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Physiological Characteristics of Mushrooms, Strawberries, Broccoli and Tomatoes: Respiration in Air and Modified Atmosphere and Transpiration

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ABSTRACT

Respiration and transpiration of mushrooms (*Agaricus Bisporus* cv. 'U3 Sylvan 381'), strawberries (*Fragaria x ananassa* Duch, cv. 'Kent'), broccoli (*Brassica oleracea* L. cv. 'Acadi') and tomatoes (*Lycopersicon esculentum* Mill. cv. 'Trust') were determined under different temperatures, atmospheric and humidity conditions in order to get information for modified humidity atmosphere packaging design. The respiration rates of all products under optimum modified atmospheres were 40 to 60% lower than in air. The respiration quotients (RQ) for the products studied were always lower than 1.0, but were significantly ($p<0.05$) higher under optimal modified atmosphere conditions than in air. The Q_{10} values for respiration varied from 2.1 (for tomatoes) to 3.3 (for mushroom). The transpiration rate was the sum of inherent, heat-transfer-induced and mass-transfer-induced transpiration. At low relative humidity, mass-transfer-induced transpiration was the dominant mechanism for all fruit and vegetables. This study provides a better understanding of the interrelationship between respiration and transpiration of fruit and vegetables under different temperatures, atmospheres and relative humidities conditions, which will lead to improve the design of controlled and modified atmosphere and humidity packaging.

Keywords: fruit and vegetables, modified atmosphere packaging (MAP), relative humidity, shelf life

INTRODUCTION

Fruit and vegetables are living tissues, which continue to respire even after harvest and the control of respiratory metabolism is the basis of all products storage technologies. Since shelf-life is inversely proportional to respiration rate, decreasing the metabolic rate will increase the shelf life of fruit and vegetables (Kader 1986; Day 1996; Gorris and Tauscher 1999; Gomez and Artès 2004; Oms-Oliu *et al.* 2007). Several factors influence respiration rate. The most important of these factors is the temperature (Zagory and Kader 1988; Kader *et al.* 1989; Church and Parson 1995; Paull 1999; Tano *et al.* 2007; Vanndy *et al*. 2008). In addition, decreasing oxygen (O_2) concentrations and increasing carbon dioxide (CO_2) concentrations in the surrounding atmosphere decreases the respiration rate of most products (Nichols and Hammond 1975; Hong and Kim 2001; Akbudak *et al.* 2007; Nielsen and Leufvèn 2008). It is well known that the respiration of strawberries is strongly decreased when stored under an atmosphere of decreased oxygen content (5-6% O_2) but rich in CO_2 (15-20% CO_2) (El-Kazzaz *et al.* 1983; Smith and Skog 1993; Jacxsens 2001; Nielsen and Leufvèn 2008). Several studies have shown that an atmosphere made up of 8% CO_2 and 3% O_2 increased the shelf-life of broccoli up to 7 weeks, delayed yellowing of the florets and reduced the number of infected sites (Bastrash *et al.* 1993; Jones *et al*. 2006; Schouten *et al.* 2009; Jia *et al*. 2009). Burton *et al.* (1987) have found that 5% O_2 was suitable to delay the development of fresh mushrooms. Sveine *et al.* (1967) and Antamann *et al.* (2008) showed that 5% CO_2 and CO_2 up to 15% delayed the opening of mushroom caps with a weight loss lower than 2%. An atmosphere composed of 2.5 to 5% O_2 also improves the storage of tomatoes, but since this product is CO_2 sensitive, the CO_2 concentration must not exceed 5% (Bhowmik and Pan 1992; Evelo and Horst 1996). Otherwise, Sabir and Agar (2010) have shown that modified atmosphere packaging (MAP) was able to store mature green tomatoes for 35 days without significant decreases in quality characteristics.

The ratio of CO_2 produced to O_2 consumed, known as the respiration quotient (RQ) depend on the atmosphere composition (CO_2 and O_2) surrounding the products and the substrate used during the respiration. RQ is normally assumed to be 1 if the metabolic substrates are carbohydrates (Renault *et al.* 1994). If the substrate is a lipid, the RQ is always lower than unity and the RQ is higher than unity if the substrate is an acid (Kader 1987; Tano *et al*. 1999). Therefore, normally RQ values in the literature are reported as ranging from 0.7 to 1.3 (Kader 1987; Tano *et al*. 1999; Beaudry *et al.* 2000). O_2 and Co_2 concentrations and temperature surrounding the fruit and vegetables affected their RQ values (Beaudry 1993; Joles *et al*. 1994; Lakakul *et al.* 1999).

Transpiration may also affect postharvest physiology and hence the quality of fruit and vegetables. Moisture loss depends on the vapour pressure deficit between the product and its surrounding atmosphere and on product characteristics such as the surface-volume ratio, the structure and the composition of the product (Grierson and Wardowski 1978; Ben-Yehoshua 1985, 1987; Patel *et al.* 1988; Cazier *et al.* 2010). The design of modified atmosphere and humidity packaging (MAHP) requires precise knowledge of the respiration and transpiration rates of the products being stored

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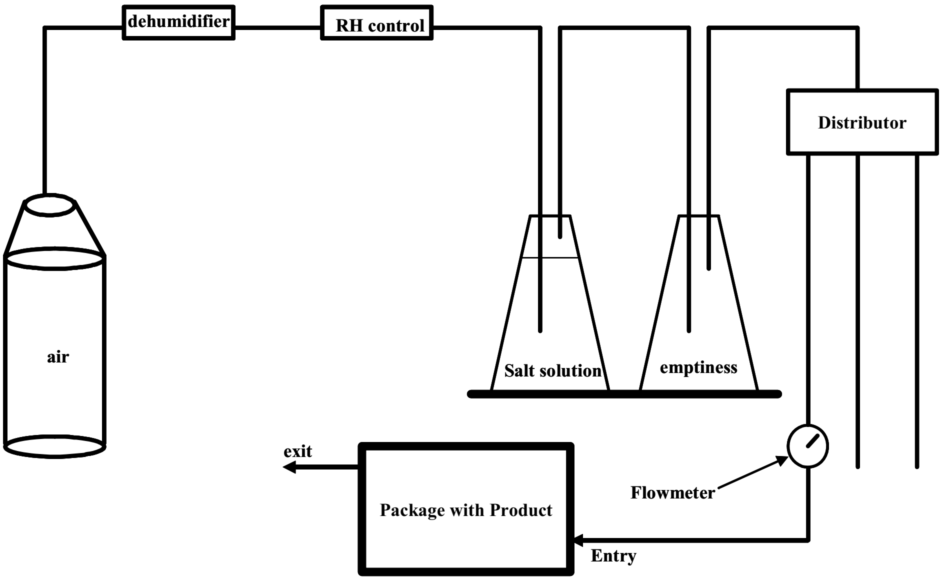

Fig. 1 Diagram of transpiration of fruit and vegetables determination method.

as well as the response of these two physiological parameters to environmental factors, namely temperature, atmospheric composition and relative humidity during storage time (Kang *et al.* 2000; Song *et al.* 2002; Villaescusa and Gil 2003; Shin *et al.* 2007). However in most studies, the respiration and transpiration rates were estimated and assumed to constants during the storage time.

Respiration and transpiration phenomena of postharvest produce have been extensively investigated (Mahajan *et al.* 2008), but the effect of modified atmospheres on transpiration has not been examined to any great extent. Song *et al.* (2002) have developed a model that characterizes the interrelationship between respiration and transpiration inside MAP, but they presented results with blueberry only.

The purpose of this study was to determine the respiration rate of four fruit and vegetables as a function of the atmosphere, temperature and storage time using a static method and also to establish a simple and precise method of measuring transpiration of these four products as a function of relative humidity.

MATERIALS AND METHODS

Sample preparation

First flush mushrooms (*Agricus bisporus*, cv. 'U3 Sylvan 381') at stage 2 of development picked from a local farm (Chamfort Inc. Montmagny, Quebec, Canada), broccoli (*Brassica oleracea* L. cv. 'Acadi') harvested from commercial fields in Ile d'Orleans, Quebec, Canada, tomatoes (*Lycopersicom esculentum* Mill, cv. 'Trust') at the mature green stage corresponding to stage 1 of the United Fresh Fruit and Vegetables Association and USDA Agricultural Marketing Service Fruit and Vegetables Classification Chart manually harvested from greenhouse plants grown locally in a commercial facility, Quebec, Canada, and mature strawberries (*Fragaria x ananassa* Duch, cv. 'Kent'), one-fourth to one-half harvested from commercial fields in Ile d'Orleans, Quebec, Canada were used for this study. All products were pre-cooled for 12 h at each optimum temperature, after sorting according to size, stage of maturity and stage of ripening.

Packaging

Two types of containers were used for the determination of respiration. Mushrooms (750 g) and strawberries (1000 g) were packaged in 4.0 l rigid plastic containers, whereas broccoli (2800 g) and tomatoes (2500 g) were packaged in 6.3 l rigid plastic containers.

Storage conditions

In the first experiment, respiration as a function of storage time was measured at the optimal temperature for each product (4°C for mushroom and strawberry, 3°C for broccoli and 13°C for tomato) (Kader *et al.* 1989; Exama *et al.* 1993) in air or under optimal MA conditions. The optimal atmospheres were 5% O_2 - 10% CO_2 for mushroom, 5% O_2 - 5% CO_2 for tomato, 6% O_2 - 15% CO_2 for strawberry and 3% O_2 - 8% CO_2 for broccoli (Kader *et al.* 1989). In the second experiment, respiration as a function of temperature was measured in air and at optimal MA composition. In the third experiment, transpiration was determined at five levels of relative humidity (RH) (65, 75, 87, 96 and 100%) at the optimal storage temperature of each product.

To maintain constant relative humidity inside each package, standard saturated salts solutions were prepared. The following salts were employed as saturated salts solutions to give water activity at each experiment temperature shown in parentheses: $NaNO_2$ (0.65), NaCl (0.75), KCl (0.87), KNO_3 (0.96). A humidity of 100% was obtained with distilled water.

Characterization of respiration rate

Respiration was measured as a function of time and at three levels of temperature by a modified Flow system method (Exama *et al.* 1993; Yam *et al.* 1993) under controlled atmosphere conditions. The rigid sealed conatianers of the different products were vented and flushed with gas mixtures corresponding to the optimal atmospheric composition for each product. The flow rates were adjusted to levels appropriate for literature values for produce respiration rate (Exama *et al.* 1993) and kept constant throughout the experiment. To measure respiration, gas flow was interrupted and a 1.0 ml sample of gas was removed from the package using a polypropylene syringe. The sample was then analysed using a gas chromatograph (GC) (Perkin Elmer, Model 8500) equipped with a thermal conductivity detector. After one to two hours, the time required for CO_2 to accumulate and for O_2 to diminish, a second 1.0 ml sample was removed for analysis. Samples were taken three times per day throughout the storage period. An air-flushed package served as a control. The experiment was done in triplicate for all treatments. The results obtained in percentage enrichment of CO_2 and depletion of O_2 were converted to ml/kg/h by using the package void volume of each product and the equations of mass balance (Exama *et al.* 1993).

Activation energy, pre-exponential factor, temperature coefficient (Q_{10}) and respiratory quotient (RQ) were calculated using the data obtained from the respiration measurement experiments conducted at the different temperatures and the Arrhenius equation (Exama *et al.* 1993).

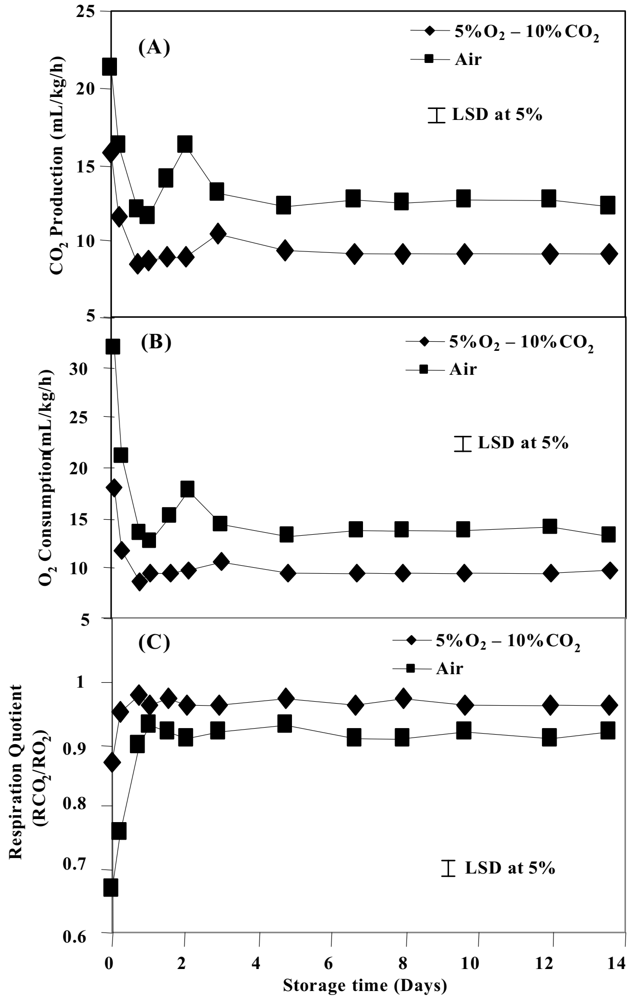

Fig. 2 Respiration rate and respiration quotient (RQ) of mushroom stored at 4°C in air and under controlled atmosphere conditions (10% CO$_2$/5% O$_2$).

Monitoring transpiration as a function of relative humidity

The rigid plastic Containers were flushed with pure air that was first dehumidified by passing it through a drying tube containing a desiccant, through a second tube packed with filter paper soaked with a saturated salt solution, through an Erlenmeyer flask containing the same solution, through an empty flask that served as a trap for droplets, through a four-way valve used as a distributor to the packages and finally through flow-meters to control flow rate (**Fig. 1**). The air flow rate was adjusted to correspond to the respiration rate of each product (9.75 ml/h for mushroom, 30 ml/h for broccoli, 10 ml/h for strawberry and 12.5 ml/h for tomato). Packages were equipped with type T thermocouple probes (POD-237/236, Omega Engineering, Stamford, CT, USA) connected to a data logger (Model RR2-1200-2, Rustrak Ranger II, Automatic RP Inc., Quebec City, Canada) that were monitored for nine days. Air flow was interrupted every three days so the package and its contents could be weighed. Transpiration rates were estimated by calculating the weight loss over the three-day intervals. Measurements were done in triplicate at each relative humidity.

Statistical analysis

All the experiments were repeated twice. Since there was no significant difference between the two replicates, the results were pooled and averaged. The experiments were laid out in a completely randomized block design with tree replicates. Data on respiration and transpiration rates were submitted to an analysis of variance (ANOVA), followed by Neuwman – Keul's multiple comparison test ($\alpha = 0.05$).

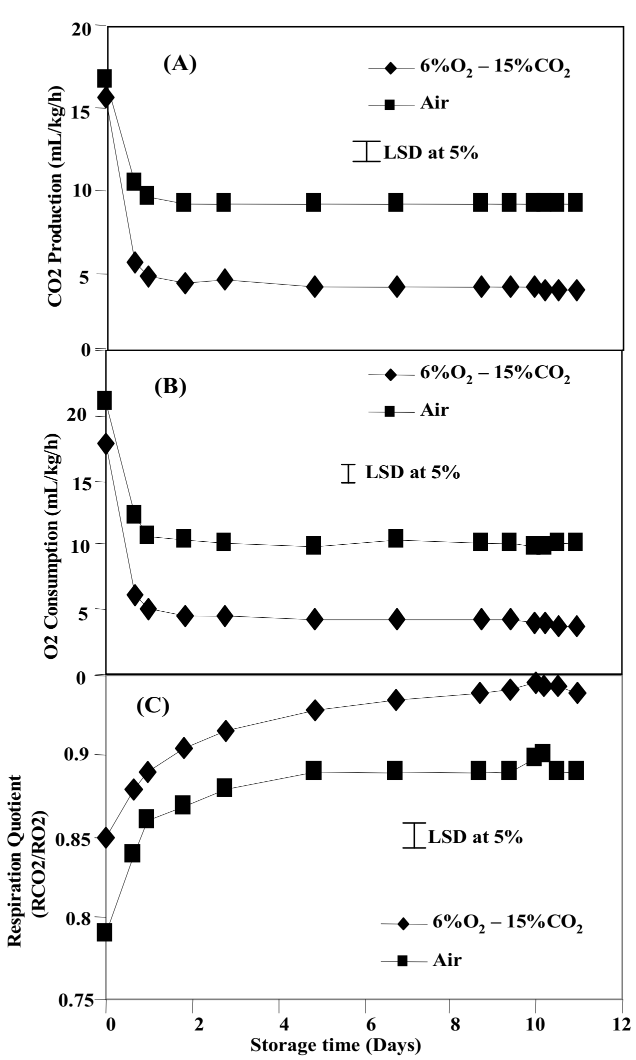

Fig. 3 Respiration rate and respiration quotient (RQ) of strawberry stored at 4°C in air and under controlled atmosphere conditions (15% CO$_2$/6% O$_2$).

RESULTS AND DISCUSSION

Effect of gas composition and temperature on products respiration rates

Figs. 2A, **2B** and **2C** represent CO$_2$ production, O$_2$ consumption and the respiratory quotient (RQ), respectively, for mushroom in air and under optimal controlled atmosphere conditions. In both atmospheres, the respiration rate oscillated for the first few days before reaching steady-state values. Under optimal atmosphere conditions, the respiratory quotient of mushroom changed from 0.87 to 0.99 in the first 16 h (**Fig. 2C**) then remained constant for the remainder of the storage period (12 days). The RQ also rose in the presence of air but remained lower than in the optimal atmosphere throughout the storage period. Respiration rates were always approximately 50% lower in the controlled atmosphere compared to air storage.

Production of CO$_2$ and consumption of O$_2$ for strawberry at the beginning of controlled atmosphere storage were 15.6 ml/kg/h and 17.9 ml/kg/h, respectively; but were 16.6 ml/kg/h and 21.0 ml/kg/h, respectively, for storage in air (**Figs. 3A, 3B**). Respiration subsequently decreased in both cases, but remained higher in the presence of air. No oscillations like those seen with mushroom were observed. The RQ in air varied from 0.79 to 0.92 and from 0.87 to 0.98 under optimal atmosphere (**Fig. 3C**). After one day of storage in this atmosphere, CO$_2$ production and O$_2$ consumption stabilized at 4.0 ml/kg/h and 4.6 ml/kg/h, respectively, while the corresponding values in air storage were

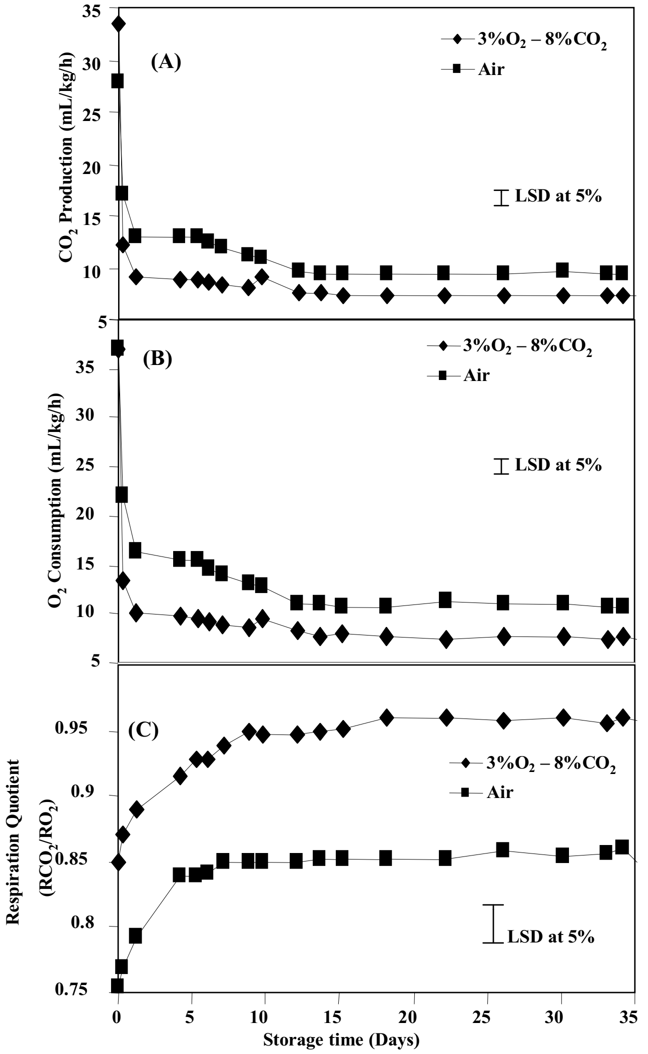

Fig. 4 Respiration rate and respiration quotient (RQ) of broccoli stored at 3°C in air and under controlled atmosphere conditions (8% CO_2/3% O_2).

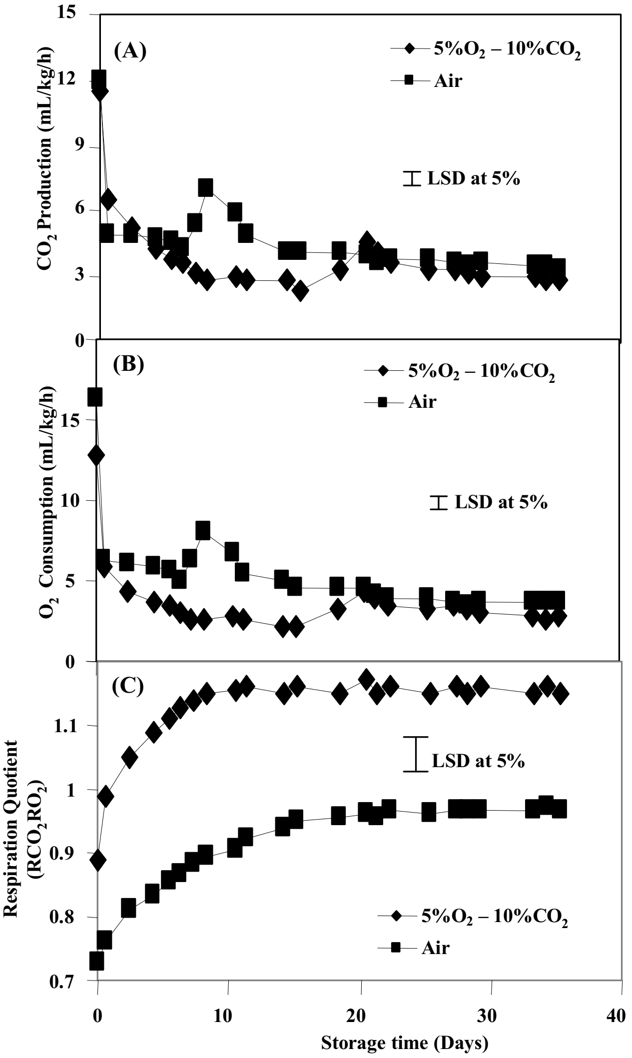

Fig. 5 Respiration rate and respiration quotient (RQ) of tomato stored at 13°C in air and under controlled atmosphere conditions (10% CO_2/5% O_2).

9.0 and 10.0 ml/kg/h, respectively. Once again, using the optimal atmosphere reduced the respirations rate by 50% approximately.

Respiration rates and the respiratory quotient of broccoli stored under the two types of atmospheres were shown in **Figs. 4A, 4B** and **4C**. Both showed three zones: a rapid decrease in respiration from days 0 to 2, a plateau then amore gradual decrease from days 2 to 10 and finally a steady state from day 10 through 35. With this product, respiration under the optimal atmosphere was only 30% lower than in air. On the other hand, compared to the respiration at t = 0, the rate decreased by 70% in both cases once steady state was achieved. The respiratory quotient under the optimal atmosphere was always higher than that in air, although both rose from their initial values and stabilized after 8 to 10 days.

The respiration rates and respiratory coefficients as a function of time for tomatoes were presented in **Figs. 5A, 5B** and **5C**. In both atmospheres, the respiration curve exhibits four zones. There was an initial drop followed by a first plateau lasting 7 days in air that extends over 20 days in the optimal atmosphere. Then, a rapid increase for three to five days, followed by a decrease to another plateau was observed. Again, respiration decreased progressively for the optimal condition, about 50% in this case, and a decrease of nearly 70% from the initial value was noted. Respiratory quotients differed significantly ($P < 0.05$), increasing to 0.95 (air) and 1.05 (optimal atmosphere).

The respiration of fruit and vegetables depends on several factors including the atmosphere surrounding the product (**Figs. 2-5**). Decreasing oxygen concentration and increasing carbon dioxide concentration significantly decreased respiration at the same temperature in all four products studied (Ersan *et al.* 2010). The rapid decrease in respiration during the first 24 h is probably due to the effect of temperature but also to the fact that respiration normally decreases after harvesting and more so in un-ripe tissues than in ripe tissues (Kader 1987; Sabir and Agar 2010). This decrease occurs as the limited substrate reserves for respiratory metabolism are depleted. Storage of tomatoes in the optimal atmosphere delayed the climacteric respiration phase (**Fig. 4A**) (Tano *et al.* 2007). Under these conditions, climacteric respiration began after three weeks of storage, while in air, the onset of this phase occurred at day 10 (Bhowmik and Pan 1992; Tano *et al.* 2007). In the case of mushrooms, the growth phase in the optimal atmosphere is delayed by two days beyond that for mushrooms stored in air (Tano *et al.* 1999, 2007).

Generally, respiration decreases with tissue water content. Product composition determines what type of substrate is available for respiration and consequently the respiratory quotient (Kader 1987). Under aerobic conditions and depending on the product, the respiratory quotient may vary between 0.7 and 1.3. However, the availability of oxygen around the product also affects the respiratory quotient of the product (Bhowmik and Pan 1992; Lakakul *et al.* 1999; Tano *et al.* 2007), as indicated in the present study. The respiratory quotient is always lower in air than in the optimal atmosphere. For Kato-Noguchi and Watada (1996), this difference may be due to the different oxygen concentra-

Table 1 Respiration rate and respiration quotient (RQ) of mushrooms, strawberry, broccoli and tomato under different temperatures and atmospheric conditions. (mean ± SD, n = 9)

Product	**Atmosphere ($\%CO_2 + \%O_2$)**	**Temperature (°C)**	**RCO_2 (mL/kg/h)**	**RO_2 (mL/kg/h)**	**RQ**
Mushroom	5 + 10	4	9.94 ± 0.45^{aA}	10.65 ± 0.39^{aA}	0.94
		14	28.83 ± 0.49^{bB}	30.67 ± 0.61^{bB}	0.94
		24	83.31 ± 0.88^{cC}	92.57 ± 0.97^{cD}	0.90
	Air	4	12.94 ± 0.44^{aE}	16.81 ± 0.79^{dF}	0.77
		14	39.41 ± 0.51^{dG}	53.26 ± 1.21^{eI}	0.74
		24	117.95 ± 0.32^{eH}	159.14 ± 2.12^{fJ}	0.73
Strawberry	6 + 15	4	5.33 ± 0.19^{fK}	5.99 ± 0.44^{gK}	0.89
		14	13.79 ± 0.21^{gL}	13.70 ± 0.27^{hL}	1.00
		20	23.31 ± 0.33^{hM}	22.21 ± 0.69^{iM}	1.01
	Air	4	9.62 ± 0.70^{iN}	11.93 ± 0.86^{jN}	0.81
		14	26.43 ± 0.39^{jO}	29.72 ± 0.62^{kQ}	0.88
		20	43.98 ± 0.96^{kR}	46.02 ± 1.17^{lR}	0.96
Brocoli	3 - 8	3	8.50 ± 0.48^{lS}	9.00 ± 0.17^{mS}	0.95
		13	19.90 ± 0.17^{mT}	20.00 ± 0.32^{nT}	0.95
		23	40.03 ± 0.85^{nU}	45.10 ± 0.69^{oV}	0.89
	Air	3	10.33 ± 0.66^{lW}	14.70 ± 0.43^{pY}	0.70
		13	34.18 ± 0.76^{oZ}	44.53 ± 0.87^{qAA}	0.77
		23	102.98 ± 1.98^{pBB}	122.22 ± 1.55^{rCC}	0.84
Tomato	5 + 5	13	1.60 ± 0.09^{qDD}	1.52 ± 0.08^{sDD}	1.05
		18	2.41 ± 0.17^{qrEE}	2.36 ± 0.10^{stEE}	1.02
		23	3.34 ± 0.13^{rFF}	3.06 ± 0.11^{tFF}	1.09
	Air	13	5.01 ± 0.21^{sGG}	5.35 ± 0.19^{uGG}	0.94
		18	8.41 ± 0.27^{tHH}	8.66 ± 0.23^{vHH}	0.97
		23	13.41 ± 0.31^{uII}	12.97 ± 0.15^{wII}	1.03

The values, followed by the same low case letter in a column and the same upper case in a row, are not significantly different at $p < 0.05$. The reading is done in the same column for lower case letters and in the same row for the upper cases

Table 2 Pre-exponential respiration, activation energy and Q10 values of mushrooms, strawberry, broccoli and tomato under different temperatures and atmospheres conditions. (mean, n=9)

Products	**Atmosphere**	**$R^*{}_{CO_2}$**	**$R^*{}_{O_2}$**	**$E^R{}_{CO_2}$**	**$E^R{}_{O_2}$**	**Q_{10}**	
	$\%CO_2 + \%O_2$	**mL/kg/h**	**mL/kg/h**	**Kj/mol**	**Kj/mol**	**CO_2**	**O_2**
Mushrooms	5 - 10	$4.99 \times 10^{14\ aA}$	$9.03 \times 10^{14\ aB}$	72.73	73.96	2.90	2.89
	Air	$2.27 \times 10^{15\ bC}$	$5.24 \times 10^{15\ bD}$	75.61	76.92	3.10	3.12
Strawberry	6 + 15	$2.95 \times 10^{12\ cE}$	$1.56 \times 10^{11\ cF}$	62.31	55.28	2.39	2.20
	Air	$1.34 \times 10^{13\ dG}$	$7.72 \times 10^{11\ dH}$	64.42	57.34	2.75	2.49
Broccoli	3 + 8	$5.99 \times 10^{11\ eI}$	$2.02 \times 10^{11\ eJ}$	57.37	54.75	2.18	2.25
	Air	$2.37 \times 10^{13\ fK}$	$1.33 \times 10^{12\ fL}$	78.15	71.98	3.30	3.02
Tomato	5 + 5	$1.83 \times 10^{9\ gM}$	$1.50 \times 10^{9\ gN}$	51.84	49.35	2.10	2.01
	Air	$6.30 \times 10^{15\ hO}$	$2.92 \times 10^{14\ hP}$	69.44	62.42	2.67	2.42

The values, followed by the same low case letter in a column and the same upper case in a row, are not significantly different at $p < 0.05$. The reading is done in the same column for lower case letters and in the same row for the upper cases

tions.

Table 1 shows the effect of temperature on respiration for the four fruit and vegetables examined. In general, respiration increased with temperature. For mushrooms stored under 5% O_2 and 10% CO_2, CO_2 production rates at 4, 14 and 24°C were 9.9, 28.8 and 83.3 ml/kg/h, respectively. Consumption of O_2 at these temperatures was 10.7, 30.7 and 92.6 ml/kg/h, respectively. Variations were similar in both atmospheres, although respiration was always higher in air. The respiratory quotient for mushrooms decreased with increasing temperature in both atmospheres but increased for the other three products. Regardless of temperature, respiration rates were highest for mushroom, followed by broccoli, strawberry and finally tomato. For all products and temperatures, the RQ was close to unity under the optimal atmosphere and was always higher than in air.

The Pre-exponential factors of respiration, activation energies and the Q_{10} values were presented in **Table 2**. The Q_{10} values for O_2 consumption and CO_2 production were also given for the optimal atmosphere and for air. For all products studied, the respiration pre-exponential factor in air was greater than under the optimal atmosphere. For all products, Q_{10} values were significantly lower in the modified atmosphere than in air, as were activation energies ($P < 0.05$).

The effect of temperature on the respiration rate of fresh fruit and vegetables is very significant (Kader 1987; Phan 1987; Cameron *et al.* 1994; Tano *et al.* 1999; Shin *et al.* 2007). A wide variety of enzymatic reactions are involved in respiration (Lee *et al.* 1992). Exama *et al.* (1993) indicated that the rate of all of these reactions increases exponentially with increasing temperature within the physiological temperature range. The exact manner by which respiration increases may be described mathematically as the temperature coefficient (Q_{10}) or activation energy (E_r). The Q_{10} of the products studied varied between 2.1 and 3.3 depending on the atmosphere surrounding the product and on the range over which the temperature varied (**Table 2**). Produce like mushrooms with higher Q_{10} values would be more affected by temperature fluctuations inside the package (Tano *et al.* 2007).

Transpiration as a function of relative humidity

All products examined showed a significant rate of transpiration even at 100% relative humidity (**Fig. 6**). The transpiration rate also appeared to significantly increase for all the products analyzed with decreasing humidity or with a difference between product and package atmosphere water vapour pressures.

Mushrooms transpired at a rate of 60.1 mg/kg/h when the differential vapour pressure (DVP) was zero (RH = 100%). This rate rapidly increased to 101.3 mg/kg/h at a difference of 2.16 mmHg. For strawberries and broccoli, the

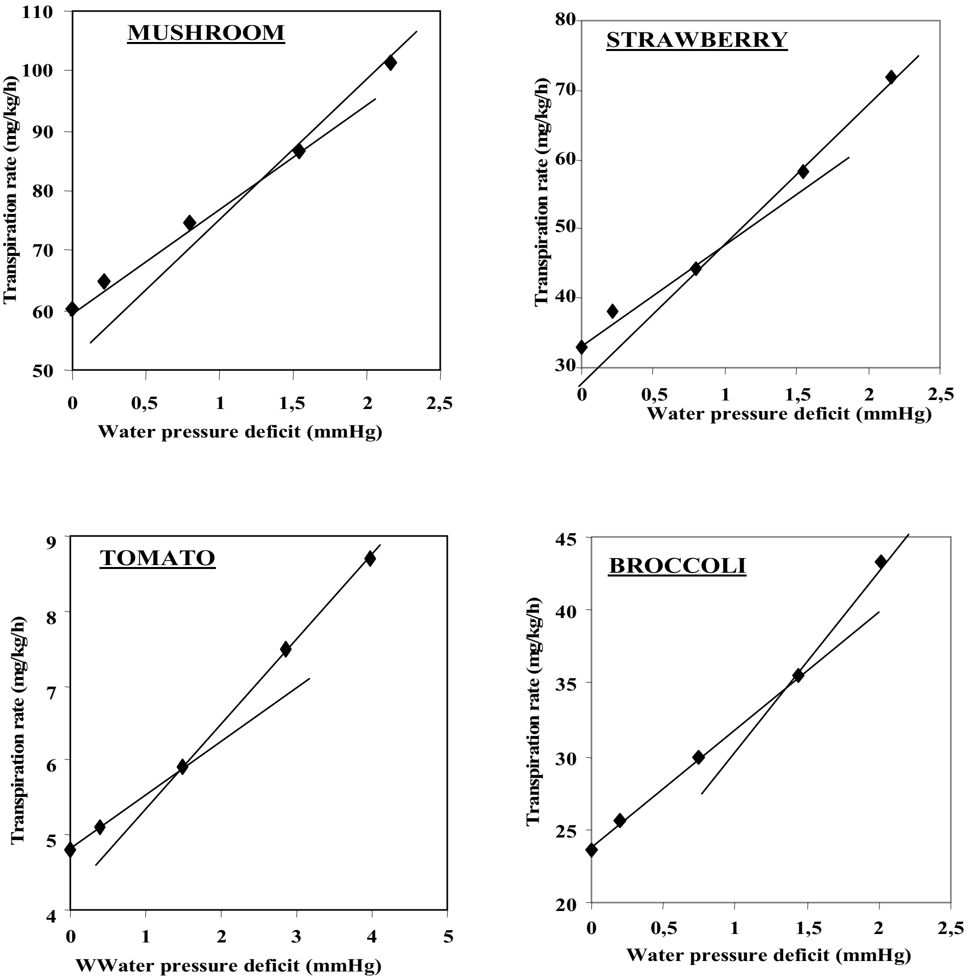

Fig. 6 Transpiration rates of mushroom, strawberry, broccoli and tomato as a function of the vapour pressure deficit.

zero differential transpiration rates were approximately half of that experienced by mushrooms. The zero differential rate for tomatoes was much smaller than was observed with the other produce (4.8 mmHg). Transpiration rates approximately doubled for mushroom, strawberry and broccoli when the water vapour pressure differential reached 2.16 mmHg. However, less dramatic transpiration rate increases were observed with tomato; with this produce, the DVP had to increase to 3.98 mmHg before a doubling of the transpiration rate was observed.

The method of transpiration used in the present study gave values close to those previously reported (Robinson *et al.* 1975; Ben-Yehoshua 1987; Sastry *et al.* 1978; Song *et al.* 2002). Sastry *et al.* (1978) found that transpiration rates for broccoli and tomato were, respectively, 31.2 and 4.2 mg/kg/h when relative humidity varied between 45 and 75%. However, the method used in this study has the advantage to directly determine product transpiration in milligrams of water evaporated per kilogram of product whereas previously reported values were given as a percentage of product weight per unit of storage time at a specified relative humidity. The latter method does not allow the determination of transpiration when the difference in vapour pressure between the product and the package atmosphere is zero.

To properly understand the various mechanisms underlying transpiration, we must start by examining respiration because the two phenomena are intimately linked. Respiration can be characterized by the following equation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2{,}816\ \mathrm{J}$$

For every 1.0 mg of glucose metabolised, 1.067 mg of O_2 is taken up and 1.467 mg of CO_2, 0.60 mg of H_2O, and 15.6 J of heat are produced. Thus, even if a very efficient heat transfer mechanism exists so that all the respiration heat energy is properly dissipated and the RH is 100%, there is still no mass transfer driving force transporting water from the produce. Nevertheless, the carbon loss resulting from the production of CO_2 will still lead to a weight loss of 0.40 mg. mg^{-1} of glucose metabolised. This inherent transpiration rate (R_{inh}) can be calculated since the O_2 uptake rates are known for the four products examined. For example, the steady-state respiration rate for mushroom in air at the optimum storage temperature was determined to be 12 and 16.8 ml O_2/kg/h (**Fig. 6**), respectively.

This O_2 uptake rate would translate to a glucose metabolic rate of 15.7 mg/kg/h, and CO_2, H_2O, and enthalpy production rates of 23.0 mg/kg/h, 9.6 mg/kg/h and 245 J/kg/h, respectively. Consequently, the inherent mushroom transpiration rate would be 6.1 mg/kg/h. By similar calculations, the R_{inh} for strawberry, broccoli and tomato were 5.1, 5.6, and 1.8 mg/kg/h, respectively. The results of Fig. 5 indicate that, even at 100% RH (i.e. differential vapour pressure (DVP) = 0), transpiration losses were much higher than the inherent transpiration rate for all four products studied.

For tomatoes, R_{inh} could account for 40% of the zero DVP weight loss whereas with mushrooms, it was only 10%. These discrepancies must therefore result from the inefficient removal of heat from the storage packages (Lentz and Rooke 1964; Burg and Kosson 1983). Heat was produced in containers at a rate of 245, 204, 225 and 71.5 J/kg/h for mushroom, strawberry, broccoli and tomato, respectively. If the enthalpy of vaporization of water is taken as 2,480 J/kg, for mushroom this would be enough heat to vaporize 98.0 g H_2O/kg/h. Obviously, this heat must be very efficiently removed if moisture loss it to be avoided.

Even with gas flowing through the container, heat did tend to accumulate in the system, leading to elevated temperatures at the center of the package. We observed that the core temperature was often 2 to 4°C higher than the wall temperature (results not showed). Thus, even if the gas was at 100% RH as it entered the package, an increase in temperature would lead to a decrease in RH at the center of the container. As a result, a mass transfer driving force would be created that would lead to water transport from the produce to the surrounding atmosphere (Grierson and Wardowski 1975; Ben-Yehoshua 1987; Cazier *et al.* 2002). This rate of water loss at 100% RH can be defined as the heat-transfer-induced transpiration rate (R_{hti}) and had values of 54.0, 27.8, 19.7 and 3.0 mg/kg/h for mushroom, strawberry, broccoli and tomato, respectively. There does not appear to be a direct correlation between the R_{hti} values and the rate of heat production for the four products examined. Other factors, such as packaging density, transport surface area and permeability of the produce skin surface most likely also play a role in determining the value of R_{hti} (Cazier *et al.* 2002) Our results showed that mushroom and strawberry are more sensitive to water stress than broccoli or tomatoes. This may be explained by the porous structure of mushroom and the permeability of the tissues of strawberry. Broccoli is more resistant than either of these but less resistant than tomato, which possess a waxy envelope, making them much more impermeable.

When the surrounding atmosphere had an RH of 100% and was at the desired storage temperature, then only the produce in the temperature-elevated core would experience water loss (Shin *et al.* 2007). However, if the RH of the gas at the optimal storage temperature dropped below 100%, an additional mass-transfer-induced transpiration (R_{mti}) would occur for all produce in the container. This increase in transpiration with increasing DVP was observed for all produce examined (**Fig. 6**). According to Fick's first law, the rate of mass-transfer-induced transpiration should be directly proportional to the concentration driving force (DVP). However, plots of transpiration versus DVP (**Fig. 6**) were not straight and tended to curve upwards as DVP increased. This curvature most likely resulted because heat-transfer-induced and mass-transfer-induced transpiration are not independent phenomena. A higher rate of mass transfer will produce more evaporative cooling at the surface of the produce. This in turn will reduce the core temperature and decrease R_{hti}. Consequently, at low DVP values, the two phenomena tend to be antagonistic. However, at higher DVP values, mass-transfer-induced transpiration would be the dominant weight loss mechanism and the curve becomes linear.

CONCLUSION

This study has provided an evaluation of some environmental factors (atmosphere, temperature, relative humidity) on the physiological behaviour (respiration and transpiration) of fresh fruit and vegetables. Knowledge of these behaviours will provide means of devising better storage methods for a given product. The data have allowed the identification of elements relevant to the design of packages for modified atmosphere and humidity packaging and the modelization of modified atmosphere packaging. Knowledge of the respiratory quotient under different atmospheric conditions and as a function of storage temperature provides information about the substrate being metabolized by a given product. Similarly, measurement of transpiration as a function of relative humidity provides means of determining the critical relative humidity below which significant amounts of water may be lost from the product. The method based on measurement of transpiration seems reliable when data already in the literature are considered. In addition, this work has demonstrated that fruit and vegetables transpiration rate depends on the difference in vapour pressure between the product and the surrounding package atmosphere, on product respiration rate (inherent respiration) and on intrinsic factors associated with each product.

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