ROADMAP TO SUSTAINABLE FRESH PRODUCE PACKAGING

Aligning Functionality, Policy, and Market Demands

BACKGROUND

Packaging is critical to enabling the sustainability of fresh produce supply chains, from ensuring food safety and minimizing food loss and waste to mitigating material waste. Sustainable packaging for fresh produce must meet all functionality needs while remaining innovative, ensuring economic viability, and endeavoring to achieve increasingly sustainable outcomes.

The purpose of this roadmap is to identify and champion opportunities for the fresh produce industry; to pave the way for a cohesive, industry-wide shift to more functional, economical, and environmentally conscious packaging. Current incongruent regulatory and divergent market requirements pose a significant risk to fresh produce supply chains in that many fresh produce packaging alternatives do not consistently meet technical functionality needs and are not reliably accessible to the fresh produce industry.

Sustainable Produce Packaging Alignment (SPPA)

This roadmap was developed by the Sustainable Produce Packaging Alignment (SPPA) consortium, a diverse industry group committed to advancing scientifically sound, achievable, and sustainable fresh produce packaging guidelines for the fresh produce industry and retail partners throughout North America. Key drivers for undertaking the work plan include:

COMMITMENT TO SUSTAINABILITY:

Sustainable packaging requires optimizing both the functionality and environmental outcomes of the packaging throughout the full life of the packaging. The fresh produce industry is committed to continuous improvement towards sustainable outcomes, to include opportunities to reduce material, food loss and waste and (Greenhouse Gas) GHG emissions.

REGULATORY DISSONANCE:

Divergent national, state and provincial regulations regarding use of specific packaging materials at point of sale for fresh produce, including varying regulations and rules of international exports. Alignment on sustainability goals is needed to move forward congruently.

RAPIDLY EVOLVING POLICY DEPLOYMENT:

State and provincial legislatures are increasingly considering new policies and regulations for allowable packaging content and disposal. The ramp up to identify, improve, and deploy new packaging materials for fresh produce is a long cycle, therefore understanding the landscape and providing market-ready alternatives is critical.

CONFLICTING BUYER EXPECTATIONS AND OBJECTIVES:

Buyers are committing to increasingly wide-reaching packaging expectations without considering key challenges in packaging functionality, emissions, supply chain, economics, and accessibility.

EXECUTIVE SUMMARY

The fresh produce industry is at a critical inflection point, confronting a series of complex and often contradictory packaging related challenges. This includes the fragmented and rapidly evolving "regulatory gauntlet" of local and national policies, conflicting mandates from buyers and retailers, to the persistent performance gap between widely used commercial packaging and their alternatives.

At the heart of this landscape lies the "sustainability paradox": the imperative to prevent food and materials waste while reducing GHG emissions, versus the public and regulatory pressure to eliminate or change packaging to fit a narrative rather than a science-based understanding of full life cycle performance and environmental impact. This roadmap highlights how a narrow focus on the composition and end-of-life fate of packaging materials risks increasing food and materials waste, production and commodity costs, and GHG emissions.

Prioritizing the functionality of fresh produce packaging is essential because it aligns sustainability efforts with the primary purpose of packaging: to protect and preserve the food it contains. Life Cycle Assessment (LCA) studies show that the agricultural production phase, which requires water, land, and energy to grow, process, and transport fresh produce crops, accounts for an important portion of the total environmental footprint. When the packaging or supply chain fails and food becomes food loss and waste, the entire environmental investment in that food is lost. Further, reducing material waste and emissions from the manufacturing of and supply chain for packaging materials is also critical to capture the full accountability of the GHG footprint of the fresh produce supply chain.

Functional Sustainability is essential as the core principle for all sustainable packaging.

Functional Sustainability

This report champions the concept of **"Functional Sustainability,"** a holistic framework that evaluates packaging based on its performance and impact throughout the entire supply chain. Sustainable packaging cannot focus simply on if materials that make up the packaging have the capability to be recycled or composted. Functional sustainability must also include the environmental impact of manufacturing the packaging materials, as well as the ability of the packaging to preserve freshness and mitigate food safety risks, protect the product from physical damage and contamination, and improve handling and transport logistics efficiency. Packaging that prioritizes functional sustainability is therefore critical to a sustainable supply chain, safeguarding the significant environmental resources entrenched in the food chain from farm to fork.

The challenge of achieving truly sustainable packaging can be understood as threefold. **Upstream considerations** involve material science and sourcing, where decisions must be informed by LCA data that correctly prioritizes food loss and waste prevention over packaging materials reduction or substitution. **Functionality** ensures the packaging performs the core protective duties across the entire supply chain journey. **Downstream considerations** address the end-of-life reality, which includes designing for compatibility with available waste management infrastructure and navigating the trade-offs between high-performance multi-layer materials and more easily recyclable mono-materials.

Sustainable Fresh Produce Packaging Roadmap

To navigate this complex landscape, SPPA puts forward this Sustainable Fresh Produce Packaging Roadmap:

COMMIT TO FUNCTIONAL SUSTAINABILITY

Educate the entire supply chain and shift the public narrative. Communicate how functionality is the most critical component of a sustainable packaging system and shift the simplistic focus on material type or end of life focus to a comprehensive, science-based understanding of full life cycle performance and environmental impact.

DRIVE TARGETED INNOVATION

Strategically identify and invest in innovation where it is needed most. Support the development of more effective and economical solutions tailored to the specific risks of each functional commodity group, such as better moisture-management materials for berries or cost-effective Modified Atmosphere Packaging (MAP) technologies for cut vegetables, for example.

ADVOCATE FOR PRAGMATIC POLICY

Collectively advocate for pragmatic, aligned, and science-based packaging related policies and regulations. This includes but is not limited to Extended Producer Responsibility (EPR) schemes, to ensure packaging systems that demonstrably reduce GHG emissions as well as food loss and waste are rewarded. Creating incongruent rules for materials based on composition alone can lead to supply chain inefficiencies and negative environmental outcomes.

By placing functionality at the heart of the strategy, the fresh produce industry can move beyond fragmented, single-issue debates and toward integrated solutions that deliver genuine environmental, economic, and social benefits.

Recommendations for Action

To achieve sustainable packaging outcomes, action will be required from all stakeholders. Outlined in more detail at the end of this roadmap, SPPA puts forward these Recommendations for Action:

For the fresh produce industry (growers, packers, and packaging manufacturers), the industry must prioritize functional sustainability in design, commit to data-driven decision-making, design for downstream reality and not theory, and collaborate to standardize formats. For retailers, educate consumers at the point of purchase, revise procurement policies to reward holistic sustainability, and advocate for improved downstream infrastructure. For policy makers and regulators, establish harmonized national standards and definitions, implement pragmatic EPR policies, and fund critical infrastructure and innovation. Lastly, for academia, fill critical research and data gaps and develop standardized testing protocols.

Sustainable fresh produce packaging cannot effectively progress in isolation. Functional Sustainability offers a unifying framework, and success will require coordinated action among all stakeholders along the full supply chain. Only through shared commitment to sustainable outcomes, science-based decision-making, and collaborative innovation can we reduce waste and emissions, and pave the way for a cohesive, industry-wide shift to more functional, economical, and environmentally conscious packaging.

CONTENT

SUSTAINABILITY FOR FRESH PRODUCE PACKAGING

Sustainable Packaging: Sustainable fresh produce packaging relies on the functional design and application of packaging systems to protect and preserve fruits and vegetables while minimizing negative impacts on the environment, economy, and society throughout the supply chain.

Functional Sustainability' vs 'End of Life Sustainability'

The fresh produce industry is committed to continuous improvement, and sustainable packaging will require optimizing the functionality of packaging throughout the full life of the packaging, while leaving minimal environmental impact at the manufacturing of and 'end of life', or disposal. Many sustainable packaging requirements and regulations focus only on the 'end of life' view of sustainability; to reduce environmental impact through better waste management, recyclability, compostability, or biodegradability. Essentially, this looks only at the disposal and processing (e.g. recycling and composting) of packaging material at the end of the functional life of the packaging, often without considering the availability of infrastructure needed to appropriately process those materials.

However, 'functional sustainability' incorporates how packaging performs and mitigates environmental impacts throughout the full life of the packaging in addition to 'end of life' sustainability. This includes the elimination (i.e., reducing the need for or total mass of packaging material), commodity longevity (i.e., extending shelf life) and protection (i.e., reducing breakage or spoilage), and efficiency (i.e., improving utility and safety in production, packing, processing, transport, at retail, or after reaching the consumer).

'END OF LIFE' SUSTAINABILITY

Only addresses the disposal and processing of packaging material AFTER the end of its functional life.

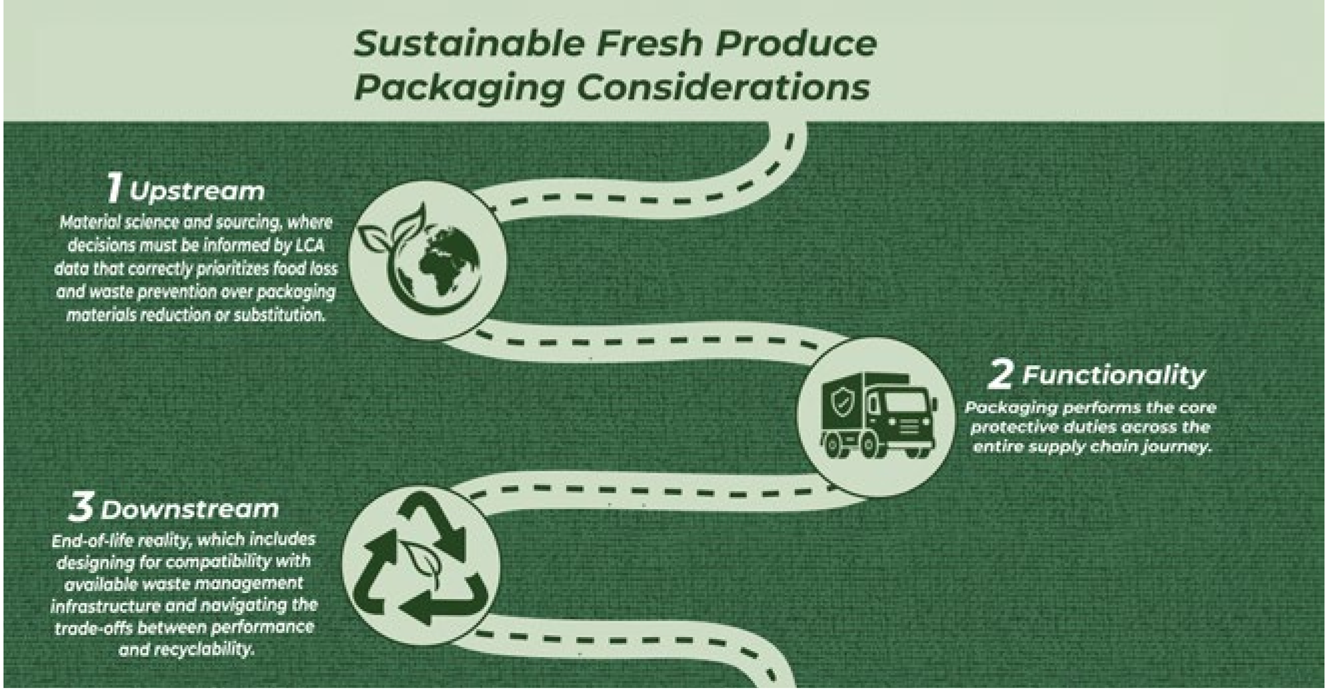
'FUNCTIONAL SUSTAINABILITY'

Incorporates how packaging performs and mitigates environmental impacts throughout the full life of the packaging, in ADDITION to the 'end of life' sustainability.

Full Life Cycle Considerations

The Three Pillars of Sustainable Produce Packaging Decision Making

When selecting packaging for produce, a comprehensive decision rests on balancing three critical considerations: the environmental cost of creating the packaging (upstream), the core role of protecting the contents (functionality), and the end of life management (downstream). This framework moves beyond single-issue thinking to create a holistic view of sustainability, from cradle to cradle.



Sustainable Fresh Produce Packaging Considerations

1 Upstream

Material science and sourcing, where decisions must be informed by LCA data that correctly prioritizes food loss and waste prevention over packaging materials reduction or substitution.

2 Functionality

Packaging performs the core protective duties across the entire supply chain journey.

3 Downstream

End-of-life reality, which includes designing for compatibility with available waste management infrastructure and navigating the trade-offs between performance and recyclability.

Upstream: The Origin Story

Upstream considerations focus on the environmental footprint of the packaging material itself, long before the packaging holds any produce. This involves a critical look at its source, for example, whether the material is derived from recycled materials, from finite, non-renewable resources such as petroleum (e.g., traditional plastics), or from renewable sources such as trees, corn, or sugarcane (e.g., paper, bioplastics). A comprehensive LCA can quantify the total environmental impact of producing the packaging, including the energy, water, and emissions generated from raw material extraction, manufacturing, and transportation. A decision at this stage sets the foundation for the overall sustainability profile of the packaging.

Functionality: Preventing the Greater Waste

The primary role of packaging is to protect its contents. The most significant environmental impact of the produce supply chain often comes from the food loss and waste that occurs when produce is left in the field or is damaged and spoiled along the supply chain. The resources (water, land, energy, labor, etc.) invested to grow and transport produce are immense and valuable. The most sustainable packaging effectively performs the function of preserving freshness, preventing physical damage, and ensuring food safety, thereby preventing the loss of the resource-intensive produce it contains.

Downstream: The End of Life

Designing for a circular system avoids delegating waste into landfills or, worse, the natural environment. The downstream pillar focuses on the end of life, or disposal of the packaging. Considerations that are critical to mitigating pollution and conserving resources include if the packaging is made from materials that are widely and easily recyclable or compostable with available infrastructure or designed to be biodegradable, returning to the earth under specific conditions. A packaging choice that neglects a clear and viable end-of-life pathway creates a long-term environmental burden, undermining any upstream or functional benefits.

See “Produce Industry Advancement” in Annex 1

See “Defining Functional Sustainability” in Annex 2

A truly sustainable packaging decision is a strategic trade-off; it requires balancing environmental cost of material selection against preventing food loss and waste and responsible end of life management.

Nexus for Change

The fresh produce industry has been increasingly challenged by new and incongruent policies and regulations for allowable packaging materials and disposal throughout North America. Additionally, fresh produce buyers are committing to increasingly wide-reaching ‘sustainability goals’ without considering key challenges in functionality, mitigating emissions, economics, and accessibility.

Leaving fresh produce providers out of the conversation when developing requirements and regulations leads to unintended consequences, including negative sustainability outcomes. For example, packaging design lacking in functionality can result in increased GHG emissions and significant economic impact on the farmers, packers, and processors who grow, pack and ship fresh produce for North American consumers.

Regulatory Landscape

Fresh produce packaging is subject to various regulations throughout North America. Historically, packaging regulations addressed priorities such as food contact safety, conveying consumer information, or directions regarding material use and recyclability. More recently, jurisdictions are generally developing or enforcing regulations regarding recyclability, materials composition labeling, recycled content, compostability, restricting the use of materials, and implementing Extended Producer Responsibility (EPR). Regulations introduced over the past few years have primarily focused on ‘end of life’ (e.g., eliminating plastics specifically or eliminating packaging materials in general). A lack of coordination between regulatory bodies has compounded the risk of non-compliance and cost for the fresh produce industry, to include logistical and economical, due to divergent and incongruent requirements between jurisdictions.

The risk to the sustainability of the fresh produce industry is regulatory and retailer pressure with incongruent requirements and the lack of available sustainable and functional alternatives.

Competing regulations and agendas have led to increased costs for growers, supply chain inefficiencies, and food and materials waste. Packaging that lacks the equivalent functionality to widely used commercial packaging, developed to maintain food quality and shelf life, increases food loss and waste and food safety risks due to cross contamination, compounding risks and costs for growers.

International Trends

Over the past few years, Canada and the EU have proposed regulations banning packaging (often plastic-based) or requiring the use of specific materials for packaging. Mexico continues work on regulations to mitigate fresh produce packaging waste, citing the goal to reduce environmental impact. The United States has not yet developed regulations specifically aimed at fresh produce packaging at the national level. However, regulations at the state level have been developed or are in the process of developing local policies on packaging and recyclability that will impact fresh produce. For example, EPR is a policy approach that assigns 'producers'[1] responsibility for the end of life of packaging products. This can include both financial and operational responsibility, though the amount and type may differ. Packaging producers are required to provide funding and/or services that assist in managing covered products after the use phase.

Extended Producer Responsibility (EPR)

Most EPR programs for packaging encourage or require producers to join a collective producer responsibility organization (PRO), though many allow producers to comply individually. The PRO develops a producer responsibility plan and manages the producer responsibility program. EPR also introduces new fees or levies to support waste accounting and management programs. For the fresh produce industry, the challenge of EPR is access to cost-effective packaging solutions to ensure compliance while maintaining functionality, product integrity, and marketability. Further, the significant research and development to incorporate recycled content into fresh produce packaging is not recognized or rewarded, disregarding a crucial upstream consideration.

Packaging regulations and retailer requirements must consider the lack of availability of innovative fresh produce packaging options necessary to ensure compliance while maintaining product integrity, functionality, and marketability.

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[1] EPR proposals define the "producers" to specify who is obligated under the plan or legislation to include brands, licensees, and importers or distributors, such as growers, packers, and shippers. The term "producer" depends on language outlined in legislation by each state or region and often refers to the entity that imports or distributes products in packaging.

Additionally, the requirements of product labeling and definitions of regulated products and producers can vary by state or region. For example, states have enacted or are considering laws restricting the use of the chasing arrows symbol on packaging to prevent misleading recyclability claims (e.g., when curbside recycling for that material is not available in that region), when other states require the symbol to indicate material composition. Further, packaging redesigned to meet recyclability or compostability standards must be harmonized across supply chains to ensure that the packaging reaches the appropriate compost stream. Non-compliance can lead to regulatory penalties, loss of markets, and contaminating waste streams with materials that vary in processing requirements (e.g., industrially compostable vs biodegradable). This incongruency in labeling requirements means that different packaging is required for different end destinations. Managing multiple packaging inventories, particularly for field packed produce, increases packaging waste, supply chain logistics, and costs.

Retailer Landscape

The fresh produce industry grapples with the significant challenge of supplying a retail landscape with widely divergent packaging requirements. On one end of the spectrum are retailers that primarily sell produce in bulk and demand a supply chain optimized for volume, speed, and cost-efficiency with minimal packaging. This model prioritizes the durability and handling of loose items from farm to store. On the other end of the spectrum, are retailers and grocers who offer pre-packaged produce (often branded). To serve these clients, suppliers must invest heavily in sophisticated packaging infrastructure to meet precise specifications for weight, size, and presentation in formats like clamshells, bags, and trays. Supplying this wide range of conditions creates a complex operational dichotomy for suppliers and distributors, requiring them to maintain dual systems for inventory, processing, and logistics. Effectively navigating this fragmented market requires immense flexibility and significant capital investment to cater to requirements ranging from bulk to value-added packaged models.

Retailers are also increasingly asking fresh produce providers to supply commodities in packaging with restrictions on packaging material composition, and requiring increased recycled content, recyclability, or compostability, with some retailers going as far as implementing plans to eliminate plastic packaging entirely (see Table 1: Retailer Sustainability Requirements). With limited commercially viable options for functional packaging, fresh produce suppliers are challenged by these incongruent requirements from retailers. Retailers imposing different packaging requirements on the same fresh produce supply chains and related products introduce a multitude of risks that can significantly impact efficiency, cost, product quality, and sustainability.

> **"Over 90% of what packaging does, it does before the consumer sees it"**
>
> **-G.L. ROBERTSON, FOOD PACKAGING: PRINCIPLES AND PRACTICES**

Table 1: Retailer sustainability requirements often do not account for the current available alternatives for fresh produce packaging. Depending on the packaging form, fresh produce packaging may meet, partially meet, or does not meet the retailer requirements. *Problematic elements can include PFAS, hard to recycle polymers such as PVC, nylon and mixed polymer constructions.

Meets ✓
Partially Meets ☑
Does Not Meet ⊘

		RETAILER REQUIREMENTS				
	PACKAGING FORM	RECYCLABILITY	REDUCE VIRGIN MATERIAL	ELIMINATE PROBLEMATIC ELEMENTS*	COMPOSTABILITY	LIGHT WEIGHTING
RIGID	Clamshell thermoform PET vented/non-vented	✓ recyclable	✓ 30% PCR possible	✓ not used	N/A	☑ possible
	Rigid Polymer Tray w/ polymer film lid	✓ recyclable	✓ 30% PCR possible	✓ not used	N/A	✓ reduced plastic w/ lidding film
	Fiber tray w/ Polymer film lid	✓ recyclable	N/A	✓ not used	✓ tray is compostable	✓ reduced plastic w/ lidding film
FLEXIBLE	Polymer bags	☑ limited recyclability (regionally dependent)	☑ some PCR content available	✓ not used	N/A	☑ possible
	Mesh bags	⊘ non-recyclable (lack of infrastructure)	☑ some PCR content used	☑ some used (mixed construction)	✓ certified compostable available	☑ possible
	Multi Polymer Bag lamination engineered OTR/ macro/ micro perf	⊘ non-recyclable (mixed construction)	☑ limited PCR possible	✓ not used	N/A	☑ possible
	Single Polymer Bag lamination engineered OTR/ macro/ micro perf	☑ recycle ready	☑ up to 30% PCR possible	✓ not used	N/A	☑ possible
	Compostable/Bio Polymer Bag lamination engineered OTR/ macro/ micro perf	⊘ non-recyclable (compostable bio polymers)	N/A	✓ not used	✓ compostable	☑ possible
OTHER	PLU Stickers	N/A	☑ some recycled content explored	✓ not used	☑ some available (limited)	N/A

Implications for the Fresh Produce Industry

Managing multiple packaging formats increases manufacturing complexity, often requiring specialized equipment, logistics, and increased labor resources and material waste. For example, field packed berries have developed a streamlined process that allows harvesters to focus on picking fruit rather than wrestling nested clamshells apart or balancing and repacking stacks of fruit. Packed clamshells often function as an accounting system, to ensure that harvesters are compensated (also called piece rate). Each packaging variation influences stacking and transport efficiency and adds to the administrative burdens, from managing multiple Stock-Keeping Units (SKU), compliance labeling for each destination, and payroll. Suppliers also face higher material costs due to smaller, diverse orders, all while managing storage and inventory in field conditions, that often include battling heat and humidity to maintain packaging structural integrity and quality. Inconsistent or suboptimal packaging reduces protection for fresh produce, leading to spoilage, shortened shelf life, and increased food loss and waste.

Throughout the supply chain, operational inefficiencies can lead to delays, which is one of the biggest challenges with fresh produce, due to high propensity for perishability. Food loss and waste significantly impact GHG emissions and lead to higher distribution costs. Inconsistent packaging dimensions and weights can also make it challenging to optimize loads, further reducing transportation efficiency. Food loss and waste along the supply chain due to delays, inefficient temperature management, or poor load optimization is an avoidable but significant source of GHG emissions.

Packaging alternatives that lack equivalent functionality to widely used commercial packaging, developed to maintain food quality and shelf life, increase the risk of food loss and waste and food safety cross contamination.

Fresh Produce Packaging Functionality

The primary packaging types and materials used will depend on the product, their unique characteristics, agricultural production practices, harvest and processing practices, logistics network, and retail and consumer preferences. Packaging within the food industry, for produce or otherwise, is carefully developed to ensure the quality of the food is preserved, no food safety risks are introduced by the packaging itself, critical handling and nutritional data are communicated to consumers, and food loss and waste and environmental impacts are minimized.

WHY IS PACKAGING FUNCTIONALITY SO CRITICAL FOR FRESH PRODUCE?

FRESH PRODUCE IS ALIVE
Packaging helps extend shelf life by maintaining freshness after harvest, ensuring quality is preserved as long as possible.

YEAR-ROUND AVAILABILITY
Packaging ensures fresh produce stays protected during global transport, maintaining ideal conditions to prevent damage, moisture loss, and contamination.

VISIBILITY QUALITY CONTROL
Clear packaging lets consumers inspect produce, ensuring only the freshest items are purchased and reducing spoilage at home.

Produce packaging's role may be cosmetic, marketing-related, informational for consumers (e.g. handling directions, nutritional labeling, origin information), and/or utilized for retailer inventory and sale management systems. However, in many, if not most applications, packaging is not cosmetic and serves a critical role in product safety and foodborne illness prevention.

The basic premise of simply "containment" as a function of packaging can get complex very quickly. Fresh produce and packaging often have a symbiotic relationship, adding a level of complexity to sustainable packaging design. Packaging that does not account for the complexity and functionality needs of fresh produce packaging will fall short in performance, leading to inefficiencies and waste. Packaging can range from a simple bag to retain the product for a period of time, to a complex Modified Atmosphere Packaging (MAP) tasked with maintaining the ideal conditions for shelf life, food safety, or product protection. Improving fresh produce packaging requires a thorough understanding

Fundamentally, food packaging is designed to keep what's in, in and keep what's out, out.

of the functionality needs. The more complex the functionality, the more difficult it is to replace and or modify. Changes made to fresh produce packaging that do not account for functionality will lead to poor performance, increased waste and inefficiencies, and deleterious economic impacts throughout the supply chain.

Functionality Considerations

Different commodities will have a unique set of packaging functionality considerations which should be accounted for in packaging guidance. Included in these functionality considerations are the following:

- **Labor and packing**: Packing style (e.g., hand packed vs machine packed) impacts packaging design and materials. For machine packed produce, changes in packaging often requires equipment modification or replacement, increasing the barrier to experiment with or invest in alternatives. Packaging can also provide a mechanism to measure and provide accountability for accurately compensating harvesting personnel.
- **Shelf Life**: Fresh produce shelf life is often directly impacted by the form and composition of the packaging or restricted by way of regulations and/or buyer requirements.
- **Light sensitivity**: Fresh produce commodities may be sensitive to light exposure during shipping, storage and stocking in commercial settings.
- **Cold chain**: Cold chain and display temperatures can vary depending on commodity and distribution channel. Packaging materials and design can stabilize temperature and humidity variations and improve cooling efficiency.
- **Protection and preservation**: Preventing moisture loss and physical protection to mitigate bruising is critical for many produce groups. Modified atmosphere can maximize transit time and mitigate loss of product quality in transit, storage and retail environments. Bruising and cuts are entry points for contamination.
- **Preventing cross contamination**: Customers moving throughout and between areas of the store and interact with objects shared among customers (e.g., shopping carts or other products) increases opportunity to transfer pathogens. Ready-to-eat fruits and vegetables can also be contaminated by customers and retail store employees handling the produce. While retail employees can be trained on optimal food handling and hygiene practices, addressing the risk from customer handling is less straightforward or controllable.
- **Visibility**: Many fresh produce items require packaging visibility for consumers to check quality. Consumers increasingly expect to have the ability to inspect the produce before purchasing.
- **Efficiency:** Throughout the production of fresh produce, packaging can play an important role in packing (e.g., stacking/footprint use efficiency in shipping) or harvesting efficiency, processing, or consumer processing (e.g., ready to cook).
- **Communications:** Nutrition facts, materials recyclability or compostability, potential allergens, certifications, or other critical information can be displayed on packaging.

> **"Fresh produce is alive. There must be a symbiotic relationship between the packaging and the produce. The packaging must allow the produce to 'breathe'. "**
>
> **-JEFFREY BRANDENBURG, QFRESH LAB**

FOOD LOSS AND WASTE

Fresh produce packaging is a critical tool in the fight against food loss and waste across the entire supply chain. Beginning immediately postharvest, field containers protect delicate produce items from initial mechanical and temperature damage that can accelerate spoilage. Cooling and storage in climate controlled conditions as quickly as possible is one of the most effective practices to reduce food loss and extend shelf life. During transit and distribution, packaging is engineered to maintain the appropriate temperature and humidity, and prevent bruising, compression, and vibration damage to ensure produce arrives at the retailer intact and of a high quality.

Beyond physical protection, advanced packaging serves as a vessel for preservation using technology such as MAP. For example, MAP creates and maintains the optimal environment within the pack, slowing respiration. This function is vital for reducing waste both in transit and on retail shelves.

MAP is a key technology associated with the shelf life extension of fresh produce. When combined with proper postharvest handling procedures and temperature control management, MAP can positively impact the quality and shelf life of fresh produce. Most extended shelf life packaging strategies use proportions of atmospheric gases that differ from those found in ambient air. Reducing oxygen (O_2) concentrations below ~10% slows respiration rates and indirectly slows the rates at which most fruits and vegetables ripen, age and decay. Reducing the O_2 concentration can, in some cases, reduce oxidative browning reactions, particularly concerning in precut leafy vegetables. MAP also increases the carbon dioxide ($CO_{2)}$ concentration within the packaging. When the increased CO_2 dissolves on the moist surface of the produce, carbonic acid is produced, causing a drop in pH. This acidification, as well as direct antimicrobial effects, can suppress the growth of spoilage microorganisms and is essential in many types of extended shelf life packaging.

At the consumer level, packaging provides a vessel to convey and mechanism for enhanced home storage while shielding produce from frequent handling and conveying crucial consumer information. For the end consumer, packaging can offer convenience while also seeking to reduce waste in the home.

See Annex 3 for "Produce Quality Degradation Risk Factors".

> Modified Atmosphere Packaging (MAP) modifies or preserves the composition of gases inside the packaging in order to extend the shelf life of fresh produce.

FOOD SAFETY

Packaging plays a crucial role in protecting fresh fruits and vegetables by forming solid, tamper-resistant barriers that reduce contamination risks during handling, transport, and storage. Packaging can prevent physical damage, which can make produce items susceptible to microbial contamination, as well as provide traceability information and MAP to control spoilage microorganisms and human pathogen growth, when present.

Food safety and quality are often misrepresented as being synonymous, but they are distinct concepts representing different measurements of a product. Food safety addresses the physical, microbial, and chemical hazards may contaminate food and associated human health risks a product, packaging or system may pose and focuses on mitigating those risks. No product is risk free, but packaging designed to help mitigate the risk of contamination is an important component of the overall food safety system throughout the supply chain.

Packaging in the Supply Chain

Primary, secondary, and tertiary packaging are used to classify different types of packaging based on their role in protecting a product and facilitating distribution or sale. Packaging is used to protect and maintain product quality and safety throughout the supply chain.

PRIMARY

Primary packaging describes the first layer of packaging that directly contacts or contains fresh produce. Also known as 'consumer' or 'sales' packaging, this is the packaging that consumers are most likely to associate with and interact with. The key functions of primary packaging are to physically protect the product, preserve freshness, and convey critical information. Examples of primary packaging include plastic clamshells, mesh bags, plastic film, plastic trays, or even Price Look-Up (PLU) stickers. PLU stickers play an integral role in fresh produce supply chains, for example, EU regulations are treating PLUs as "packaging" under the Packaging and Packaging Waste Regulation (PWR). In most cases, primary packaging end of life (disposal) is the responsibility of the consumer, and the fate of the packaging material is often determined by consumer behavior and education, in addition to availability of infrastructure and waste management facilities, which vary significantly by region.

PRIMARY PACKAGING

Direct contact food packaging where end of life (disposal) is the responsibility of the consumer.

SECONDARY PACKAGING

Aggregates or protects fresh produce or primary packaging, i.e., case or RPC.

TERTIARY PACKAGING

Packages or stabilizes secondary packaging, i.e., pallet wrap, film, or shroud.

SECONDARY

Secondary packaging is often used for aggregating primary packaging into larger containers, and can facilitate handling, display, and retail stocking. Also known as 'grouped' or 'transit' packaging, this can include boxes, trays, or 'shrink-wrap' that hold primary packs together during transport or storage in warehouses or at back-of-store.

Fresh produce secondary packaging can be referred to as 'Business to Business' (B2B) packaging, and is often in the form of a bulk packaging as in a case liner or bin liner or overwrap. In certain cases, it even can be the ocean freight shipping container. The function of this type of packaging ranges from the containment of large quantities of produce or primary packaged produce to serve as the primary MAP packaging for the bulk shipment of fresh produce.

Secondary packaging can also transition into primary packaging or can function as display packaging, allowing retailers to quickly shelve products in the tray or case. This is generally known as 'Shelf Ready Packaging' (SRP) or 'Retail Ready Packaging' (RRP). For example, fresh fruit packaged in a case can include a liner (case wrap), a sleeve that holds multiple packages, or employ a Reusable Plastic Container (RPC) with individual packages of fresh fruit. The functionality of secondary packaging can range from containment to display and, in certain cases, can become the MAP. Secondary packaging end of life (disposal) is typically addressed by the retailer or distributor.

Fresh Produce Commodity Groups

Given the immense diversity of fresh produce commodities, from a potato to a raspberry, a one-size-fits-all approach to packaging is impossible. However, when fresh produce is grouped by functional commonality, packaging can be assessed based on the functionality requirements of the commodity group. Given the commonality of packaging functionality shared among select fresh produce commodities, the following grouping is an important evolution in how to consider fresh produce packaging design and requirements. Further, groupings will help to avoid undue and unintended impacts when considering packaging for a single commodity. The proposed grouping also provides the opportunity for improved collaboration between commodity growers and other industry stakeholders (e.g., packers, processors, distributors, retailers, etc.) that share similar if not identical packaging functionality requirements.

To advance innovation in a scalable and systematic way, this roadmap proposes grouping commodities based on their shared functional requirements. This strategy simplifies the challenge by creating a manageable number of problem sets. See Table 2 for the further description of the proposed groups below:

- **Group 1: Robust** requiring basic containment and moderate physical protection.
- **Group 2: Resilient** needing moderate gas exchange and moisture retention.
- **Group 3: Delicate** demanding high gas exchange, humidity management, and gentle containment.
- **Group 4: Highly Perishable** which require crush resistance, precise atmospheric control, and moisture management.

Table 2: Fresh produce groups.

	FRESH PRODUCE GROUPS				
	1 ROBUST	2 RESILIENT	3 DELICATE	4A HIGHLY PERISHABLE (BERRIES)	4B HIGHLY PERISHABLE (CUT)
FUNCTIONALITY SUMMARY	Function of packaging is for physical protection, transit, traceability and aggregating (to include PLU stickers and tags).	Function of packaging is for all in Group 1 and adds moisture loss, chemical barrier.	Function of packaging is for all in Group 1&2 and incorporates more significant protection, aggregation, and often modified atmosphere.	Function of packaging is for all in previous Groups and adds more significant physical protection, traceability, moisture management, aggregation.	Function of packaging is for all in previous Groups and more significant moisture management, designed modified atmosphere, traceability, marketing, as well as fresh cut produce protection and shelf-life optimization.
COMMODITIES	All Citrus *Grapefruit* *Lemons* *Limes* *Oranges* *Tangerines*	Apples	Cherries	Berries	Bagged Salad
		Avocadoes	Grapes		Baby Carrots
		Pears	Nectarines		Leafy Greens
		Asparagus	Peaches		Fresh-Cut
		Corn	Beans		
	Melon	Broccoli	Cucumbers		
	Pineapple	Carrots	Head Lettuce		
	Beets	Cauliflower	Peppers		
	Cabbage	Potatoes	Tomatoes		
	Celery	Sweet Potatoes	Herbs		
	Garlic		Papaya		
	Onions		Mango		
	Squash				

Grouping commodities by similar packaging functionality offers significant benefits for both individual stakeholders and the broader industry. This approach simplifies packaging design by focusing on a few functional needs of commodity groups rather than hundreds of individual produce items, enabling scalable innovation and cost-effective platform solutions. Groups can enhance supply chain efficiency, reduce material and operational costs, and support harmonization across the fresh produce supply chain. Additionally, groups may help to prevent unintended negative impacts by addressing the shared needs of commodity groups[2].

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[2] Groupings were informed by the Agriculture and Agrifood Canada 2024 report: Quantifying the functionality importance of plastic packaging in fresh produce from a needs/benefit perspective (**Quantifying the functionality importance of plastic packaging in fresh produce from a needs/benefit perspective - agriculture.canada.ca**)

Current State of Fresh Produce Packaging Technology

Optimal sustainable packaging for fresh produce must meet all of the functionality needs while maintaining continuous innovation and improvement towards increasingly sustainable outcomes. Significant advancements in packaging technology have made it possible for fresh fruits and vegetables to be available year-round, throughout North America.

Fresh produce supply chains rely on a complex portfolio of packaging technologies to deliver hundreds of different commodities and thousands of different varieties.

Table 3: Packaging assessment of industry standard packaging for major fresh produce commodities. Commodities are separated by group.

	Bulk	Secondary Packaging (case)	Secondary packaging (case liner)	Pallet wrap	PLU	Elastic tag/bib	Plastic Netting	Fiber netting	Rigid polymer vented clamshell	**Rigid polymer non-vented clamshell	Fiber clamshell	Paper bag	**Paper lamination bag/stand up pouch macroperferated	**Polymer sleeve w/ plastic tray	**Polymer sleeve w/ fiber tray	*Rigid polymer tray w/ polymer lidding film	*Fiber tray w/ polymer lidding film	Metal tray w/p plymer lidding film	*Polymer bag engineered OTR	Polymer bag macroperferated	*Polymer bag microperferated	*Polymer bag lamnation engineered OTR	Polymer bag lamnation macroperferated	*Polymer bag lamination microperferated	Stand up pouch polymer lamination macroperferated	*Stand up pouch polymer lamination microperferated
Group 1 – Robust Produce																										
Grapefruit	X	X		X	X		X													X					X	
Lemon	X	X		X	X		X													X					X	
Lime	X	X		X	X		X													X					X	
Melon	X	X		X	X																					
Pineapple	X	X		X		X																				
Beets	X	X		X			X																			
Cabbage	X	X		X																X						
Celery		X		X		X								X	X	X				X						
Garlic	X	X		X		X	X													X						
Onion	X	X		X			X													X						
Squash	X	X		X																X						
Orange	X	X		X	X		X													X			X		X	
Tangerine	X	X		X			x																			
Group 2 – Resilient Produce																										
Apples	X	X		X	X		X		X											X			X		X	
Avocado	X	X		X	X		X		X											X			X		X	
Pear	X	X		X	X		X													X			X		X	
Asparagus	X	X	X	X	X	X														X						
Corn	X	X	X	X										X	X											
Broccoli	X	X	X	X	X	X															X			X		X
Carrots	X	X	X	X		X													X	X	X					
Cauliflower	X	X	X	X																	x			X		X
Potato	X	X		X			X	X			X	X	X			X	X			X			X			
Group 3 – Delicate Produce																										
Cherry			X	X					X											X			X		X	
Grape		X		X																X			X		X	
Nectarine		X		X																X			X		X	
Peach		X		X																X			X		X	
Beans		X	X	X																	X			X	X	X
Cucumber		X	X	X	X									X	X	X				X				X	X	X
Head lettuce		X		X										X	X					X						
Pepper		X		X	X									X	X					X	X				X	
Tomato		X		X	X				X					X	X	X									X	
Herbs		X	X	X					X	X				X	X	X									X	X
Papaya		X		X	X															X			X		X	
Mango		X		X	X															X			X		X	
Group 4a (Berries) – Highly Perishable Produce																										
Berries		X		X					X		X															
Group 4b (Fresh-cut) – Highly Perishable Produce																										
Bagged Salad		X		X						X	X					X	X		X	X	X	X		X		
Leafy Greens		X		X						X	X					X	X		X	X	X	X	X	X		
Fresh Cut		X		X						X	X					X	X		X	X	X	X		X		

KEY

- ● Potentially compostable or curbside recyclable
- ● Tray only potentially curbside recyclable; Lidding film potentially compostable or in-store recylcable if made from a single polymer
- ● Bag/ pouch only Potentially compostable or recyclable if made from a single polymer

* MAP

**Both MAP and non-MAP possible

Packaging Sustainability Challenges

As sustainability goals evolve, packaging must also adapt through continuous innovation. Today, significant advancements in packaging technology have made it possible to deliver fresh fruits and vegetables across North America, year-round. Innovations to extend shelf life, reduce spoilage, and improve food safety, are always under development. The tradeoff of leveraging widely used commercial packaging materials to improve the functionality of packaging is in sustainability gains in GHG emissions or reductions in food loss. For example, due to the considerable resources that go into producing food, efforts to reduce food loss and waste can significantly decrease environmental impact, even when the environmental impact of the packaging itself is taken into account.

Certain commodity groups may have challenges with recyclability (i.e., due to materials or infrastructure), readiness for recycling (favoring single-material packaging), and the need for strong seals and packaging integrity to handle bulky or heavy produce items. Additional challenges and concerns involve fiber packaging properties such as moisture management, strength, visibility, compostability, tear resistance, and susceptibility to wrinkling or deterioration in storage.

Assessing and Mitigating Risks

When considering the compound risks that arise from mitigating both shelf-life and quality degradation, the fresh produce industry requires a wide range of solutions – from relatively simple packaging (which addresses low shelf-life and quality degradation risk), to highly complex MAP solutions (when both quality degradation and shelf-life risks are elevated). Packaging innovation providing cost-effective solutions that address this range of considerations can further reduce either quality degradation or shelf life risks.

Conclusion

Sustainable packaging for fresh produce must balance both functionality and environmental responsibility. Functional sustainability incorporates how packaging performs and mitigates environmental impacts throughout the full life of the packaging, in addition to the 'end of life' sustainability, which looks only at the disposal and processing of packaging material at the end of its functional life. This includes the upstream manufacturing the packaging materials, as well as the ability of the packaging to preserve quality and freshness via protection from physical damage and contamination, mitigate food safety risks via prevention contamination, improve handling and transport logistics efficiency, and reduce food loss and waste.

The fresh produce industry faces a complex web of sustainability challenges for packaging, balancing environmental goals with practical constraints. There are trade-offs between reducing food loss and waste and minimizing material impact, closing the performance gap between functional industry standards and packaging alternatives, and meeting recycled content or other regulatory mandates while ensuring a safe food supply. Aspirations for a circular economy clash with the need to invest in and improve access to end-of-life infrastructure and consumer expectations for sustainability, convenience, and visibility, which are often contradictory. Regulatory pressures outpace technological readiness, and innovations face economic hurdles due to tight industry margins and the technical challenges of designing high-performance materials.

> "The whole value chain has a responsibility to explain that sustainability is not synonymous with recycling, recyclability, recycled content, biodegradability and other popular buzz words, but that it is the overall resource efficiency of the supply chain that should be the main priority."
>
> **-D. RUSSELL, SUSTAINABLE (FOOD) PACKAGING–AN OVERVIEW, 2014**

Recommendations for Action

Recommendations for Industry (Produce Growers, Packers, and Packaging Manufacturers)

PRIORITIZE FUNCTIONAL SUSTAINABILITY IN DESIGN:

Invest in and adopt packaging technologies and designs proven to extend shelf life and reduce spoilage for specific produce types. Preventing food loss and waste is a paramount sustainability goal and packaging that increases food loss and waste does not improve the sustainability of fresh produce. Functional sustainability design shifts primary design focus to food preservation concurrently with minimizing packaging material waste.

Action: Evaluate, develop, and adopt viable alternative technologies to minimize packaging and food loss and waste.

COMMIT TO DATA-DRIVEN DECISION-MAKING:

Move beyond single-attribute claims (e.g., "plastic-free") and invest in comprehensive Life Cycle Assessments (LCAs) for primary packaging options. Use these data to compare the total environmental impact, from upstream production to downstream disposal, of different materials.

Action: Conduct and share LCA data on common packaging formats to reduce costs and establish credible benchmarks.

DESIGN FOR DOWNSTREAM REALITY, NOT THEORY:

Design packaging with actual end-of-life infrastructure in mind. Prioritize materials that are widely recyclable in practice across major markets, not just technically recyclable. For compostable packaging, ensure it is clearly labeled and used only for products likely to end up in designated organics streams.

Action: Actively engage with waste management providers to understand the regional sorting capabilities and contamination challenges. Phase out materials and combinations that are known waste stream contaminants.

COLLABORATE TO STANDARDIZE FORMATS:

Work collaboratively across the industry to standardize packaging footprints and material choices where feasible.

Action: Collaborate as fresh produce groups to optimize packaging to significantly improve shipping efficiency and recycling quality.

Recommendations for Action

Recommendations for Retailers

EDUCATE CONSUMERS AT THE POINT OF PURCHASE:	Leverage in-store and digital platforms to communicate the "why" behind packaging choices, focusing on its role in reducing food loss and waste. Counteract common misconceptions with clear, simple messaging on packaging and at the shelf edge. **Action: Develop and provide consumer education materials.**
REVISE PROCUREMENT POLICIES TO REWARD HOLISTIC SUSTAINABILITY:	Consider procurement specifications focused on the three pillars (Upstream, Functionality, Downstream). Move beyond single attribute mandates. **Action: Coordinate stakeholders on best practices and current availability of technology using LCA data or food loss and waste reduction targets.**
ADVOCATE FOR IMPROVED DOWNSTREAM INFRASTRUCTURE:	Support and advocate for the improvement of local and regional recycling and composting infrastructure. **Action: Consider materials selection based on predominant recovery systems available locally for private label. Partner with municipalities to pilot hard-to-recycle materials.**

Recommendations for Action

Recommendations for Policy Makers and Regulators

ESTABLISH HARMONIZED NATIONAL STANDARDS AND DEFINITIONS:

Create clear, nationally acceptable definitions for terms like "recyclable" and "compostable" to eliminate market confusion. These definitions must be tied to the reality of available infrastructure (i.e., a packaging cannot be labeled "recyclable" if collection and processing systems are not available to a significant majority of the population).

Action: Adopt a standardized labeling system (e.g., How2Recycle) that provides clear, instruction-based disposal information to consumers.

IMPLEMENT PRAGMATIC EXTENDED PRODUCER RESPONSIBILITY (EPR) POLICIES:

Include brands and retailers in EPR. This creates a direct economic incentive to design for recyclability and reduce overall packaging use. Encourage upstream materials considerations in policy, such as recycled content.

Action: Structure EPR fees to be variable, with lower fees for packaging that is easier to recycle, contains higher recycled content, and demonstrates a lower overall life cycle impact, thereby rewarding the leaders identified in the SPPA report.

FUND CRITICAL INFRASTRUCTURE AND INNOVATION:

Support Material Recovery Facilities (MRFs) and composting facilities to handle critical packaging materials. Provide grants and tax incentives for research and commercialization of new, sustainable packaging materials and systems.

Action: Prioritize funding for facilities capable of sorting and processing post-consumer recycled (PCR) plastics into food-grade material to help create a more circular economy.

Recommendations for Action

Recommendations for Academia

FILL CRITICAL RESEARCH AND DATA GAPS:	Conduct peer-reviewed research to address knowledge gaps. Include comparative LCAs of emerging materials (e.g., bioplastics vs. conventional polymers), studies on the impact of packaging on nutrient retention, and behavioral research for consumers. **Action: Establish a public-access database of LCA results for common produce packaging systems to democratize access to high-quality data.**
DEVELOP STANDARDIZED TESTING PROTOCOLS:	Create standardized, repeatable methodologies for assessing the "functional sustainability" of packaging. **Action: Partner with industry associations to develop and validate protocols, allowing for credible, apples-to-apples comparisons of different packaging formats.**

ANNEX

Annex 1: Produce Industry Advancements

MINIMIZE PACKAGING WASTE

Evaluate, develop, and adopt viable alternative technologies to minimize packaging waste

- Reduce virgin materials and increase lightweighting
- Increase recyclability and post-consumer recycled (PCR) content
- Optimize use of secondary and tertiary packaging
- Develop economical compostable, biopolymer and fiber materials
- Utilize packaging analytical tools (LCA, ROI, etc.) to identify and confirm most sustainable options

SUPPLY CHAIN EDUCATION

Align industry and facilitate best current practice

- Coordinate stakeholders on best practices and current availability of technology.
- Identify gaps in technology for raw materials with reduced carbon footprint.

Infrastructure Advancements

ACCESS TO AND UPDATING EXISTING INFRASTRUCTURE

Improve access to and update existing recycling and composting infrastructure

- Improve access and consumer education for recycling at the residential level.
- Improve infrastructure and materials acceptance
- At Materials Recovery Facilities (MRF)
- For chemical recycling

ENERGY EFFICIENCY

Evaluate, develop, and adopt viable alternative technologies to increase energy efficiency

- Improve operational efficiency and activities related to waste, water, energy efficiency and equipment upgrades for packaging manufacturing
- Identify and transition to manufacturing equipment with reduced carbon footprint
- Transition to renewable energy sources for manufacturing when possible

Annex 2: Defining Functional Sustainability

Given the critical importance of functionality in the identification, assessment and selection of fresh produce packaging, the following definition is proposed.

Functional Sustainability: a holistic framework that evaluates packaging based on its performance and its ability to mitigate environmental impacts throughout its entire life cycle, rather than focusing narrowly on its disposal or "end-of-life" attributes.

This approach prioritizes the primary purpose of the packaging, which is to protect the food it contains. It is defined by how well the packaging performs its core functions, which include:

Longevity: Actively extending the shelf life of the produce to prevent spoilage and reduce food loss and waste.

Protection: Shielding the product from physical damage (like bruising and breakage), contamination, and other factors that cause quality degradation.

Efficiency: Improving utility and minimizing waste across the entire supply chain, including in packing operations, transportation, retail handling, and consumer use.

In essence, functional sustainability recognizes that the most critical sustainable action packaging can perform is to prevent GHG emissions, food loss and waste, and material waste, thereby safeguarding the significant environmental resources, such as water, land, and energy, invested in the production of fresh produce and the packaging materials.

Annex 3: Produce Quality Degradation Risk Factors

Potential risk factors which can contribute to produce quality degradation include:

Biological and Physiological Factors:

- Respiration: As living organisms, fresh produce continues to respire after harvest, consuming stored reserves (sugars, organic acids) and oxygen while releasing carbon dioxide, water, and heat. Higher respiration rates lead to faster deterioration, nutrient loss, and reduced shelf life. Temperature is a key driver of respiration; warmer conditions accelerate the process.
- Ethylene production and sensitivity: Ethylene is a natural, gaseous plant hormone that plays a significant role in ripening and senescence (aging). Some produce items are high ethylene producers (e.g., apples, bananas, tomatoes), while others are highly sensitive to ethylene (e.g., leafy greens, cucumbers, broccoli). Exposure of ethylene-sensitive produce to ethylene gas can lead to rapid quality decline, including premature or over ripening, yellowing, softening, and off-flavors.
- Water loss (transpiration): Fresh produce is largely composed of water, and its loss through transpiration after harvest leads to wilting, shriveling, reduced crispness, and weight loss. Factors influencing water loss include temperature, humidity, air movement, and the physical characteristics of the produce.
- Maturity at harvest: Harvesting produce at the optimal stage of maturity is critical. Immature produce may not ripen properly and can have inferior flavor and texture, while overripe produce deteriorates quickly, becoming soft and susceptible to spoilage.

Physical and Mechanical Damage:

- Bruising, cuts, and abrasions: Rough handling during harvesting, packing, transportation, and retail display can cause physical injuries. These damages not only affect the visual appeal but also create entry points for spoilage microorganisms, accelerating decay and increasing respiration and ethylene production.

Temperature Management (Cold Chain):

- Inadequate cooling: Promptly removing field heat and maintaining optimal temperatures throughout the postharvest chain (precooling, refrigerated storage, and transport) is paramount.
- Temperature fluctuations: Inconsistent temperatures can stress the produce, accelerate respiration and water loss, and promote microbial growth. Re-cooling produce in the distribution system after breaking the cold chain can be both impractical and impossible.
- Chilling injury: Some types of produce (especially those of tropical or subtropical origin like bananas and cucumbers) are susceptible to chilling injury if stored at temperatures below their optimal range but above freezing. This can manifest as pitting, discoloration, impaired ripening, and increased susceptibility to decay.
- Freezing injury: Exposure to temperatures below the freezing point of the produce can cause irreversible cell damage, leading to a mushy texture and rapid deterioration upon thawing.

Annex 3: Produce Quality Degradation Risk Factors (Continued)

Environmental Conditions (Postharvest):

- Relative humidity (RH): Maintaining appropriate RH levels is crucial. Low RH accelerates water loss, while excessively high RH can promote microbial growth and condensation, which can also foster decay.
- Atmospheric composition (oxygen, carbon dioxide): Controlled or modified atmosphere storage and packaging, which regulate O2 and CO2 levels, can slow down respiration and ripening, extending shelf life for certain commodities. Imbalances, however, can lead to physiological disorders.
- Light exposure: For some types of produce, prolonged exposure to light can lead to undesirable changes such as greening in potatoes or loss of certain nutrients.

Pests and Diseases (Pre-Harvest and Postharvest):

- Infestation: Insects and plant pathogens can damage produce directly by feeding on it or indirectly by creating entry points for pathogens. Some insects can also transmit plant diseases that impact food loss, shelf life, and quality.

MINIMIZE PRODUCE SHELF-LIFE RISK

Assess shelf-life risks via:

- The intrinsic sensitivity of the commodity under consideration to the risk factors below, and
- The effectiveness of the commodity-packaging scenario (from bulk to advanced packaging solutions) to mitigate the shelf-life optimization risk factors outlined below.

Produce Shelf-Life Optimization Risk Factors

The following is a preliminary listing of potential risk factors which can hinder shelf-life optimization logistics:

Temperature Management (the cold chain)

- Respiration rate: Fresh produce continues to respire (breathe) after harvest, consuming stored sugars and oxygen while releasing carbon dioxide, water, and heat. Higher temperatures accelerate respiration, leading to faster depletion of reserves, quality loss (e.g., flavor, texture, nutrients), and shortened shelf life.
- Enzyme activity: Temperature influences the activity of enzymes responsible for ripening quality deterioration, and deterioration. Lowering the temperature slows down these processes.
- Microbial growth: Warmer temperatures promote the growth of bacteria, molds, and yeasts that cause spoilage. Proper refrigeration significantly inhibits this growth.
- Chilling and freezing Injury: While cold is generally good, some produce (especially tropical/subtropical) can be damaged by temperatures that are too low (chilling injury), or by freezing, which destroys cell structure.

Ethylene Exposure

Ethylene is a natural, gaseous plant hormone that initiates and promotes ripening and, eventually, senescence (i.e., aging and deterioration). Some produce items are high ethylene producers (e.g., apples, bananas, avocados, tomatoes), while others are highly sensitive to ethylene (e.g., leafy greens, cucumbers, broccoli, carrots). Storing ethylene-producing items near ethylene-sensitive ones can significantly shorten the shelf life of the sensitive items.

Annex 3: Produce Quality Degradation Risk Factors (Continued)

Water Loss (Transpiration and Relative Humidity):

Fresh produce is primarily composed of water. After harvest, it continues to lose water to the surrounding atmosphere through transpiration. This water loss leads to wilting, shriveling, reduced crispness, and weight loss, all of which decrease shelf life and marketability. Maintaining high relative humidity (RH) around the produce helps to minimize water loss. However, excessively high RH can encourage microbial growth if not managed correctly with temperature.

Physical Damage (Mechanical Injury):

Bruises, cuts, abrasions, and other forms of physical damage incurred during harvesting, handling, packing, and transportation significantly reduce shelf life. Damaged areas provide entry points for spoilage microorganisms. Injured tissues often exhibit increased respiration and ethylene production, accelerating deterioration.

POSTHARVEST HANDLING PRACTICES:

- Prompt cooling: Rapidly removing field heat after harvest (precooling) is crucial to slow down metabolic processes.
- Gentle handling: Minimizing physical damage at all stages.
- Proper sanitation: Cleaning and sanitizing equipment, containers, and handling surfaces to reduce microbial loads.

INTRINSIC CHARACTERISTICS OF THE PRODUCE:

- Type of produce: Different fruits and vegetables have inherently different shelf lives due to their unique physiology, respiration rates, and susceptibility to spoilage. For example, apples generally last longer than raspberries.
- Maturity at harvest: Harvesting at the optimal stage of maturity is critical. Immature produce may not ripen properly, while overripe produce will deteriorate quickly.
- Cultivar/Variety: Within a type of produce, different cultivars can have varying shelf life potentials due to genetic differences.

ATMOSPHERIC COMPOSITION:

The levels of oxygen (O2) and carbon dioxide (CO2) in the storage environment can significantly impact shelf life. Controlled Atmosphere Storage (CAS) and Modified Atmosphere Packaging (MAP) manipulate these gas concentrations to slow respiration and ripening, thereby extending freshness for certain commodities.

Annex 4: Existing Work on Fresh Produce Packaging Functionality

AGRICULTURE & AGRI-FOOD CANADA (AAFC) FUNCTIONALITY STUDY

This government-commissioned study, titled "Quantifying the Functionality Importance of Plastic Packaging in Fresh Produce from a Needs/Benefit Perspective," is a foundational piece of research. It provides an innovative framework for describing the critical functions of produce packaging, including containment, protection, preservation, and microbial control. A key contribution is its novel approach of categorizing produce into groups with shared functionality requirements, which covers nearly 95% of fresh produce sold by volume.

Publication: https://agriculture.canada.ca/en/sector/horticulture/reports

CANADIAN PRODUCE MARKETING ASSOCIATION (CPMA) SUSTAINABLE PACKAGING GUIDE & RESOURCES

The CPMA has spearheaded numerous industry-led efforts to advance sustainable packaging. Their "Sustainable Packaging Guide for Food and Fresh Produce" offers a decision-making framework with tools and use cases to help the industry make informed choices. The CPMA's Packaging Working Group has also developed specific resources like the "Fresh Produce Plastics Packaging Design Guidelines," which provide actionable rules for reducing environmental impact while maintaining functionality.

Main Guide: https://sustainable-packaging.ca/

Working Group Resources: https://cpma.ca/industry/sustainability/packaging-working-group

AMERIPEN AND MICHIGAN STATE UNIVERSITY (MSU) STUDIES

The American Institute for Packaging and the Environment (AMERIPEN) has funded key research with MSU's School of Packaging to explore packaging's role in preventing food loss and waste. Studies like "Minding the Gap: Consumer Awareness of Packaging & Food Waste Reduction" investigate how packaging technologies can extend shelf life and how consumer knowledge (or lack thereof) affects waste. Their research has shown a correlation between the foods most wasted by households and those with the least amount of packaging.

Publications Hub: https://www.ameripen.org/publications/

SUSTAINABLE PACKAGING COALITION (SPC) RESOURCES

The SPC is a leading industry collaborative that provides a wealth of resources, educational courses, and design guides focused on making packaging more sustainable. While their scope is broader than just produce, their work provides an authoritative voice on packaging systems, design for recovery, and policy, all of which are integral to functional sustainability. Their resources help companies understand the trade-offs and opportunities in creating better packaging.

Main Website: https://sustainablepackaging.org/

GS1 US BEST PRACTICE GUIDELINES

GS1 is a global, not-for-profit information standards organization focused on improving supply chain efficiency and visibility. While their "Best Practice Guideline for Sustainability in Packaging Materials" was developed with the apparel and general merchandise sector, its principles on rightsizing packaging, optimizing materials to reduce waste, and ensuring product protection are directly transferable and relevant to the goals of functional packaging in the produce industry.

Main Website: https://www.gs1us.org/

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Sustainable Produce Packaging Alignment (SPPA)

This roadmap was developed by the Sustainable Produce Packaging Alignment (SPPA) consortium, a diverse industry group formed to address the need to align on scientifically sound, achievable, and sustainable fresh produce packaging guidelines for the fresh produce industry and retail partners in North America. Technical guidance was provided by via SPPA technical working groups, comprised of fresh produce industry stakeholders directly involved in packaging development and fresh produce industry adoption. The technical groups represent the interests of each commodity group.

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SUSTAINABLE PRODUCE PACKAGING ALIGNMENT