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Selection of a surface coating and optimisation of its concentration for use on 'Hass' avocado (*Persea americana* Mill.) fruit

JASON W. JOHNSTON
NIGEL H. BANKS
Centre for Postharvest and Refrigeration Research and
Department of Plant Science
Massey University
Private Bag 11 222
Palmerston North, New Zealand.

Abstract Effects of surface coatings on gas exchange characteristics of 'Hass' avocados (*Persea americana* Mill.) were used to select a suitable coating and to optimise its concentration for use on avocado fruit at 20°C, 60% relative humidity. Of six different surface coatings used, "Avocado wax" provided the greatest level of benefit (reduction in mass loss and enhanced sheen) for a given level of risk (modification of internal oxygen and carbon dioxide partial pressures). At the other extreme, 2% carboxymethylcellulose provided no benefit but substantially increased risk of fermentation. "Apple clear" treated fruit had lowest rates of mass loss, but had poor visual quality. Of the Avocado wax concentrations assessed, 11% was the optimum. Concentrations greater than this provided marginal further gains in the reduction of mass loss, but imposed unacceptable levels of risk of anaerobiosis in the fruit. A packhouse trial confirmed this concentration as optimum, but achieved somewhat lower levels of benefit.

Keywords avocado; *Persea americana* Mill.; carbon dioxide; fermentation; gas exchange; internal atmosphere; mass loss; optimisation; oxygen; respiration; skin permeance; surface coating; water loss; wax

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INTRODUCTION

To reduce the New Zealand avocado (*Persea americana* Mill.) industry's strong dependence on Australian markets, alternative Pacific Rim markets are being developed. In doing so, a low cost system is required to transport fruit greater distances without sacrificing fruit quality. Part of this system will need to minimise increased fruit mass loss associated with longer transit time.

After harvest, horticultural products lose mass predominantly through water loss (transpiration) but also through carbon loss associated with respiration (Gaffney et al. 1985). To compensate for mass loss associated with extended transportation and storage periods, packhouses would need to over-pack trays, thereby adding to costs of production. In addition, mass loss can have a number of adverse effects on fruit quality, including faster ripening (Littmann 1972; Adato & Gazit 1974; Cutting & Wolstenholme 1992; Joyce et al. 1995) and increased incidence of physiological disorders and rots (Bower et al. 1989; Cutting & Wolstenholme 1992). Technologies used in other crops to reduce mass loss, principally through their effects on water loss, have included low temperature storage, high relative humidity storage, tray liners, and surface coatings (Wills et al. 1989); the main focus of this paper is on the last of these options.

Although surface coatings reduce diffusion of water out of fruit, they also hinder the diffusion of other gases such as carbon dioxide (CO_2), oxygen (O_2), and ethylene (Ben-Yehoshua 1987; Ben-Yehoshua & Cameron 1989; Banks et al. 1993; Banks et al. 1997). As a result of respiration and limited skin permeance to respiratory gases, the atmosphere inside the fruit is modified, with a lowering of internal O_2 partial pressure ($p^i_{O_2}$, Pa) and elevation of internal CO_2 partial pressure ($p^i_{CO_2}$, Pa). Thus, surface coatings provide potential for reducing respiration (Meheriuk & Porritt 1972; Smith & Stow 1984; Hagenmaier & Shaw 1992) as well as water loss (Durand et al. 1984; Hagenmaier & Shaw 1992; Joyce et al. 1995). In addition, surface coatings provide some visual benefits by increasing sheen or perceived depth of colour (Hagenmaier & Baker 1995; Banks et al. 1997).

The principal disadvantage of surface coatings is that if respiratory gas exchange through the skin is excessively impaired, off-odours and off-flavours may develop from fermentation (Hagenmaier & Shaw 1992; Banks et al. 1993), which may cause the fruit to ripen unevenly (Meheriuk & Lau 1988; McGuire & Hallman 1995). This problem can be minimised through use of coatings with appropriate permeability characteristics. Some criteria for the optimisation of surface coatings have recently been explored (Banks et al. 1997) and were adopted for the purposes of this research.

Although several publications have described responses of avocado fruit to surface coatings (Peasley 1976; Durand et al. 1984; Bender et al. 1993; Joyce et al. 1995), none have attempted to compare different surface coatings, nor optimise the concentration for use on this fruit. The focus of this investigation was to determine the best type of surface coating for 'Hass' avocados and its optimum concentration for reducing mass loss without adversely affecting fruit quality. A packhouse trial was conducted to confirm the laboratory derived optimum.

MATERIALS AND METHODS

Fruit

For the first two experiments, two shipments of export quality, 23 count fruit were transported from a commercial packhouse in Northland, New Zealand, to Massey University, Palmerston North within 72 h of harvest. For the third experiment, fruit of three count sizes (23, 25, and 27) were mixed together, before being randomly allocated to treatments. These fruit were delivered to Massey University within 24 h of harvest. All fruit had the postharvest fungicide "Sportak" (Schering Agrochemicals Ltd, Germany; active ingredients—prochloraz and xylene) applied to control fungal rots.

Experimental

All experiments had completely randomised designs. Wet and dry bulb (thermistor probes and dew point hygrometer), and skin temperatures (thermistor probes) were recorded on a Grant 1200 Series "Squirrel" data logger. Water vapour pressure deficit was calculated using standard psychrometric equations (Campbell 1977).

Comparison of various surface coatings

There were 17 replicates (individual fruit) per treatment. Treatments included: a non-waxed dry control; undiluted "Apple clear" (Castle Chemicals, Australia); undiluted "Apple glaze" (Castle Chemicals, Australia); undiluted "Citruseal" (Milestone Chemicals, Australia); undiluted "Citrus gleam" (Castle Chemicals, Australia); carboxymethylcellulose (CMC; 2% in aqueous solution, low viscosity; BDH Chemicals, United Kingdom; with 0.1% w/v "Pulse" as surfactant; Monsanto, New Zealand); and "Avocado wax" (Castle Chemicals, Australia) applied undiluted or at the commercially used concentration of 1.2% in aqueous solution.

Before coating application, fruit were equilibrated on a rack in front of fans (air-flow of 2000 ± 100 mm s^{-1}) at 20 ± 2°C, 60 ± 5% relative humidity for 24 h. Coatings were applied by dipping fruit into wax emulsion for 1 min and allowing the excess to drip off. After coating application, fruit were re-positioned in front of fans to remove the boundary layer of moist air.

Measurements of mass (Mettler Toledo scales, model PR1203, grams to 3 decimal places) and rates of CO_2 emission were made 24 and 96 h after coating application. Rates of CO_2 emission were measured by placing individual fruit into opaque, air-tight containers. Gas samples (1000 mm^3) were collected from containers 0 and 15 min after sealing. Levels of CO_2 were determined by injecting gas samples into an infra-red CO_2 transducer (Analytical Development Company, Hoddeston, United Kingdom) with N_2 as the carrier gas (flow rate 580 mm^3 s^{-1}). Measurement of fruit and container volumes enabled respiration rates to be calculated.

At 96 h internal atmospheres were sampled by direct removal (Banks 1983) from the mesocarp next to the stone at the distal end while fruit were submerged in water. Aliquots of 100 mm^3 were injected into an O_2 electrode (Citicell C/S type, City Technology Ltd, London, United Kingdom) in series with a miniature infra-red CO_2 transducer (Analytical Development Company, Hoddesdon, United Kingdom) with O_2-free N_2 gas as the carrier gas (flow rate 580 mm^3 s^{-1}). Skin gloss was measured with a glossmeter (Glossgard II, Pacific Scientific, Silver Spring, MD 20910, United States).

Optimisation of surface coating concentration

Eight treatments included a non-waxed dry control and seven Avocado wax concentrations (1.2, 4.0, 11.0, 27.0, 52.6, 76.9, and 100.0% in aqueous solution).

Materials and procedures were the same as in the comparison of various surface coatings experiment.

Verification of optimum coating under commercial conditions

This experiment used a factorial arrangement of storage temperature at two levels (20 ± 2°C and 27 ± 0.5°C) and Avocado wax concentrations at six levels (non-waxed, 1.2, 4.0, 11.0, 27.0, and 50.0%). The commercial coating application method was different from that used in laboratory-based experiments, in that droplets of coating were sprayed on to fruit on a bed of rotating brushes before drying in a conveyor oven.

As these fruit were delivered to Massey University quicker than the earlier two experiments, an apple was included for a 24 h period at 18°C in each tray to ensure initiation of ripening. After ripening had been initiated (skin colour began to change from green to black), half the trays from each coating concentration were transferred to 20 ± 2°C and 60 ± 5% relative humidity, and the other half to a separate room at 27 ± 0.5°C, 60 ± 2% relative humidity. Within each temperature treatment, 20 fruit (individual fruit replicates) had weight and rate of CO_2 emission measured at 48 h, and 72 h (27°C fruit only) or 96 h (20°C fruit only) after being placed in the respective storage environments. Internal O_2 and CO_2 levels were measured at 72 h (27°C fruit only) or 96 h (20°C fruit only).

Data preparation and analysis

From these measurements, rates of mass loss (μg s^{-1}), respiration rates (nmol kg^{-1} s^{-1}), rates of water loss (μg s^{-1}), skin permeances to water (nmol s^{-1} m^{-2} Pa^{-1}), and $p^i_{O_2}$ (kPa) and $p^i_{CO_2}$ (kPa) were calculated using standard formulae (Banks et al. 1995; Yearsley et al. 1996). Skin permeance to water was calculated assuming that surface area could be estimated approximately from mass using a regression equation for apples (Clayton et al. 1995). These estimates were recognised as being only approximate, as mass would not have accounted for the bumps on avocado fruit skin and differences in shape and density between the two fruit types.

Data were analysed using the general linear model procedure of SAS for analysis of variance (Littell et al. 1991) and the non-linear procedure of SAS for curve fitting (SAS 1990). Standard error of the differences (SED) was calculated for comparison of treatments.

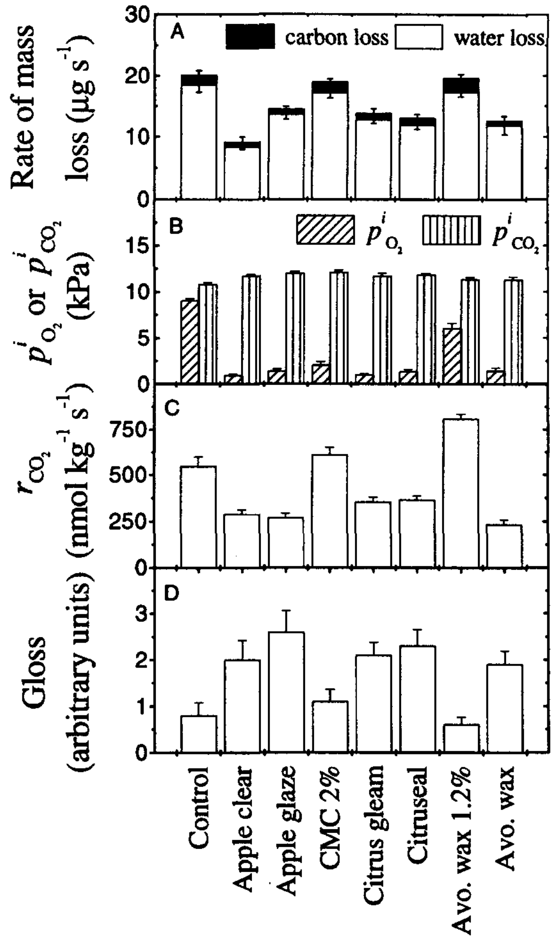

Fig. 1 Responses of 'Hass' avocado (*Persea americana* Mill.) fruit to different types of surface coatings while stored at 20°C, 60% relative humidity. **A**, Rate of mass loss (SED = 1.3 μg s^{-1}; $P < 0.0001$; 128 d.f.) attributable to carbon loss through respiration and water loss (SED = 1.0 μg s^{-1}; $P < 0.0001$; 128 d.f.). **B**, Internal oxygen partial pressure ($p^i_{O_2}$; SED = 0.4 kPa; $P < 0.0001$; 128 d.f.) and internal carbon dioxide partial pressure ($p^i_{CO_2}$; SED = 0.3 kPa; $P = 0.0024$; 128 d.f.). **C**, Respiration rate (r_{CO_2}; SED = 46.9 nmol kg^{-1} s^{-1}; $P < 0.0001$; 128 d.f.). **D**, Gloss (SED = 0.3; $P = 0.0003$; 128 d.f.). SEMs are also shown ($n = 17$). All measurements were made 96 h after coating application, with an additional weight measurement being made at 24 h to determine rate of mass loss.

RESULTS

Comparison of different surface coatings

Surface coatings differed substantially in their effects on rates of mass loss of avocado fruit (Fig. 1A). Fruit coated with 2% CMC or 1.2% Avocado wax did not differ from controls in rates of mass loss or water loss. Of the undiluted coatings, the least effective coating for reducing mass loss was Apple glaze, whereas the best was Apple clear.

Surface coatings elevated $p^i_{CO_2}$ though this effect was small in comparison to the reduction in $p^i_{O_2}$ (Fig. 1B). The combined total of $p^i_{CO_2}$ and $p^i_{O_2}$ was lower than 21 kPa for coated fruit. CMC and 1.2% Avocado wax had insignificant effects on reducing mass loss (Fig. 1A), yet reduced $p^i_{O_2}$ from 9.0 kPa to 2.0 and 6.0 kPa respectively. The remaining coatings all reduced $p^i_{O_2}$ to less than 2.0 kPa.

Undiluted coating treatments reduced the respiration rate (r_{CO_2}) of the fruit (Fig. 1C). Fruit coated with undiluted Avocado wax had the lowest r_{CO_2}, followed closely by Apple glaze and Apple clear, then by Citrus gleam and Citruseal. Fruit coated with 2% CMC or 1.2% Avocado wax had a significantly greater r_{CO_2} than control fruit.

The effectiveness of coating materials in reducing P'_{H_2O} was the same as that for reducing mass loss (Fig. 2A). Fruit treated with 1.2% Avocado wax and 2% CMC had similar P'_{H_2O} to untreated controls, whereas undiluted wax coatings reduced it significantly. All treatments reduced $p^i_{O_2}$ relative to controls, with 1.2% Avocado wax being least effective. Amongst the undiluted coatings there was some variation in effectiveness in reducing P'_{H_2O} relative to their ability to alter $p^i_{O_2}$.

Surface coatings increased the glossy appearance of avocado fruit (Fig. 1D). Control fruit and those coated with 1.2% Avocado wax had the lowest gloss, whereas Apple glaze had the highest. Of the remaining coatings, 2% CMC gave the lowest gloss. The gloss value for Apple clear should be regarded with caution as the material dried in a frothy state, leaving white markings on the skin.

Optimisation of surface coating concentration

Varying the concentration of Avocado wax significantly affected rates of mass and water loss (Fig. 3A). As the coating concentration increased, rates of mass and water loss declined in a curvilinear manner, with most of the reduction in mass and water loss occurring in the first 27% of coating concentration.

Values for $p^i_{CO_2}$ were lowest in control fruit and increased asymptotically with coating concentration, reaching c. 15 kPa for wax treatments in excess of 27% (Fig. 3B). Fruit $p^i_{O_2}$ declined in a curvilinear relationship with increased coating concentration, with most of the reduction in $p^i_{O_2}$ occurring in the first 27% of coating concentration (Fig. 3B). Again,

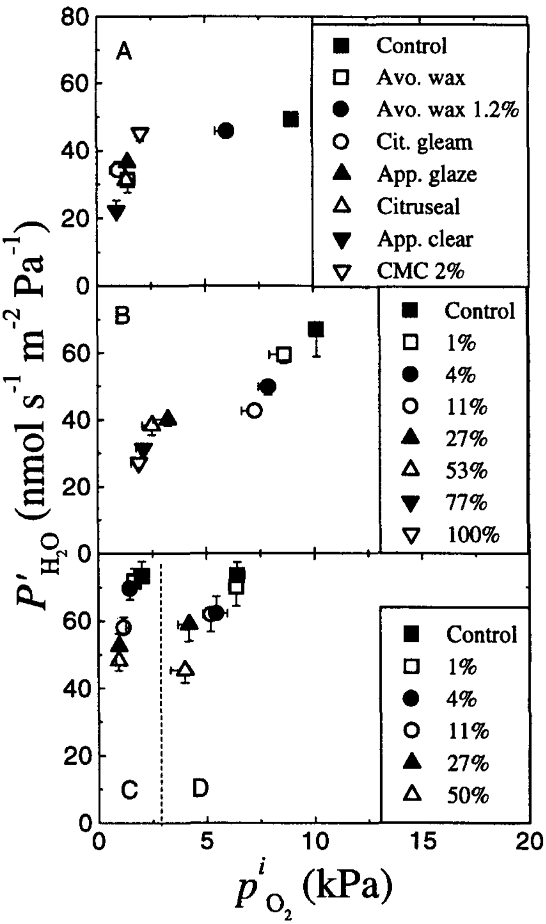

Fig. 2 Effect of surface coatings on the relationship between skin permeance to water (P'_{H_2O}) and internal oxygen partial pressures ($p^i_{O_2}$) of avocado (*Persea americana* Mill.) fruit. **A**, Effects of different surface coatings 96 h after coating and storage at 20°C, 60% relative humidity (P'_{H_2O} SED = 3.4 nmol s^{-1} m^{-2} Pa^{-1}, 128 d.f., $P < 0.0001$; $p^i_{O_2}$ SED = 0.4 kPa, 128 d.f., $P < 0.0001$). **B**, Effects of different concentrations of "Avocado wax" 96 h after coating and storage at 20°C, 60% relative humidity (P'_{H_2O} SED = 3.4 nmol s^{-1} m^{-2} Pa^{-1}, 96 d.f., $P < 0.0001$; $p^i_{O_2}$ SED = 0.7 kPa, 96 d.f., $P < 0.0001$). **C**, Effects of different concentrations of commercially applied Avocado wax 72 h after coating and storage at 27°C, 60% relative humidity (P'_{H_2O} SED = 4.8 nmol s^{-1} m^{-2} Pa^{-1}, 114 d.f., $P < 0.0001$; $p^i_{O_2}$ SED = 0.2 kPa, 114 d.f., $P < 0.0001$). **D**, Effects of different concentrations of commercially applied Avocado wax 96 h after coating and storage at 20°C, 60% relative humidity (P'_{H_2O} SED = 6.4 nmol s^{-1} m^{-2} Pa^{-1}, 114 d.f., $P < 0.0001$; $p^i_{O_2}$ SED = 0.6 kPa, 114 d.f., $P < 0.0001$). SEMs are also shown (n = 17 for A, 13 for B, and 20 for C and D).

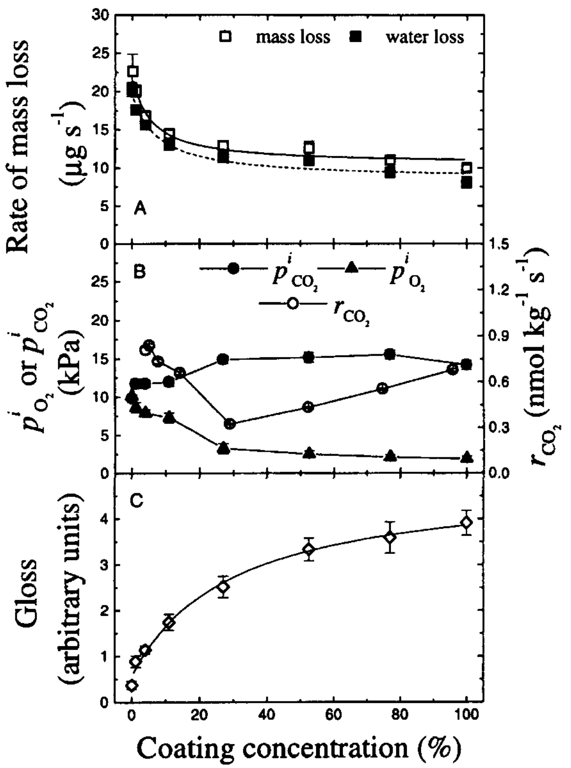

Fig. 3 Responses of 'Hass' avocado (*Persea americana* Mill.) fruit stored at 20°C, 60% relative humidity to different concentrations of "Avocado wax". **A**, Rate of mass loss (SED = 1.0 μg s^{-1}; 96 d.f.; $P < 0.0001$) attributable to carbon loss through respiration and water loss (SED = 0.9 μg s^{-1}; 96 d.f.; $P < 0.0001$). **B**, Internal oxygen partial pressure ($p^i_{O_2}$; SED = 0.7 kPa; 96 d.f.; $P < 0.0001$), internal carbon dioxide partial pressure ($p^i_{CO_2}$; SED = 0.7 kPa; 96 d.f.; $P < 0.0001$), and respiration rate (r_{CO_2}; SED = 12.6 nmol kg^{-1} s^{-1}; 96 d.f.; $P < 0.0001$). **C**, External skin gloss (SED = 0.3; 96 d.f.; $P < 0.0001$). SEMs are also shown ($n = 13$). All measurements were made 96 h after coating application, with an additional weight measurement being made at 24 h to determine rate of mass loss.

coating application depressed the sum of $p^i_{O_2}$ and $p^i_{CO_2}$.

Respiration declined with increased coating concentrations up to 27%, beyond which it increased (Fig. 3B). Coating concentration also had a significant effect on skin gloss; as coating concentration increased, so did skin gloss (Fig. 3C).

P'_{H_2O} decreased in an analogous manner to those for rates of mass loss and water loss with increased coating concentration, with most of the reduction in P'_{H_2O} occurring in the first 11% of coating concentration (Fig. 2B).

Verification of optimum coating under commercial conditions

Control fruit had slightly higher $p^i_{CO_2}$ than the remainder of treatments at 27°C (Fig. 4A), but coating concentration had no significant effect on the $p^i_{CO_2}$ of fruit stored at 20°C (Fig. 4B). Fruit at 27°C had consistently higher $p^i_{CO_2}$ than those at 20°C. At both storage temperatures, $p^i_{O_2}$ decreased in a curvilinear manner as coating concentration increased. Storage temperature also had a significant effect, where values for $p^i_{O_2}$ in fruit stored at 27°C were lower than those in fruit at 20°C. Again the total internal O_2 and CO_2 partial pressures were depressed in all fruit relative to their sum in air, an effect that was exaggerated by coating application. At both storage temperatures, r_{CO_2} steadily decreased with increased coating concentration (Fig. 4A,B).

At both storage temperatures, fruit lost mass, and water more slowly with increased coating concentration (Fig. 4C). Fruit stored at 27°C lost weight c. 10 μg s^{-1} faster than those stored at 20°C for all coating concentrations.

The effect of coating concentration on P'_{H_2O} at both storage temperatures was as described for mass and water loss. The relationship between P'_{H_2O} and $p^i_{O_2}$ was asymptotic, with $p^i_{O_2}$ apparently more sensitive to coating application than P'_{H_2O} (Fig. 2C). P'_{H_2O} was not affected by storage temperature, whereas $p^i_{O_2}$ was lower at the higher storage temperature.

DISCUSSION

Comparison of different surface coatings

The various surface coatings induced different gas exchange characteristics in avocado fruit. In common with previous research (Hagenmaier & Shaw 1992), values for P'_{H_2O} (Fig. 2A) and $p^i_{CO_2}$and $p^i_{O_2}$ (Fig. 1B) indicated that permeability characteristics for H_2O, CO_2, and O_2 were different for various surface coatings or that they interacted differently with the cuticular and pore routes of gas exchange (Banks et al. 1993). It has been proposed that O_2/CO_2 gas exchange between a fruit and its environment occurs primarily through the pores, and that CO_2 can also pass to a limited extent through the cuticle (Ben-Yehoshua 1987; Ben-Yehoshua & Cameron 1989), whereas the cuticular route is dominant in water vapour transfer (Banks et al. 1993). The

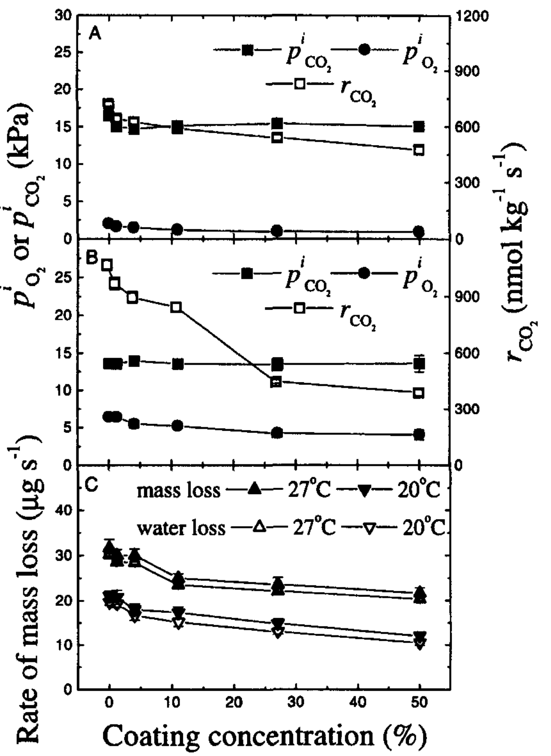

Fig. 4 Responses of 'Hass' avocado (*Persea americana* Mill.) fruit stored at 20 and 27°C to different concentrations of commercially applied "Avocado wax". **A**, Internal oxygen partial pressure (p^iO_2; SED = 0.2 kPa; 114 d.f.; $P < 0.0001$), internal carbon dioxide partial pressure (p^iCO_2; SED = 0.4 kPa; 114 d.f.; $P = 0.0002$), and respiration rate (rCO_2; SED = 23.9 nmol kg^{-1} s^{-1}; 114 d.f.; $P < 0.0001$) at 27°C, 60% relative humidity. **B**, Internal oxygen partial pressure (p^iO_2; SED = 0.6 kPa; 114 d.f.; $P < 0.0002$), internal carbon dioxide partial pressure (p^iCO_2; SED = 0.7 kPa; 114 d.f.; P = not significant), and respiration rate (rCO_2; SED = 30.9 nmol kg^{-1} s^{-1}; 114 d.f.; $P < 0.0001$) at 20°C, 60% relative humidity. **C**, Rates of mass loss (SED = 1.7 µg s^{-1}, 114 d.f. and $P < 0.0001$ at 20°C, 60% relative humidity; SED = 2.0 µg s^{-1}, 114 d.f. and $P < 0.0001$ at 27°C, 60% relative humidity) attributable to carbon loss through respiration and water loss (SED = 1.0 µg s^{-1}, 114 d.f. and $P < 0.0001$ at 20°C, 60% relative humidity; SED = 0.4 µg s^{-1}, 114 d.f. and $P = 0.0005$ at 27°C, 60% relative humidity) from 'Hass' avocado fruit stored at two temperatures. SEMs are also shown ($n = 20$ for 20 and 27°C). All measurements were made 72 h (27°C fruit) and 96 h (20°C fruit) after coating application, with an additional weight measurement being made at 24 h to determine rate of mass loss.

observation that Apple clear and Citrus gleam depressed $p^i_{O_2}$ the most (Fig. 1B), indicated they were more effective in blocking avocado pores (Banks et al. 1993). Apple clear and Avocado wax were most effective for reducing P'_{H_2O} (Fig. 2A), indicating these coatings were best at reducing cuticular permeance to water.

Differing abilities of various coating types to influence various aspects of gas exchange are determined by the characteristics of cuticular and pore routes of gas exchange, as well as the chemical composition of the coating material (Table 1). The introduction of polyethylene into wax formulations has previously resulted in greater resistance to diffusion of water vapour without much effect on the diffusion of other gases (Durand et al. 1984; Ben-Yehoshua 1987). This explains why fruit coated with Citruseal and Avocado wax had the second lowest P'_{H_2O} (Fig. 2A), and a relatively high value for $p^i_{O_2}$ (Fig. 1B). Similarly, shellac has been introduced into waxes to reduce transpiration, but it has been found to hinder movement of respiratory gases (Bender et al. 1993). This was reflected in Citrus gleam (shellac based) having one of the lowest $p^i_{O_2}$, yet the second highest P'_{H_2O} for undiluted coatings. Coating permeability data published by Hagenmaier & Shaw (1992) showed that CMC and shellac based coatings have a low permeance to O_2 and CO_2 for a given permeance to water vapour, whereas carnauba and polyethylene based coatings have high values.

CMC, a polysaccharide material which has similar properties to "NatureSeal" (Bender et al. 1993), has a low permeance to O_2 and achieves little reduction in permeance to water vapour (Hagenmaier & Shaw 1992). This explains why CMC had no mean effect on P'_{H_2O} (Fig. 2A), yet substantially reduced $p^i_{O_2}$ and elevated $p^i_{CO_2}$ (Fig. 1B). Effectively, CMC and similar coatings would be expected to provide little mass loss benefit, yet substantially increase the risk of fermentation.

Table 1 Principal effective chemical constituents in the coatings used in this study.

Coating type	Main chemical ingredient
Apple clear	carnauba wax
Apple glaze	carnauba wax and shellac
Avocado wax	polyethylene
Citrus gleam	shellac
Citruseal	polyethylene
CMC 2%	polysaccharide (carboxymethylcellulose)

The ideal surface coating would be one which decreases cuticular permeance to water vapour movement, without blocking pores in the fruit surface so that respiratory gas exchange is not hindered. Thus, decreasing cuticular permeance would be synonymous with benefit, but blocking of pores synonymous with risk. Unfortunately this trade off between benefit and risk has not been circumvented with current coating formulations.

Overall, the best coating type would be one that substantially reduces mass loss, modifies internal atmospheres to an acceptable level such that aerobic respiration is minimised (but not to an extent that off-odours and off-flavours develop from fermentation) and improves skin sheen. Avocado wax was identified as the best coating for meeting these requirements, and was used for the optimisation experiment.

Optimisation of surface coating concentration

Increasing coating concentration would be expected to result in parallel increases in proportions of blocked pores and thickening of the coating layer. Blocking of pores would reduce $p^i_{O_2}$, whereas coating thickening would reduce water loss (Banks et al. 1993). This was reflected in the parallel reduction in rates of weight loss (Fig. 3A), P'_{H_2O} (Fig. 2B), and $p^i_{O_2}$ (Fig. 3B) with increased coating concentration.

Values for r_{CO_2} decreased with increased coating concentration up to 27%, beyond which r_{CO_2} increased (Fig. 3B). The initial decrease in r_{CO_2} can be attributed to a decline in aerobic respiration associated with a decline in $p^i_{O_2}$ (Dadzie et al. 1996; Peppelenbos et al. 1996). The observed reduction in r_{CO_2} by surface coatings is also consistent with previous findings in avocado (Kader et al. 1989; Joyce et al. 1995). The increase in respiration of fruit coated with concentrations greater than 27% would relate to an increase in fermentation as $p^i_{O_2}$ would have been depressed below the lower O_2 limit for the fruit (Boersig et al. 1988; Yearsley et al. 1996). Products associated with fermentation can be detected as off-odours and off-flavours, and are therefore undesirable (Hagenmaier & Shaw 1992; Banks et al. 1993). High $p^i_{CO_2}$ levels are unlikely to have significantly stimulated off-odours and off-flavours, as low O_2 has been found to be more effective than high CO_2 in inducing fermentation in avocado fruit (Ke et al. 1995).

The same criteria used to identify the best coating type were used to deduce that the laboratory derived optimum concentration of Avocado wax in aqueous solution was 11%. Although r_{CO_2} was less at 27% wax concentration than at 11%, $p^i_{O_2}$ had been substantially depressed without additional reduction in P'_{H_2O}. The packhouse trial was conducted to confirm this conclusion.

Laboratory and packhouse trial differences

In comparison to results from the laboratory-based optimisation experiment, coatings applied commercially in the packhouse trial were less effective in reducing mass loss, P'_{H_2O}, and modification of internal atmospheres. Internal atmosphere differences probably arose from slight differences in ripeness of fruit in the two experiments. This would have affected the contribution of flesh resistance to gas movement to the total depression of $p^i_{O_2}$, as integrity of intercellular channels within the flesh was impaired as fruit became soft and approached senescence (Burton 1982).

The lesser effectiveness of commercially applied Avocado wax in reducing mass loss and $p^i_{O_2}$ relative to the laboratory coating technique could have resulted from the commercial spraying and brushing technique creating a coating that was thinner or less complete than the dipping method used in the laboratory. Likewise, increased variation in the packhouse trial could have been the result of more variation in the amount of coating that each fruit received. In the laboratory trial, fruit would have had similar coating treatments (i.e., individually placed into the coating for the same time period, and allowing the excess to drip off), whereas in the packhouse trial it seems feasible that differences in fruit position on the rollers and different speeds while passing through the coating spray could have resulted in individual fruit receiving different amounts of coating. Although, this large variation made unequivocal identification of the best concentration difficult, the 11.0% concentration provided the greatest reduction in P'_{H_2O} without excessively decreasing $p^i_{O_2}$.

Effect of storage temperature on fruit response to surface coating

The packhouse trial showed that storage temperature had a strong influence on the response to coating application. Although some coatings become more permeable at higher temperatures (Hagenmaier & Shaw 1992), it appeared that this effect was not sufficient to counteract other factors affecting $p^i_{O_2}$ associated with ripening at the higher temperature (Fig. 2C and 4A). Lower $p^i_{O_2}$ might have resulted from increased respiratory demand for O_2 but r_{CO_2} of fruit stored at 27°C was not consistently higher at the time of measurement. Alternatively, if integrity of channels for gas movement within the tissue was adversely affected by ripening at the higher temperature, this could account for the difference in $p^i_{O_2}$. Either way, it is clear that if a surface coating treatment was optimised at a low temperature, and coated fruit were subsequently exposed to high temperatures, their reduced $p^i_{O_2}$ may lead to fermentation (Banks et al. 1993). In the current work, coating concentration was optimised at 20°C, which should be as high as fruit would encounter during the New Zealand export postharvest handling chain. However if the cool chain were to be broken and coated fruit exposed to extreme summer temperatures, they could ferment and their quality be impaired. The extent to which anaerobiosis would occur in response to high temperature would depend on stage of ripening. If fruit are exposed to high temperatures while in the respiratory climacteric, the likelihood of fermentation would be significantly greater than if fruit were in pre- or post-climacteric phases of ripening (Banks et al. 1993).

Sum of $p^i_{O_2}$ and $p^i_{CO_2}$ in coated fruit

Coatings were found to depress the sum of the partial pressures of $p^i_{O_2}$ and $p^i_{CO_2}$. This can be attributed to exaggeration of differential permeability characteristics in the fruit skin of these two gases (Banks et al. 1993). Materials used to coat various fruits and vegetables have permeabilities to CO_2 which are between 2 and 8 times greater than their respective O_2 permeabilities (Hagenmaier & Shaw 1992; Banks et al. 1993). In addition, by blocking pores, the applied coatings have a greater proportional effect on O_2 permeance than CO_2 permeance (Banks et al. 1993). The net result is that depression in $p^i_{O_2}$ is generally greater than elevation of $p^i_{CO_2}$ in coated fruit.

CONCLUSION

This research has shown that both coating type and coating concentration strongly affect avocado fruit gas exchange, and that these issues are crucial when selecting a surface coating for these fruit. Of the formulations and concentrations examined, the polyethylene-based Avocado wax at a concentration of 11% was best for use on avocado fruit. Applied commercially at this level, it visibly enhanced fruit sheen, and reduced mass loss by 18% at 20°C, 60% relative humidity without adversely affecting internal atmospheres. Improvement in the uniformity of benefits from this surface coating may be gained from advances in commercial application methods.

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