

Designing packages for fresh-cut produce

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PACKAGES FOR FRESH PRODUCE ARE expected to prolong shelf life. The fruit or vegetable inside needs to breathe, so the package is designed to let oxygen and carbon dioxide pass through. Customers need to see the produce clearly to make a decision. Is this lettuce fresh? Are these carrots okay? If the bag is punctured or if its seal is broken, its perishable contents may suffer and will not be suitable for the table.

Consumers take these safeguards for granted at the grocery store, but the package design is not so simple. The package has to maintain a modified atmosphere that is favorable to the particular fruit or vegetable within. Designing the package involves calculations, consideration of chemical reactions, and a knowledge of the appropriate materials.

GATHERING THE INFORMATION

The designer has to start with information about the specific use for which the package is intended. As a first step, appropriate data should be gathered to ensure that packages are suitably designed.

First, the designer needs to know what type of produce is to be packaged. Carrots and lettuce require packages of different shapes, for example. The designer has to know the surface area needed and the approximate weight of the produce. What minimum thickness is required?

At what temperatures is the produce likely to be stored? How permeable will the film need to be at specific temperatures? Permeability

varies greatly with temperature, and the produce is directly affected by temperature as well.

The designer also has to know the respiration rate of the produce and its CO_2/O_2 respiration quotient. All of this information is needed before the designer can formulate an appropriate package made of multi-layer film.

EXTENDING SHELF LIFE

The package is designed to maintain a modified atmosphere within to extend the shelf life of the produce. This atmosphere changes, however, and the film has to breathe to allow for the respiration of the produce.

Sometimes the grower or produce packager will specify the optimal modified atmosphere and film breathability. If the package permeability is not specified by the grower, then it must be determined on the basis of postharvest physiology. This assessment requires an understanding of produce senescence and respiration and the effects of conditions on these complex processes.

Respiration

Produce continues to live and respire even after it is harvested. The fruit or vegetable in the package breathes in oxygen and gives off carbon dioxide. The respiration rate depends on what kind of produce it is, how old it is, the storage temperature, the type of wash used to clean it, and the concentrations of O_2 , CO_2 , and C_2H_4 in its surrounding atmosphere.

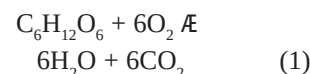
One common reaction in produce is given by Eq. 1:

ABSTRACT

Packages for fresh produce are designed to extend shelf life. Rates of transmission of oxygen, carbon dioxide, and ethylene should be high enough to match produce respiration rates at various temperatures. The package should be clear, and it must resist puncture from stems and pointed edges. Designers make mathematical models, consider the effects of chemical reactions, and make use of new materials. Among these, polyolefin plastomers are excellent for modified-atmosphere packages for fresh-cut produce.

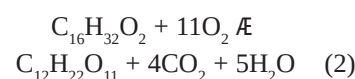
Application:

This paper maps the procedures required to design optimized Modified Atmosphere Packages (MAP) for produce. It contains basic formulas, reference information and example calculations. It also discusses the properties of polyolefin plastomers (POP).



In this reaction, the oxidation of glucose, one CO_2 molecule is produced for every molecule of O_2 depleted.

The ratio of carbon dioxide to oxygen, CO_2/O_2 , is called the "respiration quotient" (RQ). If this were the only reaction occurring, the RQ would be 1.00.¹ However, depending on the composition of the produce, other reactions occur to further characterize the respiration quotient. These reactions may include the oxidation of palmitic acid (Eq. 2, $\text{RQ} = 0.36$) and that of malic acid (Eq. 3, $\text{RQ} = 1.33$)¹:





Changes in the concentrations of oxygen, carbon dioxide, ethylene, and water can increase, decrease, or leave unaffected the reaction rates for chemical processes such as these. In many design calculations, the respiration quotient is assumed to be equal to 1.0. This assumption is adequate for many types of produce held in cool storage during the healthy phase of the life of the fruit or vegetable.

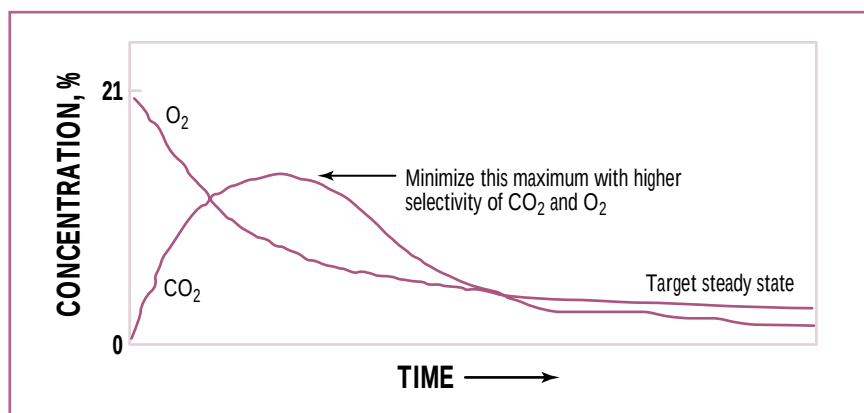
Senescence

Fruits and vegetables age through chemical reactions in a process termed "senescence." By modifying the storage atmosphere, we can gain some control over the reactions involved in senescence. The designer can create a package to achieve specific goals, such as:

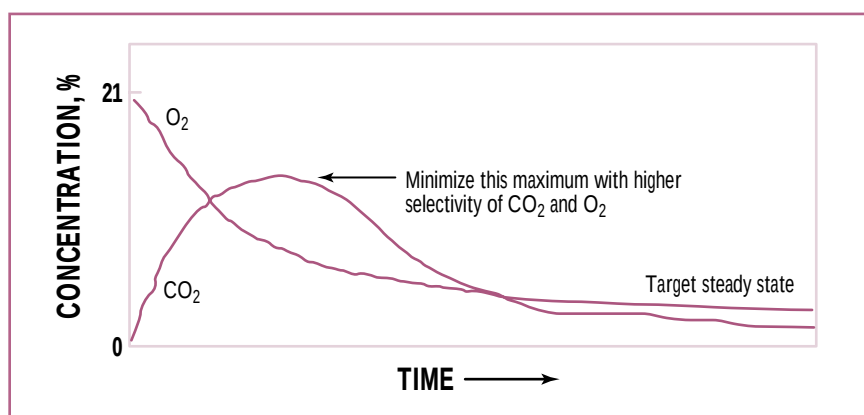
- Maintain chlorophyll in green vegetables
- Control starch-to-sugar conversions in potatoes
- Control sugar-to-sugar conversions in peas
- Retard the breakdown of pectins and other polysaccharides in fruits
- Control the lignin content in asparagus and root vegetables
- Retard various changes in organic acids and proteins that cause a peculiar taste and odor.

Storage atmosphere

Oxygen. Senescence can be slowed if the produce can be stored at cool temperatures in oxygen concentrations of 2–5%. Some types of produce, however, require higher oxygen concentrations of 5–7% to extend shelf life.¹ Lower oxygen concentrations can further inhibit respiration, but there is a risk of early rotting. If the oxygen supply is com-



1. Results of a typical mathematical model



2. Water vapor transmission rates for films made from polyolefin plastomers (POP), ethylene vinyl acetate (EVA), and ultra-low-density polyethylene (ULDPE)

pletely depleted, the produce will revert to anaerobic respiration and will spoil rapidly.

Carbon dioxide. Optimum concentrations of carbon dioxide can range from 1% to 20%. Some types of produce benefit from high concentrations of carbon dioxide, but others suffer. In packages containing strawberries, for example, carbon dioxide at a high concentration acts as a fungistat to preserve the fruit. In packages for lettuce, however, carbon dioxide at levels above 2.5% can cause brown staining, which customers will not find appealing.

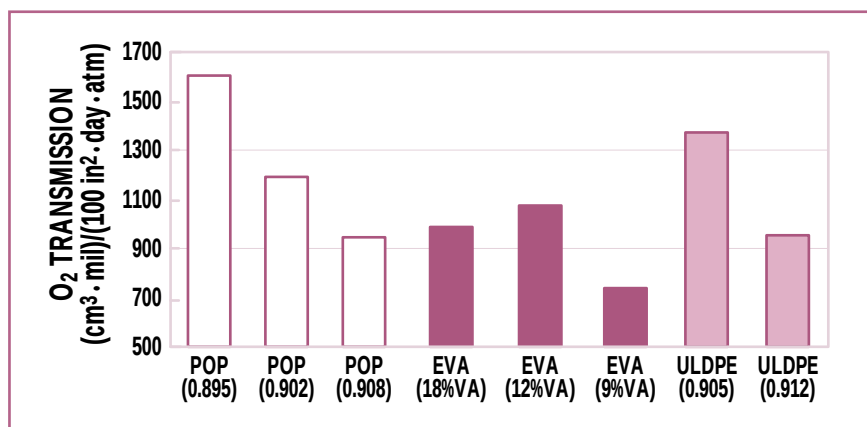
Packages should be designed to control the concentrations of both carbon dioxide and oxygen. The

package should maintain low carbon dioxide levels in the steady-state period and during the transition period. During the transition period, the oxygen level falls, and the respiration of the produce slows as the system approaches steady state. Often, films with a high selectivity of CO_2/O_2 are needed to control the level of CO_2 during the transition period.

Ethylene. Ethylene concentrations can vastly accelerate the aging of fruits and vegetables. Generally, fruit produces more ethylene than vegetables produce. Fruit is also more sensitive to the presence of ethylene.

Relative humidity. Generally,

¹Kays, J. S., *Postharvest Physiology of Perishable Plant Products*, Van Nostrand Reinhold, New York, 1991, pp. 103, 108.



3. Oxygen transmission rates for films made from polyolefin plastomers (POP), ethylene vinyl acetate (EVA), and ultra-low-density polyethylene (ULDPE)

high humidity levels should be maintained in a package to prevent the produce from drying and losing weight. For most leafy and root vegetables, 98–100% RH is recommended. For some fruits, a relative humidity of about 90% is satisfactory; higher levels of moisture are conducive to the growth of fungi, and lower levels cause rapid drying.²

MODIFIED ATMOSPHERE

Mathematical modeling

The designer gains insights by mathematically modeling the produce package. The effects that the package will have on the produce and its modified atmosphere can be different from what one might expect. Mathematical modeling can bring these effects to light. Modeling is especially helpful in the effort to predict the changes that take place during the transition period.

Figure 1 is a diagram of the results of a typical mathematical model. Initially, the oxygen concentration of the package is atmospheric, at 21%. Oxygen begins to deplete as the produce respire. The metabolism and respiration slow

until a steady-state condition is reached. At steady-state, the rate of oxygen entering the package will be equal to the rate of oxygen being consumed by the produce.

During this period, the produce releases carbon dioxide, and the CO₂ concentration increases in the package. This concentration can remain high for several days, long enough to cause lettuce to stain brown, for example. The CO₂ percentage will remain high until the gas pressure increases, creating diffusion from the inside atmosphere to the outside atmosphere. The respiration rate begins to retard, and the carbon dioxide percentage decreases to reach a steady-state condition.

With such a model, a package can be optimized to control gas concentrations during the transition and steady-state periods of the packaged life of the produce. The initial data must be empirical, but once a baseline of respiration data is established, a model can help in optimizing the produce package.

Design for the steady state

At steady state, the total amount of O₂ and CO₂ respired by the produce will be equal to the total amount of gas that permeates through the package. The permeability needed for the package may be calculated on the basis of O₂ and CO₂ respirations.

$$\text{CO}_2 \text{ out} = \text{CO}_2 \text{ respired} = \text{CO}_2 \text{ respiration rate} \times \text{produce weight} \quad (4)$$

$$\text{O}_2 \text{ in} = \text{O}_2 \text{ respired} = \text{O}_2 \text{ respiration rate} \times \text{produce weight} \quad (5)$$

The values for respiration rates are based on the predicted storage temperatures and steady-state concentrations of O₂ and CO₂.

To extend shelf life, the package must reach steady-state percentages of oxygen above about 2%. If the film permeability is too low, the oxygen can be completely depleted, causing anaerobic respiration. On the other hand, carbon dioxide may be depleted if the CO₂ transmission rate is too high.

Carbon dioxide depletion may be beneficial, however, in cases in which browning can occur, such as with lettuce. Materials for packages meant to keep produce from browning require high selectivity for O₂ and CO₂. Films made from resins such as polyolefin plastomers provide this kind of selectivity.

Designs for packages for some types of produce, such as strawberries, call for high concentrations of carbon dioxide. The steady-state design is more complicated for these packages. Low CO₂ and high C₂H₄ permeabilities might be demanded, which is difficult to obtain from a single film.

Design for the transition state

To determine the optimum permeability for the transition period of the package, the designer should use mathematical modeling. For produce for which low CO₂ levels are beneficial, designers should specify films with high selectivities for CO₂ and O₂, as mentioned. Designers can also affect the magnitude of the maximum amount of carbon dioxide by altering the headspace of the bag.

Common packaging materials

Some resins commonly used for produce packaging are ultra-low-density

²Hardenburg, R. E., Watada, A. E., and Wang, C. Y., *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks*, Government Printing Office, Washington, DC, 1986.

polyethylene resins (ULDPE), polyolefin plastomers (POP) with long-chain branching, and ethylene vinyl acetate (EVA) copolymers. Figure 2 presents water vapor transmission rates for films made from some of these materials.

Figure 3 compares these resins in terms of the oxygen transmission rate. Polyolefin plastomers have high O_2 , CO_2 , and C_2H_4 transmission rates. (The volume unit of cm^3 reflects the volume at the test temperature of $25^\circ C$.) Polyolefin plastomers are approved by the Food and Drug Administration for use at lower densities than those approved for other polyolefin resin families. The FDA approval makes it possible for designers to specify POP resins for applications in which the material directly contacts food.

PERMEABILITY

In designing packages, it is important to understand the conditions under which a film's oxygen permeability has been determined. Many factors affect this permeability value.

External testing conditions that impinge on this value include the temperature, the gas composition of the test atmospheres, and the relative humidity. The film's thickness and the layer ratios are factors that pertain to the composition of the multilayer film. Factors intrinsic to the material used in each layer are the material's crystallinity and the proportion of holes in its surface.

The designer's task is to match the permeability of the multilayer film to the permeability required for a specific package.

Temperature

The O_2 , CO_2 , and C_2H_4 permeabilities of a film are dependent on temperature. If we know the transmission rates of a film at two different temperatures, then we can solve for the Arrhenius activation energy, E_A , from the ratio of Eq. 6:

$$\frac{P_1}{P_2} = \frac{e^{\left(\frac{E_A}{RT_1}\right)}}{e^{\left(\frac{E_A}{RT_2}\right)}} \quad (6)$$

where

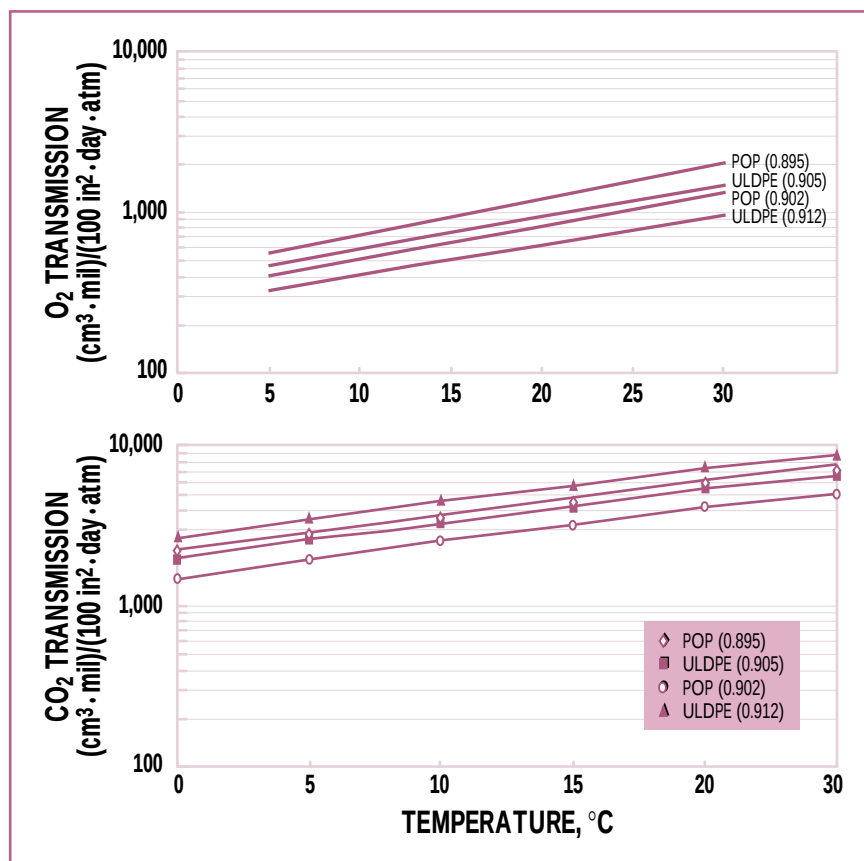
P = permeability

R = ideal gas constant

T = temperature.

The activation energy can then be used to predict the transmission rate at a third temperature.

Figure 4 shows the relationships between O_2 and CO_2 transmission rates and temperature for some polyolefin plastomers and ultra-low-density polyethylene resins. These O_2 and CO_2 transmission rates were



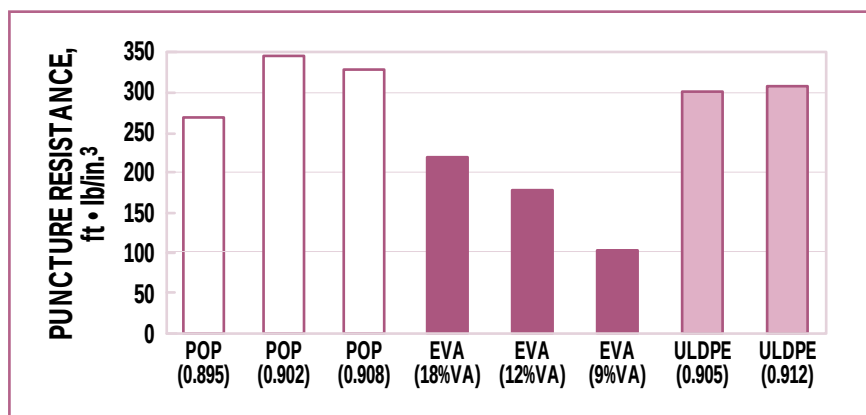
4. O_2 and CO_2 transmission rates increase with increasing temperatures for two POP resins at densities of 0.895 and 0.902 and two ULDPE resins at densities of 0.905 and 0.912.

graphed by taking data at six different temperatures. (Experiments were run three to five times for each data point.) Furthermore, the CO_2 transmission rates for polyolefin plastomers and ULDPE resins are approximately 2.2 times those of their C_2H_4 transmission rates (not shown).

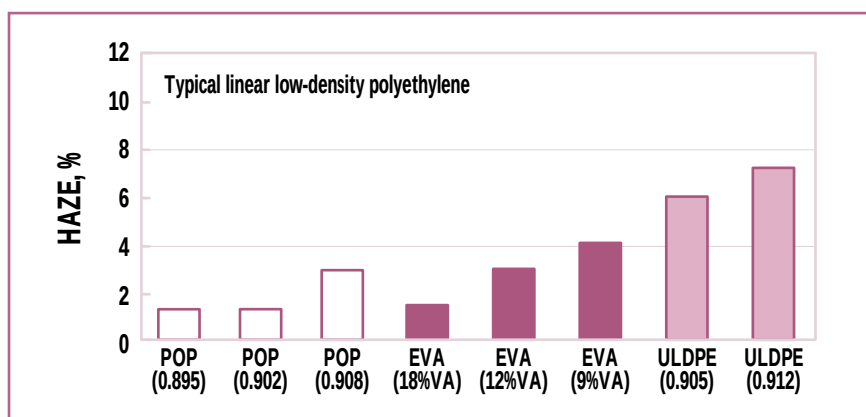
Grocers try to keep produce in storage at about $40^\circ F$ ($4-5^\circ C$). However, because of inadequate shelf space and deficient refrigeration, the storage temperature is often higher.

Composition of test atmosphere

The oxygen permeability of a film is often obtained by measuring the transmission rate across a film with 100% O_2 on one side and 0% O_2 on the other side. However, these conditions may not have been observed in



5. Puncture resistance values for POP and ULDPE show that their physical integrity exceeds that of the EVA resin.



6. Optical properties of POP, EVA, and ULDPE films are excellent, as indicated by these low percentages of haze.

testing. If not, the reported values would have to be corrected to determine the actual transmission across the film.

Suppose, for example, the tests were carried out without controls on the oxygen content. The air outside the package may have been that of the normal atmospheric composition, with 21% O₂. Inside the package, the oxygen content was maybe 3%. The permeability measured under these conditions would have to be multiplied by 21% – 3%, or 0.18.

Relative humidity

The oxygen permeability of polyethylene resin is not affected by relative

humidity. The oxygen transmission rates of polymers such as EVOH, by contrast, are affected by humidity.

Thickness

The thickness of the film will affect the transmission rate. Theoretically, the transmission rate of a 2-mil film should be exactly half that of a 1-mil film made from the same resin. However, cooling phenomena can cause films to have amorphous and crystalline regions that are different in thicker films than in thinner films. These areas of dissimilarity affect the transmission rate.

Generally, thinner films cool more quickly than thicker films. Therefore, thinner films will have

more amorphous regions, which means higher transmission rates per unit of thickness.

Layer ratios

The permeability of a multilayer film can be calculated based on the transmission rates of the films that compose it. In the following equation, P_{total} is the overall permeability of a multilayer film.

$$P_{total} = ([gas]_{out} - [gas]_{in}) / [(t_1/P_1) + (t_2/P_2) + \dots + (t_n/P_n)] \quad (7)$$

$[gas]_{out}$ = gas concentration outside the package

$[gas]_{in}$ = gas concentration inside the package

t_n = thickness of film n

P_n = permeability of film n .

Film crystallinity and film holes

Different polymer films have different O₂, CO₂ and C₂H₄ permeabilities. These films may differ in their selectivities to each gas as well. Polyolefin plastomers are highly selective to the ratio of CO₂ and O₂, for example, and this high selectivity cannot be duplicated by putting holes in a film of lower permeability.

Films with holes discriminate less effectively among the various gases. Void spaces allow gases to diffuse through the film by random gas motion, and the permeability depends largely on how much of the surface area is taken up by holes. The CO₂/O₂ selectivity of these films will therefore be closer to 1.0 than that of an unpunctured film.

The permeabilities of unpunctured polyolefin films depend to some extent on the random motion of gases through the void spaces in the film. However, the permeabilities also rely heavily on the propensity for various gases, both polar and nonpolar, to solubilize into the films.

KEYWORDS

Addition polymers, controlled atmospheres, food wrap film, gas permeability, package design, packaging films, packaging materials, permeability, physical properties, plastic films, polyhydrocarbons, polyolefins, produce, properties, thermoplastics.

Permeability target for a particular package

To determine the permeability for a specific design (SP), divide the respiration rate of the produce by the surface area of the package:

$$O_2 SP = (O_2 \text{ respired})/\text{area} \quad (8)$$

$$CO_2 SP = (CO_2 \text{ respired})/\text{area} \quad (9)$$

To begin designing a package, the designer must identify films that approximate the permeability requirements. The designer can then consider other film properties to make the final selection.

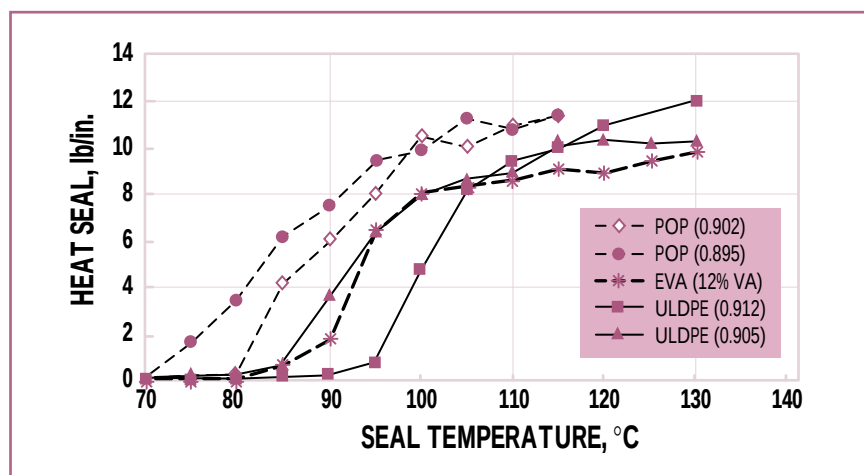
PACKAGE INTEGRITY

Designers have several other aspects of the package to consider in choosing the materials. How strong will the film be? What about its optical qualities? How well will it hold a seal?

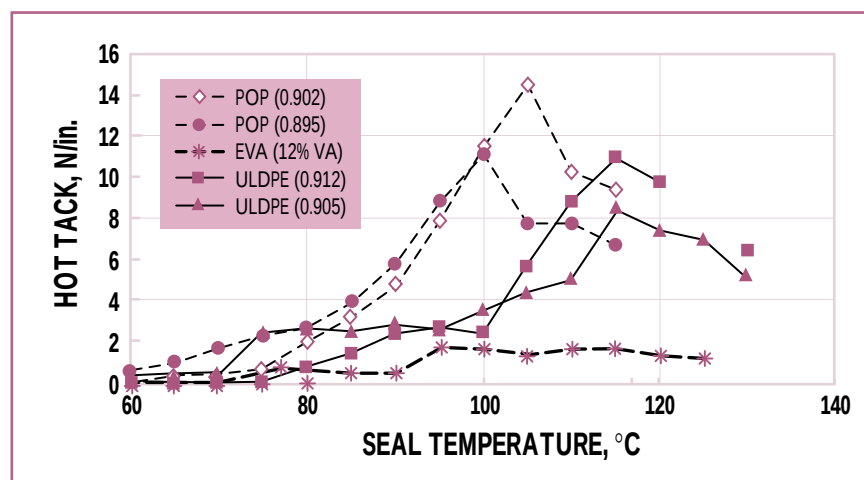
Film physical integrity

A film should resist puncturing and tearing to preserve the package integrity throughout the life of the produce. Many growers even test their bags by filling them with air and holding them underwater to check for leaks caused by tears, punctures, or seal imperfections.

ULDPE and POP resins have outstanding puncture and tear resistance, exceeding the physical integrity of EVA resins. As the bars in Figure 5 show, POP and ULDPE resins have 20–50% better puncture resistance than EVA with 18% vinyl acetate. Furthermore, these same



7. In heat seal properties, POP resins and the EVA with 18% vinyl acetate have the best seal-initiation temperatures.



8. In hot tack, POP and ULDPE resins out-perform the EVA resins.

resins have puncture resistance values that are more than 300% better than the puncture resistance of EVA with 9% vinyl acetate.

Film optics

Consumers accustomed to examining unpackaged produce will demand packages clear enough to allow them to judge the freshness of their purchases. A clear package material has a low haze value. Figure 6 presents haze values for several key resins used in this market.

Polyolefin plastomers of low density (0.895 and 0.902) and EVA resin with 18% vinyl acetate have haze

values of less than 2%. With excellent optical properties, these materials are suitable for clear packages. As the figure shows, ULDPE resins also have good optical properties, with about 6% haze. These ULDPE resins are suitable for many packages designed to contain produce that customers examine.

Film sealing performance

Heat seal and hot tack are properties that pertain to the sealing performance of the film. Heat seal is a measure of the force required to peel a seal after the seal has cured for 24 h. Hot tack is a measure of the force

required to peel a seal right after it is made, while the seal is still hot. Good heat seal and hot tack ensure high production-line speeds and leak-proof seals.

As Fig. 7 shows, the polyolefin plastomers of low density (0.895 and 0.902) and the EVA with 12% vinyl acetate have the best seal-initiation temperatures (below 85°C). These materials also have high ultimate heat seal values, which means high seal integrity. ULDPE resins and EVA of a lower percentage of vinyl acetate also have very high ultimate heat seal values, at greater than 40 N/25 mm.

In hot tack, polyolefin plastomers out-perform EVA resins by 500–600%, as Fig. 8 indicates. The ULDPE resins out-perform the EVA resin with 12% vinyl acetate by 400–500%. Such excellent hot tack performance for both POP and ULDPE resins prevents leaks from being created as form/fill/seal equipment jaws are released.

On most film for form/fill/seal operations, an outer layer resistant to heat is used to allow heat to transfer through the package to the sealant without melting or destroying the package. Polystyrene, polypropylene, and styrene–butadiene polymers can be used as heat-resistant layers. These materials yield high clarity and moderate levels of oxygen transmission. (The heat seal data presented here were generated from nylon coextrusions because nylon was readily available. Nylon is a high-barrier resin that is not appropriate for breathable packages.)

For smooth performance on form/fill/seal equipment, the coefficient of friction must be low. For most sealant resins of high clarity, the coefficient of friction must be modified by the addition of slip and antiblock additives. Designers should choose additives that least affect the optical properties of the film.

SUMMARY

Packages for fresh-cut produce must be carefully designed to sustain a modified atmosphere. The package must breathe with the produce to support a long shelf life.

The physical integrity is engineered to defend the package against punctures and tears. Seal integrity is designed to ensure that the effectiveness of the package is not lost as a result of a seal failure. Additionally, these packages demand excellent optical properties to allow the consumer to ascertain the freshness of the produce.

Polyolefin plastomers offer the highest optimized combination of these properties. As a result, polyolefin plastomers are an excellent fit for produce packaging. TJ

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