Factors Affecting Mass Loss of Apples

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"We have not succeeded in answering all your problems. The answers we have found have only served to raise a whole set of new questions. In some ways we feel as confused as ever but we believe we are confused now on a higher level and about more important things."

Anon.
Executive Summary

Mass loss from harvested apples causes direct loss in returns to growers and marketers of fruit. This thesis characterises the process of mass loss in harvested apples, exploring the effects of various factors on water vapour permeance of the fruit, a measure of the ease with which water escapes from the fruit.

Values of permeance of 'Braeburn' and 'Pacific Rose'™ apples were roughly twice those of 'Cripps Pink' and 'Granny Smith'. Permeance of 'Braeburn' and Pacific Rose™ apples increased with later harvest date whilst values for 'Cripps Pink' and 'Granny Smith' remained relatively constant. There were small differences in mean permeance of apples from different regions. Some growers produced more fruit with high water vapour permeances than others. There was no relationship between maturity indicators tested and the water vapour permeance of the fruit. Fruit from the inner regions of trees and with high numbers of fruit in contact had high permeances. Variation in water vapour permeance around the surface of the fruit had no pattern with respect to blush or sun/shade sides, nor was there any relationship with cuticular thickness. Rather, variation in water vapour permeance of fruit was linked to the extent of cuticular micro-cracking. A model was developed which explains the water vapour permeance based on the proportion of fruit surface which is cracked. Artificial stretch applied to pieces of fruit skin increased cracking and permeance. Strain in the cuticle during growth and development of the fruit created a reticulate crack network. Micro-cracking could be important in determining susceptibility to mass loss and shrivel after harvest. Permeance of 'Braeburn' apples decreased after harvest; the extent of this decrease was greater for low relative humidity and high temperature and for fruit with high initial levels of micro-cracking. Bruising caused by impact damage on
‘Braeburn’ apples increased water vapour permeance of fruit only very slightly.

A conceptual model is presented which summarises relationships between fruit attributes, environmental conditions and processes which contribute to overall mass loss of apples. A composite mathematical model from previous models developed in the thesis is presented which describes total water loss as determined by the level of micro-cracking in the fruit cuticle, time after harvest, relative humidity and temperature of the storage environment. A number of suggestions for minimised mass loss in the apple industry are presented based on three strategies: minimisation of permeance, reduction of driving force for water loss and segregation of lines of high risk and applying appropriate handling regimes. The composite model could be used to explore a range of alternative handling and marketing scenarios in terms of total mass loss.
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List of Symbols and Abbreviations

\( \alpha_1 \)  arc length of skin disc normal \( m \)

\( \alpha_2 \)  arc length of skin disc under stress \( m \)

\( a \)  non-linear regression parameter

\( A \)  surface area of the fruit system \( m^2 \)

\( A^b \)  area of bruising of the fruit system \( m^2 \)

\( A^c \)  area of cracking of the fruit system \( m^2 \)

\( A^{cut} \)  area of intact cuticle of the fruit system \( m^2 \)

\( A^{pores} \)  area of pores of the fruit system \( m^2 \)

\( A^{tot} \)  total area of the fruit system \( m^2 \)

\( a_w \)  water activity of fruit \( \% \)

\( b \)  non-linear regression parameter

\( ^\circ C \)  degrees Celsius

\( c \)  non-linear regression parameter

\( c. \)  approximately

\( CO_2 \)  carbon dioxide

\( C' \)  time conversion for days into seconds \((86,400)\) \( s \cdot day^{-1} \)

\( \Delta M \)  total mass loss \( kg \)

\( \Delta M_{H_2O} \)  total water loss \( kg \)

\( \Delta p_{H_2O} \)  difference in water vapour partial pressures between Pa environment and inside of fruit

\( \Delta p_{H_2O(1)} \)  \( \Delta p_{H_2O} \) for the first set of postharvest conditions Pa

\( \Delta p_{H_2O(2)} \)  \( \Delta p_{H_2O} \) for the second set of postharvest conditions Pa

\( \Delta p_{H_2O}^{bl} \)  gradient of partial pressure of water vapour through Pa boundary layer

\( \Delta p_{H_2O}^{ck} \)  gradient of partial pressure of water vapour through Pa cracks

\( \Delta p_{H_2O}^{cut} \)  gradient of partial pressure of water vapour through the Pa
inner cuticle

\[ \Delta p_{\text{H}_2\text{O}} \] gradient of partial pressure of water vapour through crack system \( \text{Pa} \)

\[ \Delta p_j \] partial pressure difference for diffusion of species \( j \) \( \text{Pa} \)

\[ \Delta x \] thickness of barrier \( \text{m} \)

\[ \Delta x^b \] permanent deformation of bruise \( \text{m} \)

\[ \Delta x^{bl} \] thickness of boundary layer \( \text{m} \)

\[ \Delta x^{ck} \] thickness of cracks \( \text{m} \)

\[ \Delta x^d \] deformation in centre of skin disc from stretching \( \text{m} \)

\[ \Delta x^{icu} \] thickness of the inner cuticle \( \text{m} \)

\[ \Delta x^{flesh} \] thickness of flesh at centre of a skin disc in side view \( \text{m} \)

\[ \Delta x^{m} \] thickness of centre of a skin disc in side view \( \text{m} \)

\[ \Delta x^{s1} \] thickness of side one of a skin disc in side view \( \text{m} \)

\[ \Delta x^{s2} \] thickness of side two of a skin disc in side view \( \text{m} \)

\[ \Delta x^{skin} \] thickness of visible skin at the centre of a skin disc in side view \( \text{m} \)

d \( \text{day} \)

\[ d^b \] diameter of bruised area \( \text{m} \)

\[ d^f \] diameter of fruit \( \text{m} \)

df \( \text{degrees of freedom} \)

\[ D_j \] diffusivity of species \( j \) \( \text{m}^2 \cdot \text{s}^{-1} \)

e \( \text{non-linear regression parameter} \)

\[ ERH \] Equilibrium relative humidity \( \% \)

\( \gamma \) \( \text{psychrometric constant (equals 67 Pa} \cdot \text{°C}^{-1} \text{at 20 °C)} \) \( \text{Pa} \cdot \text{°C}^{-1} \)

g \( \text{gram} \)

h \( \text{hour} \)

H$_2$O \( \text{water} \)

\[ h^b \] bruise depth \( \text{m} \)

\( j \) \( \text{gaseous species} \)
J  joule
k  proportion of cracking
K  kelvin
L  radius of skin disc  m
L  litre
m  metre
M  mass of fruit  kg
min  minute
mol  mole

% M_H2O water loss as a percentage of total mass  %
n  amount of gas  mol
N_H2O mole fraction of water in the solution
P  probability and statistical significance of F or T test
Pa  pascal

p_{tot}^\text{total}  total pressure in a system  Pa
p_0^\text{initial }  initial water vapour permeance of fruit  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{H2O}^\text{water vapour}  water vapour permeance of fruit surface  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{c}^\text{water vapour}  water vapour permeance of cracks  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{cut}^\text{water vapour}  water vapour permeance of undamaged cuticle  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{pores}^\text{water vapour}  water vapour permeance of pores or lenticels  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{s}^\text{water vapour}  water vapour permeance of crack system  mol \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{air}^\text{effective permeability}  effective permeability of air to water vapour  mol \cdot m^{-1} \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{H2O}^\text{partial pressure}  partial pressure of water vapour in air  Pa
p_{H2O}^\text{partial pressure}  partial pressure of water vapour in fruit  Pa
p_{cut}^\text{permeability}  permeability of the inner cuticle to water vapour  mol \cdot m^{-1} \cdot s^{-1} \cdot m^{-2} \cdot Pa^{-1}
p_{H2O}^\text{saturated partial pressure}  saturated partial pressure of pure water  Pa
p_{H2O}^\text{saturated partial pressure}  saturated partial pressure of water vapour at temperature (T)  Pa
$p_{H_2O}^{sat}(T_e)$ saturated partial pressure of water vapour at $T_e$ Pa

$p_{H_2O}^{sat}(T_f)$ saturated partial pressure of water vapour at $T_f$ Pa

$p_{H_2O}^{sat}(T_w)$ saturated partial pressure of water vapour at $T_w$ Pa

$p_{H_2O}^{ob}$ partial pressure of water in steady state with the solution Pa

$P_j$ permeance of a barrier to gas species $j$ mol·s$^{-1}$·m$^{-2}$·Pa$^{-1}$

$P_j'$ permeability of a material to species $j$ mol·m$^{-1}$·s$^{-1}$·m$^{-2}$·Pa$^{-1}$

$P_i'$ water vapour permeance of fruit at time $t$ mol·s$^{-1}$·m$^{-2}$·Pa$^{-1}$

$P_n'$ water vapour permeance at the end of the first set of postharvest conditions mol·s$^{-1}$·m$^{-2}$·Pa$^{-1}$

$P_{n+1}'$ water vapour permeance at the end of the second set of postharvest conditions mol·s$^{-1}$·m$^{-2}$·Pa$^{-1}$

$R$ gas constant = 8.314 m$^3$·Pa·mol$^{-1}$·K$^{-1}$

$R^2$ proportion of total variation explained by regression %

$r_{CO_2}$ specific rate of respiration mol·kg$^{-1}$·s$^{-1}$

$RH$ relative humidity %

$r_{H_2O}$ rate of water loss in a system mol·s$^{-1}$

$r_{H_2O}'$ rate of transfer of water vapour through the boundary layer mol·s$^{-1}$

$r_{H_2O}^{cracks}$ rate of transfer of water vapour through the cracks mol·s$^{-1}$

$r_{H_2O}^{inner}$ rate of transfer of water vapour through the inner cuticle mol·s$^{-1}$

$r_{H_2O}^{cracks}$ rate of transfer of water vapour through the crack system mol·s$^{-1}$

$r_j'$ rate of gas transfer of species $j$ in a system mol·s$^{-1}$

$r_{mass}'$ rate of mass loss in a system kg$^{-1}$·s$^{-1}$
% respiration as a percentage of total mass loss
s strain in skin
s seconds
SED standard error of the difference
$S_j$ solubility of gaseous species within a fluid $\text{mol} \cdot \text{m}^3 \cdot \text{Pa}^{-1}$
$\theta_1$ angle required for calculating arc lengths of skin disc with no strain
$\theta_2$ angle required for calculating arc lengths of skin disc when strained
t time d
$T$ temperature $^{\circ}\text{C}$
$t_0$ time at beginning of the first set of conditions d
$t_1$ time at end of the first set of conditions d
$T_{(1)}$ temperature during the first set of conditions $^{\circ}\text{C}$
$t_2$ time at end of second set of conditions d
$T_{(2)}$ temperature during the second set of conditions $^{\circ}\text{C}$
$T_e$ temperature of environment or air $^{\circ}\text{C}$
$T_f$ temperature of fruit $^{\circ}\text{C}$
$^\text{TM}$ trade mark
$T_w$ temperature of wet bulb $^{\circ}\text{C}$
v velocity of air $\text{m} \cdot \text{s}^{-1}$
$V$ volume $\text{m}^3$
$V^b$ volume of bruised flesh $\text{m}^3$
w/w weight per weight