recycling technology adopted, the energy inputs involved, and the way system boundaries are defined (Perugini et al., 2005; Merrild et al., 2008).

3.4 Sensitivity analysis: influence of transport distance and crate rotation rate

A one-at-a-time (OAT) sensitivity analysis was conducted to assess the robustness of the midpoint results with respect to two drivers: (i) transport distance and (ii) the effective number of reuse cycles. The base case assumes a distance of 200 km between the packing facility and large-scale retail distribution centres and 50 reuse cycles for scenario S2. Each parameter was varied independently, defining two additional systems for transport distance (100 km and 500 km) and two further levels for reuse cycles (20 and 200 uses), in order to isolate their marginal influence on GW, FPMF, TA, and FRS. The decision to explicitly subject transport distance to a sensitivity analysis aligns with the conclusions of scientific studies showing that logistics can alter the environmental ranking between reusable and single-use systems. In the study by Levi et al. (2011), focused on fruit and vegetable distribution in Italy, for instance, the comparative outcome between corrugated containers and reusable plastic crates was found to depend on transport distance, with a crossover behaviour reported beyond approximately 1200 km, highlighting the importance of testing alternative distribution configurations. Similarly, the carbon footprint study on packaging systems for fruit and vegetable transport in Europe by Krieg et al. (2018) include sensitivity checks through variations of specific supply chain transport legs, demonstrating that transport distance must be explicitly tested to ensure the transferability of results across different territorial contexts. In a comparable manner, the comparative LCA study conducted by Ramboll for FEFCO defines a distance-parameterised FU (the transport of 1 tonne of fresh products over 840 km) and includes specific sensitivity analyses on key logistical and operational parameters, such as reuse rates and transport distances. The findings confirm that the outcomes of comparative LCAs require stress-testing of operational variables, particularly when systems differ significantly in terms of the packaging solutions' unit mass and involve reverse logistics for return flows (Castellani et al., 2022).

Regarding the number of cycles, multiple lines of evidence demonstrate that the amortisation of manufacturing impacts over repeated uses can significantly reduce the environmental burden per FU; however, the magnitude of this benefit depends on the effective number of rotations achieved, breakage and non-return rates, and the efficiency of return logistics and reconditioning processes, which may become increasingly influential at higher reuse levels (Tua et al., 2019; Coelho et al., 2020; Accorsi et al., 2022b). The selection of 50 reuse cycles as the baseline scenario follows previous modelling assumptions. Krieg et al. (2018) assume 50 reuse cycles as the baseline scenario for reusable plastic containers in European fruit and vegetable transport, while Accorsi et al. (2014) includes 50 use cycles among the lifespan levels tested in its multi-scenario analysis, together with 30 and 70 cycles. At the same time, including 20 reuse cycles allows the exploration of conservative conditions close to reported break-even thresholds, which range from three uses in Tua et al. (2019) to approximately 15 rotations depending on the network configuration and impact category, as reported by Accorsi et al. (2022a). Conversely, 200 reuse cycles represent an extension toward a highly efficient long-term reuse scenario, consistent with the upper bound reported by Albrecht et al. (2013), who indicate that realistic operating conditions may lead to 50-200 fillings per crate over its lifetime.

3.4.1 Effect of transport distance

Varying the transport distance allows the evaluation of how the environmental performance of the different packaging solutions changes under increasing logistical intensity.

As shown in Figure 6 (a), all scenarios exhibit an almost linear increase in GW as distance grows. This behaviour is intrinsically linked to the proportional relationship

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between fuel consumption and CO_2 emissions in road freight transport, assuming constant vehicle configuration, load factor, and technology (Kellner & Otto, 2012). A shorter distance (100 km) results in lower overall emissions, whereas extending the distance to 500 km leads to a higher GW primarily due to the increased contribution of the distribution phase, while production and end-of-life remain unchanged under the OAT design. S2 shows a more pronounced increase compared to the single-use systems, as reflected by the steeper slope of the curve. This pattern can be explained by the higher relative contribution of logistics to the total life-cycle profile of the reusable system, which includes reverse transport flows. The literature on reusable packaging systems consistently highlights that environmental performance is strongly dependent on network efficiency, return logistics, return rates, cleaning operations, and transport distances (Coelho et al., 2020; Mahmoudi & Parviziomran, 2020). Despite this higher sensitivity, S2 maintains the lowest overall GW across the entire distance range analysed, indicating that the amortisation of production impacts over 50 reuse cycles outweighs the additional logistical burden under the boundary conditions considered.

An analogous trend is observable in the case of FPMF and TA (Figure 6 (b) - Figure 6 (c)). All the scenarios display increasing impacts with growing distance, while S2 again shows a higher slope relative to the single-use alternatives. These impact categories are particularly sensitive to combustion-related emissions from road transport activities, including NO_x, SO_2 and primary PM emissions, which are explicitly covered by the EMEP/EEA air pollutant emission inventory methodology for road transport (EEA, 2023). Since these emissions scale with fuel consumption and tonne-kilometres travelled, longer transport distances directly translate into higher midpoint results. Because the non-logistical life-cycle stages remain constant in the sensitivity design, the observed increases can be attributed mainly to distribution and handling processes.

For Fossil Resource Scarcity (Figure 6(d)), the results highlight the strong dependence of S1, based on single-use PP crates, on fossil-derived materials. This reflects the petrochemical origin of conventional plastic crates and the relevance of polymer production in the life-cycle profile of this scenario, as plastic crate production involves oil exploration, monomer production, polymer production and crate manufacturing (Albrecht et al., 2013). Increasing transport distance leads to higher values due to additional fuel consumption; however, for S1, S3 and S4 the increment remains moderate because material production continues to be the main driver of fossil resource demand. In contrast, S2 shows a more visible increase with distance, as logistics accounts for a larger share of its total impact profile.

3.4.2 Effect of reuse cycles

The sensitivity analysis (Figure 7) examines the effect of varying the number of crate reuse cycles in S2, testing

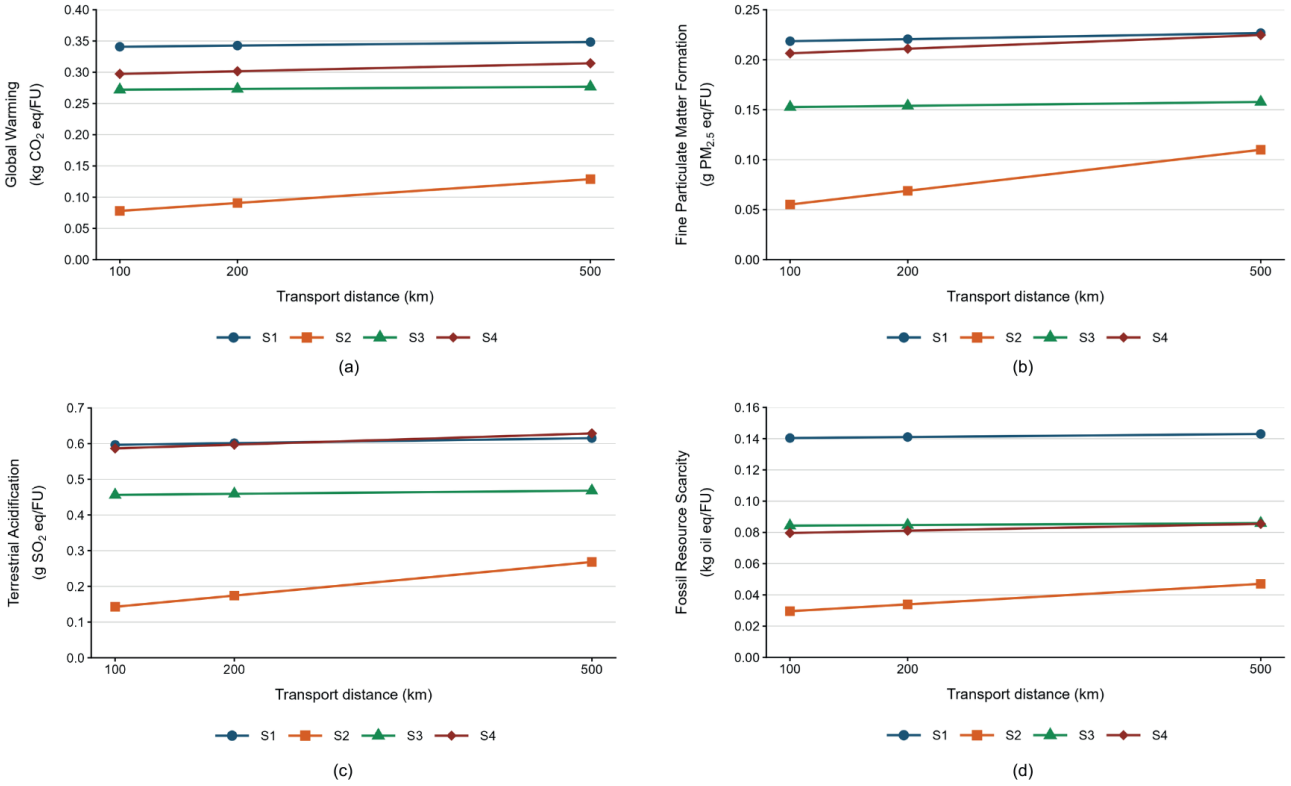


FIGURE 6: Sensitivity analysis of transport distance, varied from 100 km to 500 km, for selected midpoint impact categories and for the four scenarios. Results are expressed per functional unit (FU = 1 kg of fresh fruit). S1 = single-use rigid PP crates; S2 = reusable foldable PP crates; S3 = single-use EPS crates; S4 = single-use corrugated cardboard crates. GW = Global Warming; FPMF = Fine Particulate Matter Formation; TA = Terrestrial Acidification; FRS = Fossil Resource Scarcity.

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20 and 200 uses against the baseline of 50 cycles, while keeping the transport distance between the packing facility and large-scale retail distribution centres constant.

The results clearly show that the poorest performance occurs under 20 reuse cycles, while 200 cycles lead to the lowest impact values across all categories considered. Indeed, for a given material and manufacturing process, increasing the number of rotations reduces the production-related impact per FU, while recurring contributions, such as transport, reverse logistics and reconditioning, progressively gain relative importance (Tua et al., 2019; Coelho et al., 2020). Changing the number of reuse cycles mainly affects the allocation of crate production impacts to the FU. With fewer cycles, a larger share of the manufacturing burden is assigned to each kilogram of fruit, increasing the overall impacts. Conversely, with more cycles, this burden is spread over a greater number of uses, reducing the impact per FU. Transport and reconditioning remain recurrent contributions and therefore become relatively more relevant as production impacts are progressively diluted. Even at 20 cycles, S2 remains the most environmentally favourable option within the system boundaries considered.

However, it is important to note that reuse cycles cannot increase indefinitely. In real pooling systems, the effective number of rotations is limited by crate losses, breakage and the consequent need to replace damaged or missing units, as considered in reusable crate LCA studies that include breakage, inspection, washing and replacement assumptions (Tua et al., 2019; Del Borghi et al., 2021). Therefore, the 200-cycle scenario should be interpreted as an optimized upper-bound condition rather than as an indefinitely scalable reuse configuration. This interpretation is further supported by Levi et al. (2011), who show that increasing the number of RPC uses strongly reduces the contribution of the production phase, but that this reduction follows an asymptotic behaviour when more than 50 uses are considered. Beyond this threshold, additional reuse cycles provide progressively smaller environmental benefits, and the total impact per use tends to remain almost constant, being mainly governed by recurrent processes such as transport and washing.

4. CONCLUSIONS

This study conducted a comparative LCA of four packaging alternatives for fresh fruit distribution in the Italian large-scale retail sector, aiming to identify the operational conditions under which reuse is environmentally preferable to single-use systems. Four scenarios were assessed: single-use rigid PP crates (S1), reusable foldable PP crates managed through a pooling system (S2), single-use EPS crates (S3), and single-use corrugated cardboard crates (S4). The assessment considered 18 ReCiPe 2016 midpoint impact categories and the three endpoint damage areas, with particular focus on GW, FPMF, TA and FRS. Under baseline conditions (50 reuse cycles and a 200 km distance between packing facilities and distribution centres) S2 showed the best overall environmental performance. At endpoint level, the reusable system reduced impacts by 73% for Human Health, 72% for Ecosystem Quality and 75% for Resource Scarcity compared with the worst-performing scenarios. At midpoint level, S2 consistently recorded the lowest impacts in GW, FEc, HcT, HncT and WC. This advantage is mainly due to the allocation of production burdens over multiple use cycles, which substantially reduces the packaging mass assigned to each FU.

The contribution analysis showed a clear structural difference between reusable and single-use systems. In S1, S3 and S4, production dominates the environmental profile, whereas in S2 distribution and reverse logistics become relatively more important, although absolute impacts remain lower. This confirms that reuse is not automatically

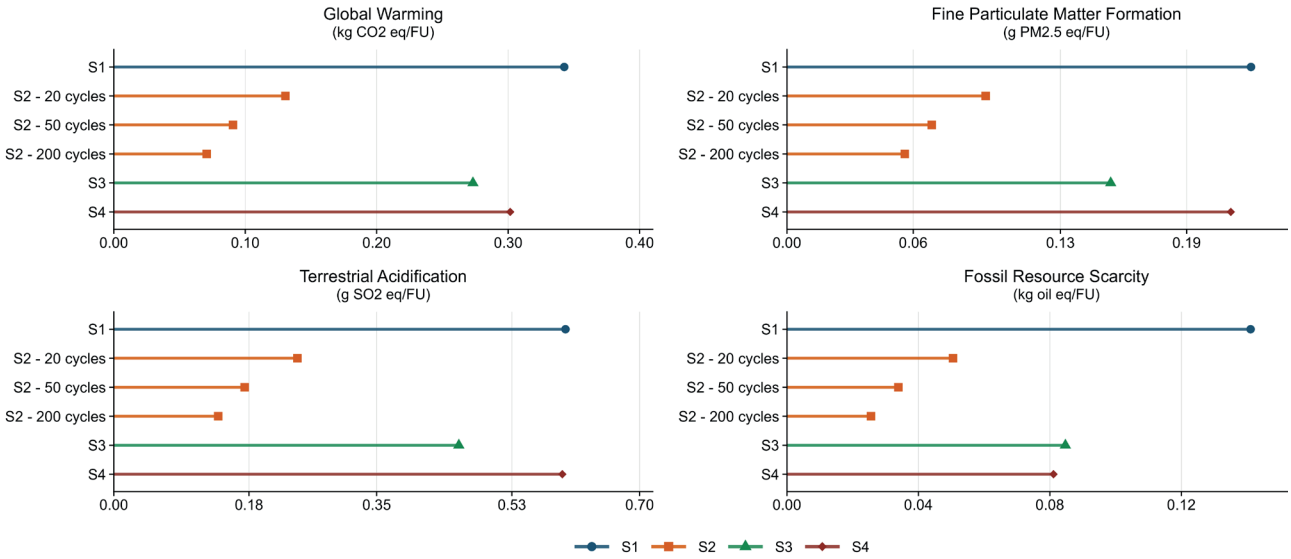


FIGURE 7: Sensitivity analysis of the number of reuse cycles for the reusable packaging scenario S2. Results are expressed per functional unit (FU = 1 kg of fresh fruit) and compared with S1, S3 and S4. GW = Global Warming; FPMF = Fine Particulate Matter Formation; TA = Terrestrial Acidification; FRS = Fossil Resource Scarcity. PP = polypropylene; EPS = expanded polystyrene.

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beneficial but depends on logistics efficiency and the effective number of rotations achieved.

Sensitivity analysis confirmed, indeed, the importance of transport distance and reuse cycles. Increasing the distance from 100 to 500 km caused an almost linear increase in impacts across all scenarios, with S2 showing higher sensitivity because of its bidirectional logistics. Nevertheless, S2 remained the lowest-impact option even at 500 km. However, previous LCA studies show that beyond critical distances, such as approximately 1,200 km, single-use cardboard may become preferable to RPCs (Levi et al., 2011). This risk increases when return rates are low, losses are high, or reverse logistics are poorly coordinated, since these factors reduce the effective number of rotations and increase replacement needs (Coelho et al., 2020; Albrecht et al., 2022).

When transport distance was fixed at 200 km, the number of reuse cycles strongly affected the results. At 20 cycles, S2 still outperformed all single-use alternatives; at 50 cycles, reductions reached 50-75% in GW, FPMF, TA and FRS; and at 200 cycles, reductions increased further across all four categories. However, 200 cycles should be interpreted as an optimized upper-bound condition, since real pooling systems are limited by losses, breakage and replacement needs.

Overall, reusable systems represent the best option only under efficient operating conditions. Their advantage may decrease or be lost when reverse logistics are inefficient, transport distances are excessive, rotation rates or return rates are low, or scrap rates are high. Although not specific to RPCs for fresh fruit distribution, recent evidence on reusable food packaging in retail supply chains indicates that high return rates above 60-70% and low scrap rates below 15% are essential to secure environmental benefits (Accorsi et al., 2025). In such contexts, lightweight single-use alternatives, such as EPS crates, may appear preferable from a strictly impact-based perspective, despite their end-of-life limitations and reliance on fossil resources. Therefore, reuse should not be treated as a simple material substitution, but as a system-level strategy requiring durable packaging design, efficient pooling infrastructure, supply-chain coordination and optimized bidirectional logistics.

Future research should extend the proposed framework to fresh-vegetable supply chains, where differences in product density, mechanical sensitivity, respiration behaviour, temperature requirements and packing efficiency may alter both packaging-related impacts and reuse break-even conditions. Further work should also incorporate primary data on product loss and damage rates, crate return and replacement rates, and alternative end-of-life configurations to evaluate the robustness of reusable systems under a broader range of operational and policy conditions.

REFERENCES

Abejón, R., Bala, A., Vázquez-Rowe, I., Aldaco, R., Fullana-i-Palmer, P., & Puig, R. (2020). When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market. Resources, Conservation and Recycling, 155, Article 104666. https://doi.org/10.1016/j.resconrec.2019.104666

Accorsi, R., Bartolotti, G., Guidani, B., Manzini, R., & Ronzoni, M. (2025). Reusable food primary packaging in retail supply chain: A multi-objective optimization framework. Sustainable Production and Consumption, 56, 364-384. https://doi.org/10.1016/j.spc.2025.04.003

Accorsi, R., Baruffaldi, G., & Manzini, R. (2020). A closed-loop packaging network design model to foster infinitely reusable and recyclable containers in food industry. Sustainable Production and Consumption, 24, 48-61. https://doi.org/10.1016/j.spc.2020.06.014

Accorsi, R., Baruffaldi, G., Manzini, R., & Pini, C. (2019). Environmental impacts of reusable transport items: A case study of pallet pooling in a retailer supply chain. Sustainability, 11(11), Article 3147. https://doi.org/10.3390/su11113147

Accorsi, R., Battarra, I., Guidani, B., Manzini, R., Ronzoni, M., & Volpe, L. (2022a). Augmented spatial LCA for comparing reusable and recyclable food packaging containers networks. Journal of Cleaner Production, 375, Article 134027. https://doi.org/10.1016/j.jclepro.2022.134027

Accorsi, R., Cascini, A., Cholette, S., Manzini, R., & Mora, C. (2014). Economic and environmental assessment of reusable plastic containers: A food catering supply chain case study. International Journal of Production Economics, 152, 88-101. https://doi.org/10.1016/j.ijpe.2013.12.014

Accorsi, R., Cholette, S., Manzini, R., & Mucci, L. (2022b). Managing uncertain inventories, washing, and transportation of reusable containers in food retailer supply chains. Sustainable Production and Consumption, 31, 331-345. https://doi.org/10.1016/j.spc.2022.02.014

Ahmad, S., Utomo, D. S., Dadhich, P., & Greening, P. (2022). Packaging design, fill rate and road freight decarbonisation: A literature review and a future research agenda. Cleaner Logistics and Supply Chain, 4, Article 100066. https://doi.org/10.1016/j.clscn.2022.100066

Albrecht, S., Bertling, J., Fischer, M., Gehring, F., Kabasci, S., Prescher, T., & Schulte, A. (2022). Reusable plastic crates vs. single-use cardboard boxes: Two packaging systems in competition. Fraunhofer UMSICHT. https://doi.org/10.24406/publica-456

Albrecht, S., Brandstetter, P., Beck, T., Fullana-i-Palmer, P., Grönman, K., Baitz, M., Deimling, S., Sandilands, J., & Fischer, M. (2013). An extended life cycle analysis of packaging systems for fruit and vegetable transport in Europe. The International Journal of Life Cycle Assessment, 18(8), 1549-1567. https://doi.org/10.1007/s11367-013-0590-4

Almasarwah, N., Abdelall, E., Suer, G., Egilmez, G., Singh, M., & Ramadan, S. (2023). Pallet loading optimization considering storage time and relative humidity. Journal of Industrial Engineering and Management, 16(2), 453-471. https://doi.org/10.3926/jiem.4613

Castellani, F., Aigner, J., & Berglykke Aagaard, S. (2022). Comparative life cycle assessment (LCA): Packaging solutions for the food segment (Technical report prepared for the European Federation of Corrugated Board Manufacturers). Ramboll. Retrieved January 18, 2026, from https://cccabox.org/pdfs/FEFCO-LCA-2022-Ramboll-Study.pdf

Coelho, P. M., Corona, B., ten Klooster, R., & Worrell, E. (2020). Sustainability of reusable packaging: Current situation and trends. Resources, Conservation & Recycling: X, 6, Article 100037. https://doi.org/10.1016/j.rcrx.2020.100037

COMIECO (2023). 28° rapporto annuale sulla raccolta differenziata e riciclo di carta e cartone in Italia: Dati 2022. Consorzio Nazionale Recupero e Riciclo degli Imballaggi a Base Cellulosica. Retrieved January 20, 2026, from https://www.comieco.org/downloads/16585/9351/COMIECO_28%20Rapporto_dati%20anno%202022.pdf

Comité National Routier. (2021). The Italian road freight transport sector: 2021. Comité National Routier. Retrieved January 22, 2026, from https://www.cnr.fr/en/italian-road-freight-transport-sector-2021

COREPLA. (2023). Relazione sulla gestione 2022. Consorzio Nazionale per la Raccolta, il Riciclo e il Recupero degli Imballaggi in Plastica. Retrieved January 24, 2026, from https://www.corepla.it/wp-content/uploads/2024/06/corepla_relazione_sulla_gestione_2022__0-4-1.pdf

Corrugated Packaging Alliance, & Quantis. (2019). Life cycle assessment of corrugated containers and reusable plastic containers (RPCs) used for produce transport, storage and display in the U.S. Corrugated Packaging Alliance. Retrieved January 26, 2026, from https://www.fibrebox.org/assets/2023/05/CPA_Comparative_LCA_Quantis.pdf

IN PRESS

CPR System. (2023). Products. Retrieved January 29, 2026, from https://www.cprsystem.it/en/products/

Del Borghi, A., Parodi, S., Moreschi, L., & Gallo, M. (2021). Sustainable packaging: An evaluation of crates for food through a life cycle approach. The International Journal of Life Cycle Assessment, 26(4), 753-766. https://doi.org/10.1007/s11367-020-01813-w

Desole, M. P., Gisario, A., Fedele, L., Aversa, C., & Barletta, M. (2024). Life cycle assessment of secondary packaging: Expanded polystyrene versus bioplastic-coated corrugated cardboard. Sustainable Production and Consumption, 46, 11-28. https://doi.org/10.1016/j.spc.2024.02.010

Deviatkin, I., Khan, M., Ernst, E., & Horttanainen, M. (2019). Wooden and plastic pallets: A review of life cycle assessment (LCA) studies. Sustainability, 11(20), Article 5750. https://doi.org/10.3390/su11205750

Dokl, M., Copot, A., Krajnc, D., Fan, Y. V., Vujanović, A., Aviso, K. B., Tan, R. R., Kravanja, Z., & Čuček, L. (2024). Global projections of plastic use, end-of-life fate and potential changes in consumption, reduction, recycling and replacement with bioplastics to 2050. Sustainable Production and Consumption, 51, 498-518. https://doi.org/10.1016/j.spc.2024.09.025

Esmaeeli, A., & Sarrafzadeh, M.-H. (2023). Reducing freshwater consumption in pulp and paper industries using pinch analysis and mathematical optimization. Journal of Water Process Engineering, 53, Article 103646. https://doi.org/10.1016/j.jwpe.2023.103646

European Commission, Joint Research Centre, Institute for Environment and Sustainability. (2010). International Reference Life Cycle Data System (ILCD) handbook: General guide for life cycle assessment—Detailed guidance (EUR 24708 EN). Publications Office of the European Union. https://doi.org/10.2788/38479

European Environment Agency. (2023). EMEP/EEA air pollutant emission inventory guidebook 2023: Technical guidance to prepare national emission inventories (EEA Report No. 06/2023). Publications Office of the European Union. https://doi.org/10.2800/795737

European Parliament and Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. Official Journal of the European Union, L 312, 3-30. https://eur-lex.europa.eu/eli/dir/2008/98/oj/eng

European Parliament and Council of the European Union. (2018). Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. Official Journal of the European Union, L 150, 109-140. https://eur-lex.europa.eu/eli/dir/2018/851/oj/eng

European Parliament and Council of the European Union. (2025). Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 December 2024 on packaging and packaging waste, amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904, and repealing Directive 94/62/EC. Official Journal of the European Union, L, 2025/40.

Ferrara, C., De Feo, G., & Picone, V. (2021). LCA of glass versus PET mineral water bottles: An Italian case study. Recycling, 6(3), Article 50. https://doi.org/10.3390/recycling6030050

Franklin Associates. (2022). Cradle-to-gate life cycle analysis of general purpose polystyrene (GPPS) resin. American Chemistry Council. Retrieved February 1, 2026, from https://www.americanchemistry.com/content/download/10598/file/Cradle-to-Gate-Life-Cycle-Analysis-of-General-Purpose-Polystyrene-Resin.pdf

Gao, S., Ren, P., Yao, J., Zhou, H., Gustavsson, M., & Wu, C. (2026). LCA studies of fruit and vegetables production, storage and transportation using different packagings in consideration of food waste and energy consumption. Biomass and Bioenergy, 208, Article 108702. https://doi.org/10.1016/j.biombioe.2025.108702

Garcia-Arca, J., Comesaña-Benavides, J. A., Gonzalez-Portela Garrido, A. T., Prado-Prado, J. C., & Garrido, A. T. G. P. (2021). Methodology for the selection of packaging alternatives: An application of "action research" in the industrial sector. Central European Journal of Operations Research, 29, 1427-1446. https://doi.org/10.1007/s10100-020-00724-3

Geier, J., Bredács, M., Witschnigg, A., Vollprecht, D., & Oreski, G. (2024). Analysis of different polypropylene waste bales: Evaluation of the source material for PP recycling. Waste Management & Research, 42(9), 767-775. https://doi.org/10.1177/0734242X241227369

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), Article e1700782. https://doi.org/10.1126/sciadv.1700782

Hallberg, L., Andersson, S., & Nellström, M. (2023). Life cycle assessment of closed loops for industrial plastic packaging: EPS packaging, PP big bags and LDPE-film (Report C 779). IVL Swedish Environmental Research Institute. Retrieved February 3, 2026, from https://www.diva-portal.org/smash/get/diva2:1794419/FULLTEXT01.pdf

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe 2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. The International Journal of Life Cycle Assessment, 22(2), 138-147. https://doi.org/10.1007/s11367-016-1246-y

INFIA. (2014). Technical data sheet: CFR245 h 65 PP C. Retrieved February 4, 2026, from https://www.infia.it/Public/Pdf/CFR245%20h%2065%20PP%20C%20%28SPT4.3.%20139%20REV%201%2020140429%29%20EN.pdf

International Organization for Standardization. (2006a). ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework. ISO.

International Organization for Standardization. (2006b). ISO 14044:2006 Environmental management—Life cycle assessment—Requirements and guidelines. ISO.

Jiang, X., & Bateer, B. (2025). A systematic review of plastic recycling: Technology, environmental impact and economic evaluation. Waste Management & Research, 43(8), 1159-1178. https://doi.org/10.1177/0734242X241310658

Kellner, F., & Otto, A. (2012). Allocating CO emissions to shipments in road freight transportation. Journal of Management Control, 22(4), 451-479. https://doi.org/10.1007/s00187-011-0143-6

Khan, M. M. H., Deviatkin, I., Havukainen, J., & Horttanainen, M. (2021). Environmental impacts of wooden, plastic, and wood-polymer composite pallet: A life cycle assessment approach. The International Journal of Life Cycle Assessment, 26, 1607-1622. https://doi.org/10.1007/s11367-021-01953-7

Krieg, H., Gehring, F., Fischer, M., & Albrecht, S. (2018). Carbon footprint of packaging systems for fruit and vegetable transports in Europe: Final report. Fraunhofer Institute for Building Physics IBP. Retrieved February 6, 2026, from https://www.stiftung-mehrweg.de/fileadmin/user_upload/SIM_CF_Final_report_for_publication.pdf

Levi, M., Cortesi, S., Vezzoli, C. A., & Salvia, G. (2011). A comparative life cycle assessment of disposable and reusable packaging for the distribution of Italian fruit and vegetables. Packaging Technology and Science, 24(7), 387-400. https://doi.org/10.1002/pts.946

Lupi, G., Accorsi, R., Battarra, I., & Manzini, R. (2024). Life cycle assessment of reusable plastic containers throughout the fruit and vegetables supply chain. IFAC-PapersOnLine, 58(19), 451-456. https://doi.org/10.1016/j.ifacol.2024.09.253

Mahmoudi, M., & Parviziomran, I. (2020). Reusable packaging in supply chains: A review of environmental and economic impacts, logistics system designs, and operations management. International Journal of Production Economics, 228, Article 107730. https://doi.org/10.1016/j.ijpe.2020.107730

Marmora, G., Ferrara, C., Roselli, V., & De Feo, G. (2026). A comparative life cycle assessment of conventional and reusable packaging systems under alternative logistic configurations. Recycling, 11(1), Article 13. https://doi.org/10.3390/recycling11010013

Merrild, H., Damgaard, A., & Christensen, T. H. (2008). Life cycle assessment of waste paper management: The importance of technology data and system boundaries in assessing recycling and incineration. Resources, Conservation and Recycling, 52(12), 1391-1398. https://doi.org/10.1016/j.resconrec.2008.08.004

Mondello, G., Salomone, R., Ioppolo, G., Saija, G., Sparacia, S., & Lucchetti, M. C. (2017). Comparative LCA of alternative scenarios for waste treatment: The case of food waste production by the mass-retail sector. Sustainability, 9(5), Article 827. https://doi.org/10.3390/su9050827

Nolanplastica. (2023). Film estensibili in LLDPE / LLDPE stretch films. Retrieved February 8, 2026, from https://nolanplastica.it/wp-content/uploads/2023/04/FilmEstensibiliInLLDPE_v01-1.pdf

OECD. (2022). Global plastics outlook: Economic drivers, environmental impacts and policy options. OECD Publishing. https://doi.org/10.1787/de747aef-en

Pålsson, H., & Hellström, D. (2016). Packaging logistics in supply chain practice: Current state, trade-offs and improvement potential. International Journal of Logistics Research and Applications, 19(5), 351-368. https://doi.org/10.1080/13675567.2015.1115472

IN PRESS

Pålsson, H., & Olsson, J. (2023). Current state and research directions for disposable versus reusable packaging: A systematic literature review of comparative studies. Packaging Technology and Science, 36(6), 391–409. https://doi.org/10.1002/pts.2722

Perugini, F., Mastellone, M. L., & Arena, U. (2005). A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. Environmental Progress, 24(2), 137-154. https://doi.org/10.1002/ep.10078

Plastic Soup Foundation. (2025). Plastic facts & figures. Retrieved February 10, 2026, from https://www.plasticsoupfoundation.org/en/plastic-facts-and-figures/

PlasticsEurope. (2022, October). Plastics—The facts 2022: An analysis of European plastics production, demand, conversion and end-of-life management. Retrieved February 12, 2026, from https://plasticseurope.org/wp-content/uploads/2022/10/PE-PLASTICS-THE-FACTS_V7-Tue_19-10-1.pdf

PlasticsEurope. (2024). Plastics—The fast facts 2024. Retrieved February 10, 2026, from https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2024/

Plastic Packaging S.r.l. (2023). PSA/PSO 304009: Plastic crate for fruit and vegetables. Retrieved February 10, 2026, from https://plasticpackaging.it/prodotti/psapso-304009

PRé Sustainability B.V. (2024). SimaPro 9.6 LCA software. Amersfoort, The Netherlands.

Polruang, S., Asokbunyarat, V., Bouthong, P., Rizqa, F., & Somprasong, A. (2025). Simulated environmental weathering of expanded polystyrene foam and polypropylene under UV and wave agitation. Scientific Reports, 15, Article 38649. https://doi.org/10.1038/s41598-025-22367-7

Ponsioen, T. C., Vieira, M. D. M., & Goedkoop, M. J. (2014). Surplus cost as a life cycle impact indicator for fossil resource scarcity. The International Journal of Life Cycle Assessment, 19, 872-881. https://doi.org/10.1007/s11367-013-0676-z

Rigamonti, L., Ferreira, S., Grosso, M., & Marques, R. C. (2015). Economic-financial analysis of the Italian packaging waste management system from a local authority's perspective. Journal of Cleaner Production, 87, 533–541. https://doi.org/10.1016/j.jclepro.2014.09.069

Rodrigues, P. M., & Esteves da Silva, J. (2024). Towards a circular economy: A comprehensive policy framework for packaging waste management in the European Union. Detritus, 29, 4-14. https://doi.org/10.31025/2611-4135/2024.19442

Tkaczyk, S., Drozd, M., Kędzierski, Ł., & Santarek, K. (2021). Study of the stability of palletized cargo by dynamic test method performed on laboratory test bench. Sensors, 21(15), Article 5129. https://doi.org/10.3390/s21155129

Tonini, D., Albizzati, P. F., Caro, D., De Meester, S., Garbarino, E., & Blengini, G. A. (2022). Quality of recycling: Urgent and undefined. Waste Management, 146, 11-19. https://doi.org/10.1016/j.wasman.2022.04.037

Tua, C., Biganzoli, L., Grosso, M., & Rigamonti, L. (2019). Life cycle assessment of reusable plastic crates (RPCs). Resources, 8(2), Article 110. https://doi.org/10.3390/resources8020110

USDA Foreign Agricultural Service. (2017). 2017 Apple Report – Revised: Korea, Republic of. GAIN Report No. KS1733. United States Department of Agriculture, Foreign Agricultural Service.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. The International Journal of Life Cycle Assessment, 21(9), 1218-1230. https://doi.org/10.1007/s11367-016-1087-8

Wikström, F., Williams, H., Verghese, K., & Clune, S. (2014). The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies: A neglected topic. Journal of Cleaner Production, 73, 100-108. https://doi.org/10.1016/j.jclepro.2013.10.042

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