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Defining Critical Evaluation Criteria for Sustainable and Intelligent Packaging in the Cold Supply Chain of the Fruit and Vegetable Industry

Svetlana Dabic-Miletic*

Faculty of Transport and Traffic Engineering, University of Belgrade, 11000 Belgrade, Serbia

* Correspondence: Svetlana Dabić-Miletić (cecad@sf.bg.ac.rs)

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Abstract: Growing consumer awareness and increasingly stringent regulatory frameworks have intensified the demand for sustainable and intelligent packaging solutions within the fruit and vegetable industry. Packaging serves not only as a means of preserving product freshness, extending shelf life, and reducing food waste but also as a determinant of environmental and economic performance across cold supply chain (CSC) operations. Within this context, packaging exerts a direct influence on carbon emissions, waste management efficiency, operational costs, and social acceptance, thereby positioning it as a pivotal component in sustainability-oriented supply chain strategies. However, the selection of packaging solutions remains complex, as decision-makers must reconcile environmental responsibility, economic feasibility, technical functionality, and societal expectations. To address this challenge, the importance of defining critical evaluation criteria has been investigated. A preliminary framework comprising twelve key elements has been developed through an integration of literature review, industry practices, and stakeholder consultation. This framework is intended to provide a systematic basis for the assessment of sustainable and intelligent packaging, ensuring that decision-making processes are guided by balanced and transparent considerations. Emphasis is placed on the necessity of continuous engagement of stakeholders from both the packaging and agricultural sectors, as well as on iterative refinement of the criteria through empirical validation and the incorporation of emerging knowledge. Such an approach is expected to foster the advancement of packaging systems that enhance environmental stewardship, cost-effectiveness, technological adaptability, and social relevance, thereby reinforcing the long-term resilience and performance of the CSC in the fruit and vegetable sector.

Keywords: Fruit and vegetable industry; Smart packaging; Cold supply chain (CSC), Sustainability, Criteria

1. Introduction

Fruits and vegetables are essential components of a healthy diet, providing vital nutrients such as vitamins, minerals, dietary fiber, and antioxidants that contribute to disease prevention and overall well-being. A diet rich in fruits and vegetables is widely recommended to reduce the risk of chronic diseases, including cardiovascular disease, obesity, and certain types of cancer (Dilucia et al., 2020). As such, ensuring the availability and quality of these products is not only an economic imperative but also a public health priority. At the same time, packaging significantly contributes to environmental impacts, including resource consumption, carbon emissions, and waste generation (Brennan et al., 2020; Zuo et al., 2022). This dual role highlights the importance of selecting packaging solutions that not only meet functional requirements, such as protection, transportability, and extended shelf life, but also advance sustainability objectives (Sheibani et al., 2024). According to vulnerable market conditions, the fruit and vegetable industry is facing mounting pressure to adopt sustainable and smart packaging solutions that align with contemporary environmental, economic, and social demands (Zhang & Sablani, 2021). Packaging is not merely a protective layer for produce; it also plays a critical role in extending shelf life, reducing food waste, and maintaining product quality throughout increasingly complex and globalized supply chains (Azeredo & Correa, 2021). Sustainable and intelligent packaging can help balance the need for fresh, high-quality produce with the goal of reducing the environmental footprint associated with packaging production, use, and disposal (Drago et al., 2020; Sheibani et al., 2024).

More than 50% of fruits and vegetables are wasted in the CSC, so special attention must be paid to packaging (Zhang & Sablani, 2021). By integrating considerations of product quality, nutrition, and environmental responsibility, the fruit and vegetable industry can make significant strides toward supporting healthy diets while aligning with global sustainability goals. Packaging designs for fruits and vegetables often vary in composition and quantity, depending on the perishability of the food item, which contributes to the complexity and volume of plastic waste (Navarre et al., 2022). Many companies, such as Coca-Cola, Nestlé, and PepsiCo, have set targets to increase the use of recycled materials and reduce the share of virgin raw materials in packaging. Although consumer awareness is growing, a lack of trust and understanding of the role of packaging in preventing food waste remains an obstacle. Also, 50 % of award-winning packaging innovations never reach the market, indicating a gap between theoretical solutions and real-world implementation, which is a particular challenge for fruit and vegetable packaging, which already has significant losses (Boz et al., 2020). However, decision-makers in the industry often face the challenge of balancing a diverse set of criteria when evaluating packaging alternatives (Azeredo & Correa, 2021). Economic considerations, such as unit cost and investment requirement, need to be weighed against ecological factors like carbon footprint and recyclability. Social aspects, including worker health and consumer acceptance, and technical dimensions, such as product compatibility and durability, further complicate the selection process (Brennan et al., 2020; Navarre et al., 2022). Recognizing this complexity, it becomes essential to define a clear set of evaluation criteria that can guide systematic assessment and ranking of sustainable and intelligent packaging options.

This study aims to address this need by developing an initial set of critical evaluation criteria for packing selection in the fruit and vegetable industry, structured into a comprehensive, multi-dimensional framework. Based on thorough literature reviews, industry guidelines, and stakeholder feedback, the suggested criteria take into account technical, social, ecological, and economic factors, enabling a comprehensive approach to decision-making. By establishing this foundation, the study seeks to support the industry's transition toward packaging solutions that meet sustainability goals while ensuring product quality, supply chain efficiency, and consumer satisfaction.

2. Packaging Importance in Food Quality

Each year, the amount of food lost and wasted worldwide continues to increase. Approximately 1.5 billion tons of food are wasted globally every year, which refers to the loss of food in both quality and quantity throughout various stages of the supply chain, including production, post-harvest handling, and processing (Chen et al., 2020). It's essential to recognize that food loss also means a waste of vital resources, such as water, land, and energy. Financially, the costs related to food waste management amount to about $700 billion in developed countries and $300 billion in developing ones (Drago et al., 2020; Râpă et al., 2024). The growing volume of waste has become a serious burden for governments worldwide. Typically, such waste is disposed of via landfilling or incineration, as these remain the most affordable and accessible methods for most municipalities (Boz et al., 2020; Dilucia et al., 2020). However, this approach is increasingly problematic, leading to reduced landfill space, leachate formation, biogas emissions, and the uncontrolled release of methane, all of which significantly contribute to climate change.

Fruits and vegetables are among the most consumed foods globally, yet they also account for a significant portion of food waste. According to the Food and Agriculture Organization (FAO, 2019), approximately 14% of food is lost post-harvest, while the United Nation (2021) reports that 931 million tons of food waste are generated annually. Fruits and vegetables contribute approximately 16% of this waste, which is responsible for around 6% of global greenhouse gas emissions (Râpă et al., 2024). Fruit and vegetable waste also includes non-edible parts such as peels, seeds, and pulp, which, due to their natural properties, such as biodegradability and low cost, have the potential for further use (Sheibani et al., 2024).

Fruit and vegetable by-products are often redirected for use as animal feed or repurposed in the production of biomaterials, biofuels, biogas, platform chemicals, and biofertilizers, typically through biological techniques like fermentation or bio-electrogenesis (Brennan et al., 2020; Navarre et al., 2022). Additionally, they can serve as feedstock for lactic acid production, which is useful in the food, chemical, and pharmaceutical industries and is also used to create polylactic acid (PLA) (Zhang & Sablani, 2021). Commonly, food by-products have great potential for reuse because they are rich in naturally occurring bioactive compounds like simple sugars (e.g. glucose, fructose), dietary fibers, carbohydrates, pectin, polysaccharides, and important micronutrients such as phenolic acids, carotenoids, flavonoids, tocopherols, vitamins, and aromatic substances. These are valued in human nutrition due to their antioxidant and antiviral effects (Linke & Geyer, 2013; Râpă et al., 2024).

Packaging plays a critical role in shaping consumer purchasing behavior, particularly in the context of fresh fruits and vegetables (Azeredo et al., 2021; Brennan et al., 2020). Within the CSC, packaging serves as a protective barrier that maintains product integrity while also influencing visual appeal and perceived freshness at the point of sale. Functional and visually appealing packaging that preserves organoleptic characteristics such as texture, color, aroma, and taste can significantly enhance consumer trust and satisfaction (Brennan et al., 2020; Dilucia et al., 2020).

Innovative packaging technologies that incorporate natural bioactive compounds such as antioxidants and antimicrobials help extend shelf life and preserve nutritional and sensory quality during transportation and storage. These solutions are especially important for perishable products, where rapid quality degradation can occur after harvest (Boz et al., 2020; Zuo et al., 2022).

However, despite these benefits, conventional plastic packaging materials derived from fossil resources remain a major environmental concern. Poor end-of-life management results in substantial leakage of plastic into the environment, and current recycling rates remain low, with only around 10% of plastic packaging being recycled (Navarre et al., 2022). This challenge is particularly pressing in the fruit and vegetable sector, where maintaining product quality under cold chain conditions further complicates the selection of sustainable packaging alternatives (Zhang & Sablani, 2021).

The use of advanced or biodegradable packaging materials can also impact the final price of the product, creating tension between sustainability, functionality, and affordability (Drago et al., 2020). Achieving a balance among these factors is critical to ensuring consumer acceptance and market competitiveness. At the same time, increasing ecological awareness among consumers has led to a shift in expectations toward environmentally responsible products (Brennan et al., 2020). Packaging solutions made from renewable resources or food industry by-products support circular economy principles and promote waste valorization. These approaches not only reduce environmental impact but also contribute to improved brand image and consumer loyalty.

In summary, the use of bio-based and intelligent packaging materials, particularly those derived from fruit and vegetable processing residues, offers a promising direction for more sustainable and consumer-focused packaging systems. This is especially relevant in the fresh produce sector, where both visual presentation and preservation performance are essential for success in a highly sensitive and competitive market environment.

3. Key Challenges in Fruit and Vegetable Packaging

Packaging of fruits and vegetables presents a complex set of challenges driven by the unique biological characteristics of these products, as well as by the evolving demands of consumers, retailers, and regulatory frameworks (Zhang & Sablani, 2021). One of the most critical challenges lies in preserving product freshness, nutritional value, and sensory quality throughout extended and often globalized supply chains. Fruits and vegetables are highly perishable, with short shelf lives and sensitivity to environmental conditions such as temperature, humidity, and ethylene exposure. They are particularly vulnerable to moisture loss, microbial spoilage, mechanical damage, and oxidative degradation during handling, storage, and transportation (Dilucia et al., 2020). To mitigate these risks, many supply chains rely on the CSC as a temperature-controlled network developed to maintain optimal conditions from harvest to point of sale. However, maintaining the CSC is resource-intensive and vulnerable to disruptions, especially in regions with inadequate infrastructure or high energy costs. Any disruption in the CSC can significantly reduce product quality and shelf life, increasing waste and economic losses. In addition, seasonality indicates logistical and packaging challenges (Brennan et al., 2020; Zuo et al., 2022). The supply of multiple fruits and vegetables is seasonal, while consumer demand remains relatively constant throughout the year. This mismatch often requires long-distance imports, extended storage periods, or processing, all of which increase the complexity of packaging requirements in terms of durability, protective properties, and environmental impact. Moreover, cultural differences in consumption patterns affect packaging needs and design. For example, preferences for bulk versus pre-packaged produce, organic versus conventional labeling, or plastic-free versus convenience-oriented solutions vary widely across countries and consumer segments (Sheibani et al., 2024). These variations require packaging systems to be adaptable to local market expectations, food habits, and sustainability requirements, further complicating standardization and production (Boz et al., 2020).

Research suggests that fruit and vegetable waste can play a key role in shaping more sustainable packaging choices, especially within the context of environmental impact and resource efficiency. A study conducted in the United States for the period 1970 to 2017 found that vegetable waste was five times greater than that of cereals and twice as high as that of fruit, underlining the urgent need to prioritize vegetable waste reduction (Râpă et al., 2024). These findings highlight the disproportionately high loss rates associated with perishable crops, which not only contribute to environmental degradation but also lead to substantial economic losses across the supply chain.

In terms of environmental footprint, vegetable waste alone was responsible for approximately 50% of the total CO_2 emissions and around 30% of water consumption related to food waste. By comparison, cereals accounted for over 30% of emissions and roughly 50% of water use, while fruit contributed around 20% of emissions and 25% of water use (Râpă et al., 2024). These figures point to the critical importance of addressing fruit and vegetable waste through improved preservation strategies and resource-conscious packaging solutions.

Beyond the environmental implications, fruit and vegetable waste also results in significant financial losses for producers, retailers, and consumers (Brennan et al., 2020). Losses occur at multiple stages, including picking, processing, transportation, warehousing, and retail, with inadequate packaging frequently cited as a contributing factor. As such, integrating food waste reduction goals into packaging design not only supports sustainability targets but also enhances economic efficiency (Azeredo & Correa, 2021). Utilizing by-products from fruit and vegetable processing for packaging production represents a promising strategy for valorizing waste streams while contributing to circular economy principles (Linke & Geyer, 2013). This approach has the potential to reduce dependency on conventional raw materials, minimize environmental impact, and create added value from agricultural residues that would otherwise go unused.

In light of these challenges, packaging needs to function as more than a passive barrier. Packaging requires becoming an active enabler of food quality, CSC efficiency, and environmental responsibility, tailored to the specific needs of perishable produce and diverse global markets. One of the major challenges involves environmental sustainability. Plastic food packaging for fruits and vegetables is a major contributor to ocean plastic pollution, especially when exported to countries with weak waste infrastructure (Navarre et al., 2022). Traditional packaging materials, such as single-use plastics, often end up in landfills or oceans, contributing to pollution and greenhouse gas emissions. Finding alternatives that balance protective functions with recyclability, compostability, or biodegradability is essential but remains a technical and economic challenge. Economic considerations are also central to packaging decisions (Zhao et al., 2022). Newer, more sustainable or intelligent packaging solutions often come at a higher cost compared to conventional options, posing barriers to adoption, especially for small and medium-sized enterprises (Chen et al., 2020). Ensuring that packaging remains cost-effective while meeting performance and regulatory standards is a persistent challenge for producers and distributors.

In addition, regulatory compliance adds another layer of complexity, as packaging must often adhere to national and international standards related to food safety, labeling, and environmental impact. The lack of detailed data on fruit and vegetable packaging waste hampers the development of targeted innovations and policies aimed at reducing marine plastic debris from this sector (Navarre et al., 2022). Keeping up with evolving regulations and ensuring that packaging solutions meet both legal and market requirements requires significant effort and coordination. Finally, consumer expectations are increasingly shaping packaging choices. Today's consumers demand not only freshness and convenience but also packaging that aligns with their values regarding health, sustainability, and waste reduction (Brennan et al., 2020). Consequently, packaging requires a balance of functionality with aesthetic appeal, ease of use, and sustainability compliance, while maintaining or enhancing product quality. These challenges highlight the need for integrated, multi-criteria decision-making approaches that can support the fruit and vegetable industry in navigating the reciprocations between product protection, environmental responsibility, cost efficiency, and consumer satisfaction.

4. Sustainable Packaging Alternatives for Fruits and Vegetables

In light of increasingly uncompromising regulations and growing environmental awareness, selecting sustainable packaging for fruits and vegetables has become essential to reducing ecological impact. This chapter exemplifies common fruits and vegetables packaging alternatives, focusing on the importance of their applications in the sustainable CSC. By outlining these alternatives, it lays the groundwork for understanding their respective advantages, drawbacks, challenges, and limitations in fruit and vegetable packaging practice.

1. Compostable packaging made from plant-based starch (PLA)–packaging made from vegetable starches, most often polylactic acid, is an environmentally friendly option because it is biodegradable and can be composted under industrial conditions. The advantage is that it is produced from renewable sources, such as cornstarch or sugarcane, which reduces dependence on fossil fuels. However, this material is often more expensive than conventional plastics, which can affect the price of the final product. Also, PLA has a lower resistance to moisture and heat, which can limit its use for certain products, especially those that require long-term protection or storage in humid conditions. Another challenge is that PLA decomposes in nature only under specific industrial composting conditions, so it can remain intact in home compost or in landfills for a long time, which somewhat reduces its effectiveness as a sustainable solution (Zhang & Sablani, 2021).

2. Recycled Polyethylene Terephthalate packaging (rPET) - recycled PET packaging uses existing plastic, which directly reduces the need for new plastic raw materials and reduces waste. This option is more sustainable in terms of the circular economy, as it helps in recycling and reducing plastic waste. The advantage is a relatively low price and good resistance to moisture and mechanical damage, which makes it suitable for a wide range of products. However, although recycled PET is a better choice than new, it is still plastic, and degradation can take decades under natural conditions, posing a long-term environmental challenge. In addition, the quality of recycled material can vary, and the recycling process requires additional energy and infrastructure. Limitations include the fact that PET cannot be endlessly recycled because it loses its properties over time (Rasines et al., 2024).

3. Reusable plastic crates (RPC) - reusable plastic boxes are a very effective packaging solution in closed supply chains, especially in the fruit, vegetable, and beverage sector. The advantage is that they can be used hundreds of times, which significantly reduces the total amount of waste and the need for disposable packaging. RPC systems

support the circular economy and can contribute to significant savings in the long term. However, this system requires complex logistics, including collection, washing, disinfection, and storage of boxes, which can be expensive and require additional resources and infrastructure. Also, cooperation between manufacturers, distributors, and retail chains is needed for this model to be successful. Challenges are also related to maintaining hygiene and quality of boxes during repeated use, as well as the need to standardize dimensions and capacities to facilitate transport and storage (Abejón et al., 2020).

4.1. Criteria Specifying

Specifying criteria for selecting alternative packaging for fruits and vegetables is essential for the sustainability of CSC, as it enables knowledgeable, objective, and sustainable decision-making in a complex environment shaped by ecological, economic, technical, and social demands. Packaging must fulfill multiple functions, including protecting the product, extending shelf life, ensuring logistical efficiency, and appealing to consumers, while minimizing environmental impact (Rodriguez et al., 2024; Zhao et al., 2022). Clear criteria allow for the balanced evaluation of options across dimensions such as cost-effectiveness, recyclability, and carbon footprint. They also reduce subjectivity and conflicts of interest among stakeholders, including producers, retailers, consumers, and regulators, by providing a transparent decision-making framework (Dladla & Workneh, 2023). Additionally, appropriate packaging tailored to specific produce types helps reduce food waste and improve resource efficiency. As environmental regulations tighten and consumer awareness grows, criteria ensure sustainability compliance and alignment with market trends. Furthermore, structured criteria assessment supports innovation, encouraging the adoption of smart, biodegradable, or active packaging solutions and enabling strategic, evidence-based planning. Without such criteria, packaging decisions risk being random, short-term, and driven solely by cost, undermining efforts toward a sustainable and intelligent packaging system for the fruit and vegetable industry. Table 1 offers some of the key criteria that are essential for sustainable decision-making and highly relevant from a practical standpoint when selecting alternative packaging for fruits and vegetables.

Table 1. Selected key criteria for ranking packaging alternatives

Criterion	Type	Unit	PLA	rPET	PRC	Weight (%)
Cost per unit	Economy	€/kg product	0.3	0.25	0.2	10
Investment fees	Economy	,000 €/	200	150	100	5
Return of investments (RoI)	Economy	Years	4	3	2	5
Carbon footprint	Environmental	kg CO_2/ton product	50	70	40	10
Recyclability	Environmental	Score (1-5)	4	5	5	10
Waste reduction level	Environmental	% reduction	80	50	60	10
Employee suitability	Social	Score (1–5)	4	4	5	5
Consumer acceptance	Social	Score (1–5)	4	4	3	5
Job potential	Social	New jobs	15	10	20	5
Impact on quality	Technical	% spoilage reduction	10	5	15	10
Durability	Technical	Score (1–5)	3	4	5	10
Compatibility with logistics	Technical	Score (1–5)	3	4	5	10

The "Weight" column represents the estimated relative importance of each criterion within the overall evaluation framework. The weights shown in the table are examples meant to illustrate the structure of a Multi-Criteria Decision-Making (MCDM) tool. In real applications, assigning weights involves input from stakeholders such as packaging engineers, CSC managers, sustainability experts, and consumers (Chen et al., 2020; Rodriguez et al., 2024). Their views and priorities are collected through surveys, workshops, or structured decision-making methods such as the Analytic Hierarchy Process (AHP), which uses pairwise comparisons to determine relative importance. For example, a company focused on reducing carbon emissions may assign a higher weight to the carbon footprint criterion, while a company focused on reducing expenses may place more weight on cost-related criteria.

The values in the table (such as 0.30 €/kg of product for unit cost or 200,000 € for implementation costs) are provided as examples. These values are not based on real data but are intended to guide users in identifying the types of information needed for evaluation. In practice, these values would come from a variety of sources, some of which are:

• Cost per unit might be calculated based on supplier quotations, previous procurement data, or market surveys.

• Investment costs could be derived from project proposals, feasibility studies, or supplier contracts for new packaging equipment or materials.

• Carbon footprint values often come from Life Cycle Assessments (LCAs) or databases, where data on raw materials, manufacturing, transport, and end-of-life treatment are compiled.

• Social and technical criteria (such as job creation potential, worker health and safety, or spoilage reduction) might be estimated through case studies, interviews with industry experts, or published literature on packaging performance.

Expert assessments, standardized test results, or validated benchmarks typically form the basis of scoring systems (1–5) for criteria like recyclability and durability. These benchmarks may come from recognized standards organizations or peer-reviewed research studies that are adapted to the conditions of the research.

This evaluation table offers a comprehensive assessment of alternative sustainable packaging options for the fruit and vegetable industry by integrating economic, ecological, social, and technical criteria. It enables decision-makers to balance trade-offs and supports transparency through consistent evaluation (Dladla & Workneh, 2023; Sheibani et al., 2024). The flexibility to assign weights allows customization based on specific priorities, and the structure is compatible with MCDM methods. However, limitations include data availability, subjective weighting, and assumptions of linearity and independence between criteria. To improve reliability, it is recommended to use empirical data, engage stakeholders, apply sensitivity analysis, and consider advanced MCDM tools. Despite its constraints, the table provides a solid foundation for informed and transparent decision-making.

4.2. Regulatory Framework as Important Element in Fruit and Vegetable Packaging Selection

In addition to technical, economic, and environmental challenges, the packaging of fruits and vegetables must comply with increasingly stringent regulatory frameworks, both at the national and international levels. Regulations cover a wide range of areas, including food safety, materials in contact with food, and requirements related to packaging waste reduction and recycling (Zhao et al., 2022). In the European Union, for example, Regulation (EC) No 1935/2004 stipulates that materials intended to come into contact with food must not transfer their constituents into food in quantities that could endanger human health or alter the composition, taste, or odor of the food. The regulation also mandates full traceability of packaging materials throughout the CSC, placing additional responsibility on producers and distributors. Simultaneously, under the CEAP 2020, special attention is given to the Packaging and Packaging Waste Regulation (PPWR) related to the Packaging and Packaging Waste Directive (94/62/EC), which sets targets for recycling rates, promotes material minimization, and encourages the reuse of packaging (Cruz et al., 2020; European Union, 2020). The upcoming revisions to this directive are expected to introduce even stricter measures, including mandatory use of recycled content and bans on certain single-use plastic materials. At the national level, countries enforce additional rules, certification requirements (such as eco-labels and organic packaging standards), and labeling obligations. For producers operating across multiple markets, such regulation creates a complex compliance landscape requiring packaging solutions that meet multiple sets of legal criteria. In many regions at the global level, consumer information regulations also mandate that packaging include data on product origin, storage conditions, and usage instructions. In the context of sustainable and smart packaging, additional regulatory uncertainty exists about emerging technologies such as embedded sensors, QR codes, and biodegradable or compostable materials (Drago et al., 2020; Zuo et al., 2022). These innovations often fall into regulatory gray areas, with limited or evolving legal standards. As a result, regulatory compliance is a critical criterion in evaluating packaging alternatives to maintain consumer trust and ensure competitiveness in a highly regulated global marketplace.

While there is no globally binding directive that specifically regulates fruit and vegetable packaging in detail, the European Union remains the most advanced and comprehensive regulatory environment in this field. The EU Packaging and Packaging Waste Directive (94/62/EC), along with related laws like the Single-Use Plastics Directive and upcoming changes in the Packaging and Packaging Waste Regulation, focuses heavily on using packaging that is sustainable, recyclable, and reusable, especially for fresh produce (European Union, 2020). For the fruit and vegetable industry, this means that packaging must not only protect perishable goods through extended shelf life and reduced spoilage but also meet strict environmental criteria. Materials such as expanded polystyrene trays, PVC wraps, and multilayer plastics, commonly used in produce packaging, are increasingly discouraged or being phased out in favor of monomaterials, compostables, or fiber-based alternatives (Kaplinsky & Morris, 2018). The EU also enforces mandatory recycling targets and eco-design principles, pushing producers to consider packaging's full life cycle and post-consumer impact.

At the global level, there is no unified approach, but several influential frameworks offer guidance. The Basel Convention indirectly affects fruit and vegetable packaging through restrictions on plastic waste exports, while the ISO 18600 series provides voluntary standards for packaging optimization, recyclability, and compostability that are relevant for global produce exporters (Cruz et al., 2020). Moreover, the UN Sustainable Development Goals (SDG 12) promote reduced food and material waste, encouraging innovations in smart and sustainable packaging (Manzoor et al., 2024). Voluntary initiatives have also prompted major food producers and retailers to rethink their produce packaging strategies, prioritizing reusability and plastic reduction. Despite these efforts, Europe leads in terms of enforceable detail and technical implementation. Producers aiming to export fruits and vegetables to the

EU need to be carefully aligned with its packaging standards, not only to ensure compliance but also to meet growing consumer expectations for transparency, environmental responsibility, and food safety.

4.3. Economic Viability of Proposed Alternatives

Based on customer preferences, market trends, and how products are presented, shifting to more eco-friendly yet economically sustainable packaging in the fruit and vegetable industry requires a detailed analysis of the available options. It is essential to primarily consider costs, but also take into account environmental impact, social factors, and technical requirements (Brennan et al., 2020; Linke & Geyer, 2013). The discussion includes previously analyzed PLA, rPET, and PRC packaging solutions, using measurable economic factors like investment cost, ROI, payback period, and NPV to support estimating their overall sustainability performance. This discussion evaluates three packaging systems based on quantitative indicators (investment cost, ROI, payback period, and NPV in Table 2), providing a basis for the appropriate estimation of qualitative performance across more comprehensive sustainability dimensions.

Table 2. Economic indicators for comparing alternatives

Packaging Alternative	Initial Investment (€)	Estimated Ann. Net Benefit (€)	Payback Period (years)	ROI (3 years)
PLA (biodegradable)	200,000	80,000	2.5	20%
rPET (recycled PET)	150,000	65,000	2.31	30%
PRC (reusable plastic crates)	100,000	40,000	2.5	20%

$$Payback\ Period\ (year) = \frac{Initial\ Investments}{Annual\ Net\ Benefit} \tag{1}$$

$$ROI\ (year) = \frac{3 \times Annual\ Net\ Benefit - Initial\ Invesments}{Initial\ investments} \times 100\% \tag{2}$$

PLA presents a sustainable approach that aligns agreeably with evolving sustainability standards. Although it involves the highest upfront investment, the significant annual returns make it financially viable, yielding the greatest net present value over five years. Beyond profitability, its strategic advantage lies in anticipating stricter environmental policies and shifting consumer preferences. Environmentally, PLA is sourced from renewable materials like cornstarch and is industrially compostable, offering a low-carbon alternative to conventional plastics (Zhang & Sablani, 2021). However, its biodegradation is dependent on specific industrial composting conditions, which limit its effectiveness in areas lacking proper waste infrastructure. On the social front, PLA enjoys strong approval from eco-conscious consumers and enhances a brand's sustainable image, especially in high-end markets focused on natural, health-oriented, and environmentally friendly products (Drago et al., 2020; Râpă et al., 2024). Technically, it performs well in terms of appearance and barrier properties, but may be vulnerable to moisture and temperature changes, which can be problematic for long-distance transport or humid warehouse conditions. Nevertheless, its environmental credentials and market appeal make it an attractive choice for companies aiming to lead in sustainable innovation.

rPET packaging offers a practical and economically sound path toward more sustainable packaging solutions. With a moderate upfront cost and an annual net benefit, it provides the strongest short-term return on investment among the available alternatives. This financial advantage is further enhanced by its environmental value, regarding rPET being made from post-consumer plastic waste, minimizing the demand for new plastic and promoting circular economy practices. Although it is still derived from fossil-based sources and is not biodegradable, its high recyclability and reduced carbon emissions position it as a more sustainable and scalable choice (Rasines et al., 2024). On the social side, rPET is increasingly favored by consumers who support recycling and resource conservation, even though it may lack the "green" branding power of compostable options like PLA. From a technical perspective, rPET is durable, lightweight, and integrates well into current manufacturing and logistics systems (Abejón et al., 2020). It is especially suited for cold-chain transport and humid conditions, helping to maintain product integrity throughout the CSC. Overall, rPET provides a robust balance between cost-efficiency and environmental responsibility, making it an appealing solution for companies aiming to boost sustainability without major operational changes (Manzoor et al., 2024).

RPCs offer a promising and cost-efficient solution for businesses operating within closed-loop CSC. They require the lowest upfront investment and generate a stable yearly benefit, making them financially attractive, especially for companies that can establish effective reverse logistics. From an environmental perspective, RPCs stand out because they can be used multiple times, which considerably reduces single-use plastic and cuts down on overall packaging waste (Abejón et al., 2020). However, they do require regular washing and maintenance, which consumes water and energy that need to be taken into account in a full life-cycle assessment. On the social side, the sustainability benefits of these crates are most visible in business-to-business contexts and often go unnoticed by end consumers, allowing companies to meet sustainability goals and reduce manual handling and repackaging costs. Technically, RPCs provide essential protection for fragile produce, can be easily stacked for efficient transport, and fit well into automated handling systems (Cruz et al., 2020). The main limitation is the need for infrastructure that supports returning, cleaning, and redistributing the crates, which can be difficult to achieve across decentralized or export-focused CSCs. Even so, for companies with established distribution networks, reusable crates represent a practical and environmentally responsible packaging strategy.

The assessment of sustainable packaging systems for fruits and vegetables shows that each option offers its own set of advantages and limitations. When choosing a solution, it is important to consider economic feasibility, environmental impact, consumer acceptance, and technical requirements within the CSC.

PLA stands out as the most forward-thinking option because it is biodegradable, sourced from renewable materials, and aligns well with long-term sustainability goals and green market trends. Despite its higher initial cost and sensitivity to transport and storage conditions, it brings long-term benefits and strong branding value for companies targeting eco-conscious customers and export markets. rPET provides a practical and cost-effective alternative (Rasines et al., 2024). Made from recycled plastic, it benefits from a well-developed recycling infrastructure and solid performance, and it integrates easily into existing logistics. Although not biodegradable, its affordability and scalability make it a good choice for mainstream distribution and quick improvements in sustainability without disrupting operations. RPCs perform agreeably in closed-loop or regional CSC. They are highly durable, reduce single-use waste, and protect produce well, but they require established systems for collecting, washing, and redistributing crates. This can limit their practicality in more complex or decentralized distribution networks of CSC.

Based on the comparative analysis, some practical implications can be made for stakeholders in the fruit and vegetable packaging sector. Namely, companies aiming to position themselves as sustainability leaders or enter environmentally sensitive markets (e.g. EU export markets) should prioritize PLA despite its higher investment, as it offers greater long-term brand and market value. For producers and retailers seeking immediate and financially accessible improvements, rPET presents the most practicable solution due to its lower initial cost and compatibility with existing packaging lines (Rodriguez et al., 2024). However, logistics-intensive companies, cooperatives, and local distribution networks with established return systems may benefit most from implementing RPCs, especially in reducing physical damage and minimizing the use of single-use materials. Public policy measures such as subsidies, extended producer responsibility (EPR) schemes, and infrastructure development (e.g. composting facilities or reverse logistics networks) could further enhance the adoption of sustainable packaging alternatives (Dladla & Workneh, 2023). To facilitate optimal packaging selection, companies and the fruit and vegetable industry are encouraged to adopt multi-criteria decision-making tools such as AHP or TOPSIS, permitting estimation weighting of criteria based on specific company priorities or regulatory requirements.

In summary, while no single packaging solution is universally functional, a structured evaluation based on clearly defined sustainability criteria allows stakeholders to make informed decisions that balance environmental responsibility, economic performance, and technical feasibility. Future research should focus on empirical validation of criteria weights, lifecycle assessments, and stakeholder-centered design of packaging systems to support a more sustainable transition in the fruit and vegetable industry.

4.4 Analysis and Comparison of Sustainable Packaging Options for Fruits and Vegetables

The selection of an optimal sustainable packaging solution within the fruit and vegetable sector necessitates a nuanced, context-specific approach rather than a universal application. This process demands a rigorous assessment of critical criteria that directly impact both the operational viability and strategic benefits of each packaging alternative (Azeredo & Correa, 2021; Navarre et al., 2022). These criteria are interpreted as evidence-based recommendations that are customized to address the distinct requirements of producers, retailers, distributors, and exporters across CSC, focusing on variable customer demands.

Practical criteria provide a concise, descriptive framework to inform decision-making in real-world contexts. They enable stakeholders to qualitatively assess the advantages and disadvantages of alternatives based on intuitive factors such as cost, logistics, and sustainability. Typically, these criteria are not quantitatively weighted or scored but form the basis for context-driven recommendations aligned with business priorities. Conversely, MCDM criteria underpin formal decision-support methodologies, which require the assignment of explicit numerical weights and systematic evaluation of alternatives against predefined performance metrics (Dladla & Workneh, 2023; Rodriguez et al., 2024). The primary objective of MCDM approaches is to produce an objective ranking of options through rigorous mathematical analysis, particularly in scenarios involving multiple, often conflicting, decision objectives. In essence, practical criteria facilitate qualitative understanding and knowledgeable preference, whereas MCDM criteria enable quantitative evaluation and prioritized ranking. Accordingly, Table 3 recapitulates the main guidelines for specifying essential criteria in prioritizing sustainable fruit and vegetable packaging alternatives, taking into account the specific requirements for their practical use and implementation in the MCDM approach.

Table 3. Guidelines for defining criteria in practical and MCDA implementation

Aspect	Practical Criteria (Recommendation-Oriented)	MCDM Criteria (e.g., AHP, TOPSIS)
Purpose	Assist to compare options and guide real-world recommendations	Serve as input for formal decision-making models
Form	Qualitative and descriptive	Quantitative, often numerical with weights and scores
Weighting of criteria	Not explicitly defined; interpreted implicitly	Explicitly assigned (e.g., weight = 0.3, 0.2, etc.)
Flexibility	Suitable for quick assessment and communication	Suitable for in-depth analysis and modeling of complex trade-offs
Function	Provides guidance based on user type or business context	Mathematically supports objective ranking of alternatives
Typical users	Managers, producers, distributors (no modeling needed)	Analysts, researchers, decision-makers using analytical tools
Output	Practical suggestions (e.g., “if you are X, choose Y”)	Ranked list of alternatives based on total weighted score

Table 4. Comparative analysis of PLA, rPET, and PRC packaging alternatives across key practical criteria

Criteria	PLA (Bioplastic)	rPET (Recycled PET)	PRC (Reusable Packaging)
Initial investment	High	Low	Medium to High
Compatibility with existing lines	Limited (may require adaptation)	High	Medium (depends on system)
Environmental Impact (LCA)	Low (if composting system is in place)	Lower than virgin plastic	Very low (due to reuse)
Biodegradability	Yes (in industry)	No	No
Recyclability	Limited (depends on infrastructure)	Yes (widely accepted)	Yes (at end-of-life or if damaged)
Lifespan	Single-use	Single-use	Multi-use
Operational costs	Medium to High	Low	Low per unit (over time)
Export/EU market suitability	Yes (positive perception and regulations)	Yes (if properly labeled)	Depends on return logistics
Product protection	Limited	Satisfactory	Excellent
Logistics/Infrastructure needs	Composting facilities	Standard logistics	Reverse logistics, cleaning, storage
Most suitable for	Brand-driven & sustainability-focused firms	Companies seeking quick, low-cost improvements	Cooperatives, local distributors, logistics-heavy operations

Table 4 compares in detail three widely discussed packaging alternatives: PLA, rPET, and PRC, across a number of key practical criteria. These criteria include investment costs, environmental impact, and the ability to protect products, as well as logistical requirements. Understanding the interplay of these factors enables stakeholders to align their packaging decisions not only with specific operational needs but also with broader sustainability goals. Investment costs are often the first and most visible aspect when choosing packaging. PLA usually requires a larger initial investment, both in the procurement of materials and in eventual customized manufacturing processes. However, this type of packaging brings significant added value in terms of environmental friendliness, which is especially important for companies targeting regulated or environmentally conscious export markets. For them, investing in PLA can be justified and desirable because it not only enables compliance with stricter environmental norms but also strengthens the brand’s image as an environmentally responsible entity. On the other hand, rPET represents a compromise between viability and cost. As packaging made from recycled plastic, rPET reduces the need for new fossil resources and contributes to the circular economy. In addition to the environmental benefits, its cost and characteristics are similar to conventional plastics, allowing for easier integration into existing production and distribution chains without significant additional investment or adaptation. This makes rPET a suitable choice for companies that want to quickly and efficiently improve the sustainability of their products without disrupting existing operational flows or increasing costs. A third alternative, PRC, or reusable plastic boxes, brings a different set of advantages and challenges. This packaging is intended for multiple uses and is often part of closed logistics systems, where the packaging is collected, washed, and reused. Such a model significantly increases resource efficiency and reduces total waste but requires a developed logistics infrastructure, including the collection and systematic processing of packaging. Companies with complex CSC and pre-existing packaging management systems are agreeably positioned to take advantage of PRC solutions. They can significantly reduce operating costs in the long term through reusable packaging while reducing the environmental footprint. It is important to emphasize that the criteria from Table 4 can assist as a concrete decision-making basis that can be adapted to specific business contexts. For example, a company in a country with stricter environmental regulations and a clear intention to improve the relationship with customers may prefer PLA even with higher initial costs. Conversely, a company with a limited budget and the need to quickly transition to more sustainable solutions may choose rPET, while logistically complex operations with established packaging collection and a focus on the circular economy may benefit most from the introduction of RPC.

5. Conclusions

The fruit and vegetable sector faces unique packaging challenges due to product perishability, sensitivity to temperature and handling, and the need to preserve freshness. At the same time, growing demands to reduce plastic waste and carbon emissions add pressure to innovate. Balancing protection, recyclability, and cost is complex, especially across varied supply chains from local markets to global exports. Practical innovations such as biodegradable films, smart packaging with freshness indicators, and reusable crate systems are emerging to address these challenges. The importance of choosing sustainable packaging for fruit and vegetables is that it can reduce waste, conserve resources, and mitigate negative impacts on the environment. Consumers tend to prefer packaging made with natural additives over synthetic ones, as it is perceived as safer, more sustainable, and health-conscious, which in turn boosts market acceptance. Given the vast amount of fruit and vegetable by-products generated by the food industry, reusing them in packaging materials not only helps in reducing food waste but also contributes to innovation in the growing global plastic food packaging market, offering both environmental and economic benefits.

When selecting sustainable packaging for the fruit and vegetable sector, it is crucial to establish criteria that reflect the industry's specific needs and challenges. Under fluctuating market conditions, economic feasibility generally constitutes a key criterion for companies, considered in parallel with environmental impact, social sustainability, and product protection performance. Packaging solutions should safeguard highly perishable products sensitive to temperature and handling, while also contributing to the reduction of plastic waste and carbon emissions. Given the diversity of CSC, from local distribution to global exports, these criteria need to be flexible enough to accommodate different logistical and operational conditions.

Economic viability involves assessing initial investments, ongoing costs, and potential savings from improved efficiency and waste reduction. For instance, biodegradable materials like PLA offer strong environmental advantages and long-term brand benefits but come with higher upfront costs. On the other hand, recycled PET is a more affordable and scalable option that fits easily into existing systems. RPCs perform best in closed-loop CSC with established infrastructure but may be less practical for more dispersed or export-oriented networks. Therefore, defining sustainability criteria requires a balanced approach that weighs financial considerations alongside environmental performance and technical suitability. Packaging choices should support both sustainability goals and business profitability, enabling companies in the fruit and vegetable industry to meet market demands while maintaining operational efficiency and competitive advantage. Future research should focus on validating sustainability criteria, lifecycle analysis, and collaborative design involving producers, retailers, consumers, and policymakers. This inclusive approach is essential to develop packaging solutions that are both sustainable and practical for the industry's diverse needs.

The choice between PLA, rPET, and RPC packaging solutions is largely shaped by a company's specific operational context, strategic goals, and the characteristics of its CSC. PLA can drive product and brand innovation while enhancing a company's green image, making it particularly appealing in markets where environmental branding plays a decisive role. In contrast, rPET represents a more economically viable and easily scalable pathway to improved sustainability, offering a balance between environmental benefits and cost considerations. RPCs stand out as the most environmentally advantageous option, provided that reverse logistics systems are robust enough to support their repeated use and efficient return flows. Given these diverse attributes, economic feasibility becomes a central factor in the decision-making process, influencing companies to weigh initial capital investments, ongoing operational expenditures, and potential long-term savings. By carefully integrating economic analysis with environmental and market considerations, businesses can identify packaging strategies that not only align with sustainability objectives but also strengthen competitiveness and ensure resilience under varying market conditions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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