

# Proposal for a Rationalized System of Units for Postharvest Research in Gas Exchange

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In postharvest studies of gas exchange, evaluation of previous research is greatly complicated by the plethora of units used in presenting data. Conversions made by the end user of data from alternative systems of units must rely on assumptions that may not be true. Although each system of units has advantages and disadvantages for different sets of circumstances, expediency is often the basis for selection because some systems require more computational effort than others. We propose a set of units for presenting postharvest research on gas exchange, developed from a preliminary proposal discussed at the Sixth Controlled-atmosphere Research Conference (Banks and Cleland, 1993). The objective of this proposal is to provide a system of units that facilitates accurate and clear representation of information on gas exchange characteristics of harvested horticultural crops.

## PROPOSAL

We suggest units for basic and derived quantities used to express gas exchange and symbols for these quantities (Table 1). We have based the proposal on SI units; for example, hours and centimeters are replaced with seconds and meters. The proposal follows the rules for use of SI units presented by Salisbury (1991) and Downs (1988). For ex-

ample, in the SI system, it is standard for prefixes to relate to the base unit by multiples of  $10^3$  and only one prefix to be used per set of units, normally in the numerator. Table 2 provides factors for converting alternative units frequently used in the literature to those of the new system.

## DISCUSSION

*Measured variables.* All data presented for publication on gases ultimately derive from the analysis of gas samples with equipment that responds to the absolute amount of gas present in a given sample volume ( $= n$  mol). Calibration of this equipment is usually achieved with volumetrically prepared standards and the raw data used in subsequent calculations are therefore *mole fractions* (Nobel, 1991; p. 71) such as %,  $\mu\text{l}\cdot\text{liter}^{-1}$ , or  $\text{mol}\cdot\text{mol}^{-1}$ . These should be distinguished from true *concentrations*, which are absolute amounts of gas per unit volume (e.g.,  $\text{mol}\cdot\text{m}^{-3}$ ).

Other variables are calculated from mole fractions, characteristics of the system under study (container volumes, gas flow rates, total pressures, temperatures, molecular weights, and periods of time), and with knowledge of their interdependence summarized in the Ideal Gas Law (Nobel, 1991):

$$pV = nR(T + 273.15) \quad [1]$$

where:  $R$  = gas constant ( $8.3143 \text{ m}^3\cdot\text{Pa}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$ ) and  $p$  = either partial or total system pressure (Pa).

*Units for rates of transfer.* We suggest that rates of transfer of all gases of physiological interest in postharvest research be expressed in absolute terms, either per unit mass ( $\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$ ) or for the entire system under consideration, such as a fruit, package, or storage room ( $\text{mol}\cdot\text{s}^{-1}$ ). Rates of exchange for gases that are similar with respect to the number of molecules appear quite different if expressed on a mass basis, because of differences in their molecular weights. For example, even though rates of  $\text{O}_2$  and  $\text{CO}_2$  transfer expressed in moles are the same for a commodity with a respiratory quotient of unity ( $= 1$ ), the mass of  $\text{CO}_2$  released is  $44/32$  times as great as the mass of  $\text{O}_2$  taken up per unit time. Molar quantities are based on the number of molecules, and their use enables comparison of rates of transfer for gases in physiologically meaningful terms. This practice, in turn, would facilitate development of increasingly realistic models of gas exchange between the commodity, its package, and the outside environment. Use of these absolute units avoids the ambiguities inherent in nonabsolute systems of units (Banks and Cleland, 1993) and aligns gas exchange units used in postharvest research

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Table 1. Basic and derived variables used to express gas exchange data in the proposed system.

Quantity	Units	Symbol
Distance	m	$x$
Area	$\text{m}^2$	$A$
Volume	$\text{m}^3$	$V$
Mass	kg	$m$
Moles (amount of gas)	mol	$n$
Gas constant	$\text{m}^3\cdot\text{Pa}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$	$R$
Time	s	$t$
Temperature	$^{\circ}\text{C}$	$T$
Partial pressure of gas $j$	Pa	$p_j$
Total pressure in system	Pa	$p_{tot}$
Concentration of gas $j$ in medium $k$ at temperature $T$	$\text{mol}\cdot\text{m}^{-3}$	$c_{j,k}^T$
Solubility of gas $j$ in medium $k$ at temperature $T$	$\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$	$s_{j,k}^T$
Rate of transfer of gas $j$ per unit mass	$\text{mol}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$	$r_j$
Rate of transfer of gas $j$ for system	$\text{mol}\cdot\text{s}^{-1}$	$r_j^T$
Diffusivity of gas $j$ in medium $k$ at temperature $T$	$\text{m}^2\cdot\text{s}^{-1}$	$D_{j,k}^T$
Permeability of medium $k$ to gas $j$	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$	$P_{j,k}$
Permeance of barrier $b$ to gas $j$	$\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}\cdot\text{Pa}^{-1}$	$P_{j,b}$

Table 2. Factors for converting alternative units to the proposed system (*mw* represents the molecular weight of the gas under consideration, *T* is in °C, and *p<sub>tot</sub>* is in Pa). Conversion factors are based on the assumption that gases conform to the Ideal Gas Law (Eq. [1]). Data in the alternative units given in column 2 can be converted to those in the proposed system by multiplying by the conversion factor given in column 3. All concentration-based driving forces are based on the gas phase. The unit “atm” is taken to be one standard atmosphere pressure (101,325 Pa). The unit “mil” is one-thousandth of an inch.

Variables and units of proposed system	Alternative units	Conversion factor
Rate of transfer (mol·kg <sup>-1</sup> ·s <sup>-1</sup> )	mg·kg <sup>-1</sup> ·h <sup>-1</sup>	2.778 × 10 <sup>-7</sup> / <i>mw</i>
	ml·kg <sup>-1</sup> ·h <sup>-1</sup>	3.341 × 10 <sup>-11</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	μl·kg <sup>-1</sup> ·h <sup>-1</sup>	3.341 × 10 <sup>-14</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
Driving force (Pa)	%	<i>p<sub>tot</sub></i> × 10 <sup>-2</sup>
	mol·mol <sup>-1</sup>	<i>p<sub>tot</sub></i>
	μl·liter <sup>-1</sup> mol·m <sup>-3</sup>	<i>p<sub>tot</sub></i> × 10 <sup>-6</sup> 8.3143 × ( <i>T</i> + 273.15)
Permeability (mol·s <sup>-1</sup> ·m·m <sup>-2</sup> ·Pa <sup>-1</sup> )	mmol·cm·cm <sup>-2</sup> ·h <sup>-1</sup> ·kPa <sup>-1</sup>	2.778 × 10 <sup>-8</sup>
	g·mil·m <sup>-2</sup> ·day <sup>-1</sup> per mm Hg	2.205 × 10 <sup>-12</sup> / <i>mw</i>
	ml·mil·m <sup>-2</sup> ·day <sup>-1</sup> ·atm <sup>-1</sup>	3.492 × 10 <sup>-22</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·mil·cm <sup>-2</sup> ·day <sup>-1</sup> ·atm <sup>-1</sup>	3.492 × 10 <sup>-18</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm·cm <sup>-2</sup> ·h <sup>-1</sup> ·atm <sup>-1</sup> (= cm <sup>2</sup> ·h <sup>-1</sup> ·atm <sup>-1</sup> )	3.297 × 10 <sup>-14</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm·cm <sup>-2</sup> ·s <sup>-1</sup> ·atm <sup>-1</sup> (= cm <sup>2</sup> ·s <sup>-1</sup> ·atm <sup>-1</sup> )	1.187 × 10 <sup>-10</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm·cm <sup>-2</sup> ·s <sup>-1</sup> ·Pa <sup>-1</sup> (= cm <sup>2</sup> ·s <sup>-1</sup> ·Pa <sup>-1</sup> )	1.203 × 10 <sup>-5</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm·cm <sup>-2</sup> ·s <sup>-1</sup> per cm Hg (= cm <sup>2</sup> ·s <sup>-1</sup> per cm Hg)	9.023 × 10 <sup>-9</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
Permeance (mol·s <sup>-1</sup> ·m <sup>-2</sup> ·Pa <sup>-1</sup> )	mmol·m <sup>-2</sup> ·s <sup>-1</sup>	1.0 × 10 <sup>-3</sup> / <i>p<sub>tot</sub></i>
	mmol·m <sup>-2</sup> ·s <sup>-1</sup> ·atm <sup>-1</sup>	9.869 × 10 <sup>-9</sup>
	mmol·cm <sup>-2</sup> ·h <sup>-1</sup> ·kPa <sup>-1</sup>	2.778 × 10 <sup>-6</sup>
	g·m <sup>-2</sup> ·day <sup>-1</sup> per mm Hg	8.681 × 10 <sup>-8</sup> / <i>mw</i>
	mg·m <sup>-2</sup> ·s <sup>-1</sup> ·kPa <sup>-1</sup>	1.0 × 10 <sup>-6</sup> / <i>mw</i>
	ml·cm <sup>-2</sup> ·s <sup>-1</sup> (= cm·s <sup>-1</sup> )	1.203 × 10 <sup>-3</sup> / ( <i>T</i> + 273.15)
	ml·cm <sup>-2</sup> ·h <sup>-1</sup> ·atm <sup>-1</sup> (= cm·h <sup>-1</sup> ·atm <sup>-1</sup> )	3.297 × 10 <sup>-12</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm <sup>-2</sup> ·s <sup>-1</sup> ·atm <sup>-1</sup> (= cm·s <sup>-1</sup> ·atm <sup>-1</sup> )	1.187 × 10 <sup>-8</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	m <sup>3</sup> ·m <sup>-2</sup> ·s <sup>-1</sup> (m·s <sup>-1</sup> )	0.1203 / ( <i>T</i> + 273.15)
	ml·m <sup>-2</sup> ·day <sup>-1</sup> ·atm <sup>-1</sup>	1.374 × 10 <sup>-17</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
	ml·cm <sup>-2</sup> ·s <sup>-1</sup> per cm Hg (= cm·s <sup>-1</sup> per cm Hg)	9.021 × 10 <sup>-7</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)
ml·cm <sup>-2</sup> ·s <sup>-1</sup> ·Pa <sup>-1</sup> (= cm·s <sup>-1</sup> ·Pa <sup>-1</sup> )	1.203 × 10 <sup>-3</sup> <i>p<sub>tot</sub></i> / ( <i>T</i> + 273.15)	
Resistance (Pa·m <sup>2</sup> ·s·mol <sup>-1</sup> )	atm·s·cm <sup>-1</sup>	8.424 × 10 <sup>7</sup> ( <i>T</i> + 273.15) / <i>p<sub>tot</sub></i>
	s·cm <sup>-1</sup>	831.43 × ( <i>T</i> + 273.15)
	s·m <sup>-1</sup>	8.3143 × ( <i>T</i> + 273.15)

with those used in ecophysiological research (Mitchell, 1992).

Assume that a fruit has a rate of CO<sub>2</sub> production ( ) of 40 mg·kg<sup>-1</sup>·h<sup>-1</sup> at 25°C; this would be expressed as 253 nmol·kg<sup>-1</sup>·s<sup>-1</sup>, calculated as follows:

[2]

The terms in parentheses can be combined to give the appropriate conversion factor in Table 2. If this fruit weighed 0.16 kg, then its would be 40.4 nmol·s<sup>-1</sup>.

The same fruit, with a surface area of 0.016 m<sup>2</sup>, a water vapor permeance of 30 nmol·s<sup>-1</sup>·m<sup>-2</sup>·Pa<sup>-1</sup> kept in a water vapor-pressure deficit of 1.5 kPa (≈50% relative humidity at 25°C), would have a rate of transpiration ( ) of 720 nmol·s<sup>-1</sup> (equivalent to a of 4.5 μmol·kg<sup>-1</sup>·s<sup>-1</sup>):

[3]

If the fruit were producing ethylene at a rate of 100 μl·kg<sup>-1</sup>·h<sup>-1</sup> at 25°C and standard pressure, its would be 1.14 nmol·kg<sup>-1</sup>·s<sup>-1</sup>:

[4]

Again, the figures in parentheses can be combined to give the appropriate conversion factor in Table 2.

*Units for driving force.* Although concentration differences (mol·m<sup>-3</sup>) are the prime driving forces for diffusion-mediated gas transfer (Nobel, 1991; p. 409), we recommend partial pressures as units for expressing driving forces in the gas phase for a number of reasons. At standard pressure, partial pressures in kPa are close in numerical values to the mole fraction percentages familiar to post-harvest researchers (1% = 1.013 kPa at standard pressure), a feature likely to favor use of this system rather than using expression in true concentrations, as suggested by Banks and Cleland (1993). In addition, information on gas *j* expressed in partial pressures (*p<sub>j</sub>*, Pa) provides more information than mole fractions (*N<sub>j</sub>*), because they incorporate variation in gas status due to total pressure of the system from which a sample is taken:

[5]

Like the mole fraction, partial pressure of a gas is not responsive to temperature in an open system at constant total pressure because volume increases in proportion to absolute temperature. In contrast, concentration (mol·m<sup>-3</sup>) of the same gas in such a system is related inversely to temperature, as can be readily shown by rearrangement of Eq. [1].

Use of partial pressure units aligns work on exchange of permanent gases with that on transpiration (Sastry et al., 1978); driving forces for water vapor transfer are usually expressed in pressure units because water vapor pressure can be calculated readily given the known psychrometric properties of air (American Society of Heating, Refrigeration, and Air-conditioning Engineers, 1989). Partial pressure units are also used for driving force in the literature on polymeric films used for packaging horticultural produce (Pauly, 1989).

Regular presentation of data on gas driving forces in partial pressures will require that researchers obtain data on pressure within their experimental systems. This would ideally be achieved in the system itself with a pressure transducer, but approximations to ambient total pressure could be obtained using data from a nearby meteorological station.

Concentration of gas *j* in a liquid or solid medium, *k*, at equilibrium at a given temperature, *T* ( , mol·m<sup>-3</sup>), can be calculated from its partial pressure in the gas phase if its solubility in *k* is known (Lendzian and Kirstiens, 1991; p. 77):

[6]

The solubility of gas *j* in *k* at temperature *T* ( , mol·m<sup>-3</sup>·Pa<sup>-1</sup>) is equivalent to the Henry's Law constant. The partition coefficient for the gas in the liquid phase at a given temperature is an analogous constant for calculating the concentration in the liquid or solid phase if the concentration, as distinct from partial pressure, in the gas phase is known (Lendzian and Kerstiens, 1991). The use of partial pressures to express driving forces in the gas phase also avoids the potential for confusion with concentration of gases in the liquid or solid phases, a critical point in avoiding ambiguity in work on gas exchange across plant cuticles (Lendzian and Kirstiens, 1991).

*Units for permeance and permeability.* Units for permeability of medium *k* to gas *j* (*P<sub>j,k</sub>*, mol·s<sup>-1</sup>·m·m<sup>-2</sup>·Pa<sup>-1</sup>) follow from those used for rate, driving force, barrier thickness (Δ*x*), and area, from Fick's Law:

[7]

where Δ*p<sub>j</sub>* = difference in partial pressures of gas *j* on the two sides of the barrier (Pa).

Permeance, equivalent to the term “conductance” used in the ecophysiological literature, is the inverse of resistance to gas diffusion. Permeance of barrier *b* composed of medium *k* is related to permeability of *k* by:

[8]

Permeance is particularly useful in post-harvest research because barriers may be heterogeneous or of unknown thickness. Perme-

ability is the product of diffusivity and solubility of a gas in the medium, a feature that can be useful in understanding responses of homogeneous systems, such as polymeric films, to temperature and pressure (Pauly, 1989). On this basis, permeance is equivalent to:

[9]

However, diffusion of a gas through barriers, such as fruit skins, involves parallel transfer through several phases, such as pores and cuticle, in which effective diffusivity and solubility of the gas may differ substantially (Banks et al., 1993; Ben-Yehoshua et al., 1985; Cameron, 1982; Lenzian and Kirstiens, 1991). It may, therefore, be difficult to separate  $P_j'$  of fruit skins into the diffusivity and solubility components.

A typical low density polyethylene film permeability to  $O_2$  of  $2.5 \times 10^{-8}$  mmol·h<sup>-1</sup>·cm·cm<sup>-2</sup>·kPa<sup>-1</sup> at 25°C (Beaudry et al., 1992) would be expressed as  $6.945 \times 10^{-16}$  mol·s<sup>-1</sup>·m·m<sup>-2</sup>·Pa<sup>-1</sup>. A typical apple skin permeance to  $O_2$  diffusion of 10<sup>-4</sup> cm·s<sup>-1</sup> would be expressed as 403 pmol·s<sup>-1</sup>·m<sup>-2</sup>·Pa<sup>-1</sup>. The original units of cm·s<sup>-1</sup> are the canceled form of ml·cm<sup>-2</sup>·s<sup>-1</sup> (see Table 2); units conversion therefore proceeds as follows:

[10]

Again, the figures in parentheses can be combined to give the appropriate conversion factor in Table 2. The term "transpiration coefficient" is equivalent to skin permeance to water vapor. A typical apple with a transpiration coefficient of 0.50 mg·s<sup>-1</sup>·m<sup>-2</sup>·kPa<sup>-1</sup> at 25°C would have a permeance to water vapor of 27.8 nmol·s<sup>-1</sup>·m<sup>-2</sup>·Pa<sup>-1</sup> calculated as follows:

[11]

The proposed units for permeance are more explicit than those obtained when mole fractions are used as the driving force (mol·s<sup>-1</sup>·m<sup>-2</sup>·mol·mol<sup>-1</sup>), because the latter are invariably canceled to produce an apparently unitless driving force for diffusion. Compared with measures of permeance obtained with a concentration-based driving force (mol·s<sup>-1</sup>·m<sup>-2</sup>·m<sup>3</sup>·mol<sup>-1</sup> or m·s<sup>-1</sup>), permeance expressed in the proposed units has less dependence on temperature and is independent of total pressure (Nobel, 1991; p. 410–411). In addition, values for concentration-based permeance may vary by several orders of magnitude when there are different media on the two sides of the barrier because of the different partition coefficients for the gas in these media relative to the barrier (Lenzian and Kirstiens, 1991). Using partial pressure units for driving force avoids this potential for confusion because reported permeance values always clearly relate to driving forces in the gas phase, which is quite appropriate for systems under study in postharvest research.

## CONCLUSIONS

The system for use of units in postharvest research on gas exchange proposed in this paper is explicit and unambiguous. Its adoption by postharvest researchers should promote development of improved understanding of factors governing responses to, and transfer of, the permanent gases and water vapor in postharvest systems.

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