

Material Selection Challenges and Application Limitations of Biodegradable Films for Fresh-Cut Produce Packaging

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Abstract

Biodegradable films for fresh-cut produce packaging must provide gas exchange, moisture control, and physical protection suited to the product. This article examines material selection challenges using fresh-cut lettuce and apple slices as examples. Oxygen supply and carbon dioxide removal need to match produce respiration, while water vapour transfer must limit dehydration without allowing excessive moisture accumulation. Refrigeration affects these relationships because temperature changes influence respiration, film permeability, and condensation. Evidence from published experiments shows that improvements in one property can create limitations elsewhere. A modified film may preserve colour and firmness while increasing water loss, and a suitable film may perform poorly when seals are unreliable. Material selection should connect film properties with product quantity, package design, storage duration, and production conditions. Practical suitability depends on the performance of the complete package under its intended conditions of use.

Keywords: biodegradable films, fresh-cut produce, material selection, gas permeability, moisture control, refrigerated storage

1. Introduction

Fresh-cut produce places specific demands on packaging. Cutting removes natural protective surfaces and exposes moist tissue to the surrounding air. The produce continues to respire after packaging, consuming oxygen and releasing carbon dioxide. Water loss can reduce firmness and cause wilting, while changes at cut surfaces can affect colour and appearance. A suitable film must control these processes well enough to maintain acceptable quality during storage.

Biodegradable films offer a possible replacement for conventional plastic films, but biodegradability does not establish their suitability for fresh-cut produce. The material must also provide the gas exchange and moisture control required by the product. These functions can create competing demands. A film that strongly restricts oxygen transfer may reduce some forms of deterioration, yet it may also allow oxygen inside the package to fall below the needs of the produce. A film that retains moisture can limit dehydration, but moisture may accumulate inside the package when storage conditions change. Material selection requires a balance between these effects.

This balance depends on the product and the conditions of use. Fresh-cut lettuce needs protection against wilting and visual deterioration. Apple slices require control of browning and firmness loss at exposed cut surfaces. Their packaging needs cannot be reduced to a single preferred barrier value. Experimental work on minimally processed lettuce has shown that differences in film gas permeability can affect quality during refrigerated storage. This makes gas transport a central part of material selection rather than an isolated material property.

Refrigerated storage adds another requirement. Temperature affects both produce respiration and gas transfer through packaging. It also influences moisture movement and condensation. A permeability value measured under one set of laboratory conditions may provide limited guidance for a package used under different

conditions. Film thickness, package area, product quantity, and seal integrity also affect the environment around the produce. The performance of the finished package matters more than any single property of the film.

This article examines how biodegradable films can be matched to the packaging needs of fresh-cut produce, with particular attention to gas permeability, moisture control, and refrigerated use. Fresh-cut lettuce and apple slices provide examples for analysing these relationships. The discussion concerns standalone packaging films used to form bags or close containers. Edible coatings applied directly to produce surfaces operate through a different form of contact and are treated separately. The central question is which combinations of material properties and storage conditions make a biodegradable film suitable, and where competing requirements limit its application.

2. Packaging Requirements of Fresh-Cut Produce

Fresh-cut produce remains biologically active inside its package. Its cells consume oxygen and release carbon dioxide, while water moves from the tissue into the package atmosphere. Cutting increases the area of exposed tissue and creates sites where browning, softening, and microbial growth can occur. Packaging must respond to these processes throughout storage. Its purpose is to maintain conditions that slow quality loss while supporting the needs of the living tissue.

Gas exchange is a basic requirement. Oxygen enters through the film as the produce consumes it, and carbon dioxide leaves as it is released by respiration. The atmosphere inside the package depends on the balance between these movements. If oxygen enters too slowly, its concentration may fall enough to promote fermentation and unpleasant odours. Excessive carbon dioxide can also damage sensitive tissue. If gas exchange is too rapid, the atmosphere may remain close to ordinary air, reducing the benefit of modified atmosphere packaging. The required gas transfer must therefore be judged in relation to the respiration of the packaged product.

Product quantity and package design affect this balance. Adding more produce to a bag increases total oxygen demand without necessarily increasing the film area available for gas transfer. A film that works for a small portion may perform poorly when the same bag contains a larger quantity. Headspace provides an initial supply of gas, but it cannot maintain suitable conditions throughout storage if gas transfer remains poorly matched to respiration. Material selection must consider the amount of produce and the dimensions of the package together.

Moisture control presents a different balance. Fresh-cut lettuce can lose its crisp texture when water escapes from the leaves. Apple slices can also lose weight and firmness as exposed surfaces dry. Keeping a humid atmosphere around the product helps reduce this loss. Yet high humidity and visible liquid water are different conditions. Water left after washing, liquid released from damaged tissue, and condensation can all contribute to wet surfaces inside the package. These sources require attention to washing, draining, handling, and temperature control as well as film selection.

Lettuce and apple slices show why packaging priorities differ between products. The marketable quality of lettuce depends heavily on leaf appearance and texture. Wilting, discolouration, and damaged edges can make it unacceptable even when much of the tissue remains intact. For apple slices, browning at cut surfaces is a major concern. Oxygen restriction may help control browning, but the package must still provide enough oxygen for respiration. A film selected mainly for its ability to reduce browning may create other quality problems if it restricts gas exchange too strongly.

Experimental results also show that improvements in quality do not always occur together. In a study of fresh-cut apples, PLA films containing cinnamaldehyde and ZnO nanoparticles retained several quality attributes better than pure PLA but caused greater weight loss by the end of storage. The result illustrates a practical selection problem: a formulation may improve colour or firmness while providing weaker protection against dehydration. The value of that formulation depends on which changes determine whether the product remains acceptable.

Physical protection is another requirement. The film must withstand filling, sealing, transport, and handling without tearing or developing leaks. A failed seal changes gas and moisture movement, making the intended film properties less useful. Flexible bags also provide limited protection against compression. Delicate leaves or soft fruit pieces may require a supporting container, with the biodegradable film serving as the closure. The packaging format should reflect the product's vulnerability to damage.

Storage duration sets the period over which these functions must remain effective. A film suitable for a short distribution period may allow excessive water loss or an unsuitable atmosphere during longer storage. Acceptability should be assessed through several connected outcomes, including appearance, texture, odour, weight loss, and microbial condition. Selecting a film begins with identifying the product's main routes of deterioration and the intended conditions of use. These requirements provide the basis for judging gas permeability, water vapour transfer, and package strength.

3. Matching Gas Permeability to Produce Respiration

3.1 Oxygen Supply and Carbon Dioxide Removal

Gas permeability determines how readily oxygen and carbon dioxide pass through a film. For fresh-cut produce, the aim is to establish a suitable atmosphere around living tissue. Oxygen must enter at a rate that supports respiration, while carbon dioxide must leave fast enough to prevent harmful accumulation. The required balance depends on the product, its quantity, and its storage temperature.

A strong oxygen barrier can create a problem when oxygen consumption exceeds the supply through the film. The oxygen concentration inside the package then falls. Moderate oxygen reduction may slow respiration and some reactions associated with quality loss. Further reduction can promote fermentation, leading to off-odours and changes in flavour. The useful range lies between these outcomes. Selecting the film with the lowest oxygen permeability can move the package beyond that range.

Fresh-cut apples illustrate this tension. Oxygen is involved in enzymatic browning at cut surfaces, so reducing its availability can help preserve appearance. The apple tissue still needs oxygen for respiration. A material chosen mainly to limit browning may restrict oxygen supply too much when product loading is high or storage temperature rises. Browning control must be assessed together with the atmosphere that develops during storage.

Carbon dioxide requires separate attention. Its concentration increases as the produce respire. Some accumulation can contribute to quality preservation, but excessive levels can injure sensitive tissue or affect flavour. A film's ability to admit oxygen does not fully describe its ability to release carbon dioxide. Both properties influence whether the package can maintain suitable conditions.

Experimental work on minimally processed lettuce supports this approach. A study comparing conventional and biodegradable films during storage at 4°C found that gas permeability played a major role in quality retention. The tested biodegradable films provided longer shelf life than the OPP film used in that experiment. The practical lesson is that preservation depends on how gas transport matches the product's needs, rather than on whether the film belongs to a conventional or biodegradable material category.

The atmosphere also changes over time. Immediately after sealing, the package contains the gases introduced during filling. Respiration and transfer through the film then alter their concentrations. An acceptable initial atmosphere does not guarantee acceptable conditions later. A suitable film must support the product throughout the intended storage period, including the period before a relatively stable atmosphere develops.

3.2 Film Properties and Package Design

Gas permeability is a property of the material under stated test conditions. Gas transmission describes movement through a film of a particular thickness and area. This distinction matters because packages made from the same material can behave differently.

Increasing film thickness generally reduces gas transfer through a given area. A thicker film may improve resistance to handling damage while restricting oxygen supply. A thinner film can allow greater exchange but may provide less physical strength. Thickness should be selected together with mechanical requirements and respiration demand.

Film area also affects the total amount of gas that can cross the package. A larger exposed area provides more space for oxygen entry and carbon dioxide removal. Product mass works in the opposite direction by increasing total respiration demand. The relationship between film area and product mass is therefore more useful for selection than the polymer name alone. Changing portion size can require a change in film thickness, package dimensions, or perforation.

Perforation offers another way to adjust gas exchange. Small holes provide routes for gases to move without passing through the polymer itself. This can make a film usable when its inherent permeability is too low for the selected product. The number and size of holes become part of the package design. Their contribution to gas exchange must be considered alongside their effect on moisture loss.

A study of microperforated PLA films examined this approach for equilibrium modified atmosphere packaging of fresh fruits and vegetables. It showed how perforation and the water vapour transfer of PLA could be combined when designing packages for specific applications. The study supports treating film choice and package design as connected decisions.

Seals introduce a further practical constraint. Unintended leaks can supply oxygen and release carbon dioxide, but they make gas exchange difficult to control. A package may appear to maintain an acceptable atmosphere because of leakage rather than because the film has suitable permeability. This weakens the basis for applying the same material in commercial production, where seal quality may differ between packages.

Material selection should link reported permeability values to a defined package. The relevant questions are how

much produce the package contains, how much film is exposed, whether perforations are present, and what temperature the package will experience. Gas measurements during product storage can then show whether these choices provide adequate oxygen and prevent excessive carbon dioxide accumulation. The preferred material is the one that maintains a workable atmosphere under those conditions.

4. Balancing Moisture Retention and Condensation Control

4.1 Limiting Water Loss

Fresh-cut produce contains a large amount of water, and its quality depends partly on retaining that water during storage. Cutting exposes tissue that previously had some protection from the skin or outer surface. Water can move from these exposed areas into the package atmosphere and then pass through the film. When this loss becomes excessive, the product may lose weight, firmness, and visual appeal.

The consequences differ between products. Lettuce leaves depend on water within their cells to maintain a crisp structure. Water loss reduces cell pressure and causes wilting. In apple slices, dehydration can affect the texture and appearance of cut surfaces. A film must limit moisture loss enough to preserve the qualities that make each product acceptable.

Water vapour transfer through the package depends on the film and the conditions on both sides of it. A humid package stored in relatively dry air creates a driving force for moisture to leave. Film thickness and exposed area influence the amount transferred. Storage duration also matters because small daily losses can become significant over a longer period. A film that performs adequately during short storage may provide insufficient moisture protection for a longer distribution period.

The fresh-cut apple experiment using PLA films containing cinnamaldehyde and ZnO nanoparticles illustrates this trade-off. The modified films had higher water vapour permeability than pure PLA, and the packaged apples showed greater weight loss at the end of storage. Several other quality attributes were better retained. Improving colour, firmness, or microbial control did not remove the need to assess dehydration.

This creates a selection problem when different quality indicators point towards different materials. A film may keep the product visually attractive while allowing greater water loss. Another may retain moisture well but provide less suitable gas exchange. The choice should reflect the changes that determine the product's useful storage life. For lettuce, resistance to wilting may carry substantial weight. For apple slices, moisture retention must be considered together with browning and texture.

Water vapour permeability and water vapour transmission rate also need to be distinguished. Permeability describes transport through the material after accounting for thickness and the vapour pressure difference under the stated test conditions. Transmission rate describes the amount passing through a unit area of a particular film over time. Neither value can be interpreted fully without its temperature and humidity conditions. Comparing values measured under different conditions can produce a misleading ranking of materials.

4.2 Managing Moisture Inside the Package

Restricting water loss helps maintain a humid package atmosphere, but humidity can reach a level at which water condenses on cooler surfaces. Condensation occurs when moist air is cooled below its dew point. The resulting droplets may collect on the film or contact the produce. Temperature differences within a package can create this condition even when the average storage temperature appears suitable.

Water inside the package can also come from washing or damaged tissue. Inadequate draining leaves liquid on the product before sealing. Cut or compressed tissue may release fluid during handling and storage. These sources add to the moisture load that the package must manage. Selecting a film with greater water vapour transmission cannot reliably compensate for produce that enters the package excessively wet.

High humidity and free liquid water serve different roles. A humid atmosphere reduces the tendency of the tissue to lose water. Liquid accumulation can leave cut surfaces wet and reduce the visual quality of the package. Its effect on microbial growth depends on the organisms present and the wider storage conditions. Moisture control should preserve tissue water while limiting prolonged surface wetness.

Increasing water vapour transmission may help release some moisture, but it also increases the risk of dehydration. The useful level depends on how quickly moisture enters the package atmosphere and how much can leave without damaging the product. Perforation creates a similar trade-off. Openings used to improve gas exchange also provide routes for moisture movement. A perforated package may support respiration adequately while allowing unacceptable wilting.

Other package features can address specific moisture problems. Anti-fog treatments can improve visibility by spreading condensed water across the film surface, but they do not remove that water from the package. Absorbent components can collect liquid released by the product, yet they do not determine water vapour

transfer through the film. These features should be assessed according to the problem they solve.

Moisture performance is best judged through the combined condition of the product and package during storage. Product weight loss and texture show whether too much water has escaped. Droplets, pooled liquid, and wet surfaces show whether moisture is accumulating. These observations help identify whether the limitation comes from the film, product preparation, package design, or temperature control. A suitable biodegradable film maintains enough moisture to protect the tissue while allowing the complete package to manage excess water over its intended storage period.

5. Film Performance under Refrigerated Storage

Refrigeration slows many processes that reduce the quality of fresh-cut produce, but it also changes the conditions under which packaging films operate. Gas transfer, water vapour movement, and produce respiration are temperature-dependent. Material selection must account for their combined behaviour at the intended storage temperature. Room-temperature measurements alone provide an incomplete basis for choosing a film for refrigerated use.

The main challenge is that respiration and gas permeability may respond differently to temperature. When a package warms, the produce generally consumes oxygen more quickly. Gas transfer through the film may also increase, but the additional oxygen supply may be insufficient to meet the increased demand. A package that maintains a suitable atmosphere during steady refrigeration can then develop a lower oxygen concentration and greater carbon dioxide accumulation. The effect depends on the product, film, package dimensions, and duration of the temperature change.

Temperature-dependent permeability has been examined in biodegradable packaging research. Makino and Hirata tested a chitosan–cellulose and polycaprolactone laminate and found that its gas permeability increased as temperature rose over the tested range of 10–25°C. They also used shredded lettuce and cabbage to assess package gas composition. These findings support including temperature in material selection. Measurements closer to the intended refrigeration temperature would help determine whether the same film can provide sufficient exchange during cold storage.

The intended storage period should include the temperature conditions likely to occur during distribution and sale. Fresh-cut produce may experience brief warming during loading, shelf replenishment, or transfer between storage areas. The package atmosphere can respond to these changes before visible deterioration appears. Returning the package to refrigeration does not necessarily restore product quality if tissue damage or fermentation has already occurred. A material that works only under a narrowly controlled temperature may offer limited tolerance for routine handling.

Temperature variation also affects moisture control. Warm air can hold more water vapour than cold air. When humid air inside a package cools, water may condense on the film or produce. Repeated warming and cooling can redistribute moisture within the package, leaving some surfaces wet even when overall product weight loss remains low. A film's moisture performance should therefore be assessed through both water loss and condensation under the expected storage conditions.

This relationship creates a limit to solving moisture problems through film permeability alone. Greater water vapour transmission may help moisture leave the package during some conditions, yet it can increase dehydration during prolonged storage. Stronger moisture resistance may preserve product weight while allowing condensation during cooling. The material must operate alongside effective draining, suitable package design, and stable refrigeration. These measures influence the amount and location of water that the film is expected to manage.

Refrigerated use also requires mechanical performance under humid conditions. Some film formulations absorb moisture, which can change their strength, flexibility, or dimensions. Other formulations may have limited flexibility during handling. The relevant question is whether the selected film can withstand filling, transport, and storage while maintaining the required gas and moisture control. Strength measured on a dry film does not fully describe its behaviour after prolonged exposure to the package environment.

Seal integrity is particularly important because a leak changes the atmosphere around the produce. Experimental work on pre-cut lettuce demonstrated how sealing equipment could affect package performance. Brown and colleagues found frequent seal failures when the tested films were processed with thermal-bar sealing equipment. Impulse sealing produced hermetic seals, and lettuce in those packages showed deterioration similar to that in the commercial comparison packages after 14 days. The experiment links preservation performance to the compatibility between film and sealing method.

A refrigerated application should consequently be evaluated using the finished package. Film measurements help explain transport and mechanical behaviour, while storage trials show whether those properties work together

around the product. Gas composition, weight loss, condensation, texture, appearance, and seal condition provide connected evidence. Testing at the intended temperature establishes normal performance. Including realistic temperature changes reveals whether the package has enough tolerance for its expected distribution conditions.

6. Material Selection Trade-Offs

Selecting a biodegradable film involves choosing among properties that may improve different aspects of preservation. Gas exchange, moisture retention, mechanical strength, and sealing behaviour must work together. A material that performs well in one test may still be unsuitable for a particular fresh-cut product. The selection problem is to identify which properties are essential for the application and which compromises the product can tolerate.

PLA-based films provide a useful example. Their suitability depends on formulation, thickness, processing, and package design. For a product with substantial oxygen demand, gas transfer through an unperforated film may be insufficient. Perforation can increase exchange, but it also changes moisture movement. If the resulting package allows excessive water loss, the adjustment solves the gas problem at the expense of texture and appearance. Choosing PLA therefore requires decisions about the complete film structure and its use.

Adding other components can change several properties at once. In the fresh-cut apple experiment discussed earlier, incorporating cinnamaldehyde and ZnO nanoparticles into PLA lowered oxygen permeability and increased water vapour permeability compared with pure PLA. The packaged apples retained several quality attributes better but lost more weight by the end of storage. These results make the trade-off concrete: improved appearance and texture occurred alongside weaker protection against water loss. The active components also contributed to preservation, so the outcome reflects the combined formulation.

The importance of that trade-off depends on the product's main route of quality loss. For apple slices that become unacceptable because of browning, a formulation that retains colour may provide a useful benefit if dehydration remains within an acceptable range. For lettuce that loses marketable quality through wilting, the same increase in water vapour transfer could be a more serious limitation. A material ranking based on one quality indicator would miss this difference. Selection should consider when the product becomes unacceptable and which packaging properties contribute to that change.

Blends and multilayer films offer ways to distribute functions across different components. One component may support flexibility, while another contributes to gas or moisture control. This can broaden the range of usable properties, but the resulting structure must still operate as a complete film. Layer thickness, adhesion, and sealing behaviour influence its performance. A barrier layer that improves oxygen resistance may become restrictive for a respiring product. Greater structural complexity is useful only when it resolves a defined packaging need.

Thickness creates another compromise. Increasing thickness can improve resistance to puncture and handling damage, but it generally reduces gas and water vapour transfer through a given area. This may help moisture retention while limiting oxygen supply. Reducing thickness has the opposite effects and may increase the risk of damage. The preferred thickness depends on product loading, package dimensions, and the support provided by the packaging format. A film used as a tray closure may face different mechanical demands from one used to form a flexible bag.

Conventional films provide a practical benchmark for assessing these choices. Comparing a biodegradable package with the package currently used for the product helps establish whether the proposed replacement maintains acceptable quality under the same conditions. The comparison should include product mass, storage duration, temperature, and package design. Differences in these conditions can alter the outcome as much as the material itself. A useful comparison identifies which functions the replacement performs adequately and where further adjustment is needed.

Reported material properties should also be interpreted according to how they were measured. Oxygen permeability, water vapour transmission, and tensile strength describe different aspects of performance. A low permeability value cannot compensate for an unreliable seal, and high tensile strength cannot establish suitable gas exchange. Measurements taken under different temperature or humidity conditions may also give an incomplete picture of relative performance. The most useful evidence connects film properties with the behaviour of a package containing the intended product.

A practical choice can begin by setting essential requirements. The package must provide adequate oxygen, avoid damaging carbon dioxide accumulation, maintain acceptable moisture levels, and remain intact during use. Materials that fail these requirements need changes in formulation or package design before other benefits become relevant. Among the remaining options, selection can weigh preservation quality, processing needs, material use, and disposal conditions. This approach gives each property a clear role and makes the reasons for accepting a particular trade-off explicit.

7. Application Boundaries and Practical Selection Priorities

The suitability of a biodegradable film depends on a defined application. Produce type, cutting method, portion size, package dimensions, and storage conditions determine the demands placed on the material. A change in any of these factors can alter gas balance or moisture loss. Material recommendations should therefore identify the conditions under which the film provides acceptable preservation.

Product loading is an important boundary. Increasing the amount of produce raises total oxygen consumption and carbon dioxide production. If film area remains unchanged, gas exchange may become insufficient. Reducing the portion can create a different problem: more film area is available per unit of produce, which may increase moisture loss relative to product mass. Commercial portion sizes need to be considered when deciding whether a tested film can be used without further adjustment.

Preparation also affects packaging needs. Smaller pieces expose more cut surface and may release more moisture or undergo faster quality changes. Washing and draining influence how much liquid enters the package. Handling damage can add another source of fluid and deterioration. These conditions help explain why the same film may produce different results across studies or processing operations. A packaging recommendation becomes more useful when it specifies the product preparation as well as the material.

The intended shelf life provides another boundary. An acceptable result after a few days does not establish suitability for a longer storage period. Moisture loss can accumulate, package gases can change, and the film may face prolonged contact with a humid environment. The relevant endpoint is the period during which the product must remain acceptable for sale and consumption. Evaluation should cover that period under the expected storage conditions.

Material selection can begin with the product's main quality problem. For lettuce, maintaining leaf texture and appearance may be the immediate priority. For apple slices, browning and firmness loss may carry greater weight. These priorities guide the choice of film properties, but gas balance remains essential in both cases. A material that addresses the most visible defect while creating unsuitable oxygen or carbon dioxide levels will require changes before practical use.

The next step is to connect the film to a specific package. Product mass, exposed film area, thickness, headspace, and perforation should be considered together. Available permeability measurements can help narrow the choices. Storage evidence from packages containing the product can then show whether oxygen supply, carbon dioxide removal, and moisture retention remain adequate. Where results are unsatisfactory, the cause should guide the adjustment. Excessive water loss may call for changes in moisture resistance or perforation, while low oxygen may require greater gas exchange or reduced loading.

Production compatibility must be assessed alongside preservation. A film needs to run through the intended packaging equipment and form reliable seals at workable settings. Changing the sealing method may resolve a problem that would otherwise appear to be a material limitation. Evidence from the pre-cut lettuce study showed that seal quality and product performance changed when a different sealing method was used. This supports evaluating the film with the equipment intended for its application.

Disposal requirements add a separate selection criterion. The term biodegradable does not identify the conditions or time needed for a finished package to break down. Selection should use information for the complete film structure, including its additives and layers. If a package is intended for a particular composting route, its documented suitability and access to that route become part of the application decision. The disposal claim should correspond to the finished package and its expected destination.

Wider use requires evidence that connects material measurements, packaged-product quality, and production conditions. For a new formulation, useful work would include gas and moisture measurements at the intended refrigeration temperature, storage trials with commercial portion sizes, and sealing checks on the selected equipment. Temperature fluctuations should reflect those likely to occur during distribution and retail handling. These results would show whether a film can tolerate routine changes in use and identify which adjustments are needed before adoption.

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