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REVIEW ARTICLE

Respiration rate of fruits and vegetables for modified atmosphere packaging: a mathematical approach

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ABSTRACT

Modified atmosphere packaging is a well-proven technology for preserving the natural quality of food products and extending the storage life. It is one of the most successful preservation techniques suitable for various agricultural and horticultural products. Proper control of temperature, relative humidity and manipulation of gas composition in storage can successfully extend the shelf life and minimize the extent of postharvest losses. Respiration is one of the critical elements of the postharvest loss of fresh fruits and vegetables. Modified atmosphere packaging relies on modifying and controlling the atmosphere inside the storage, achieved by the natural interplay between two processes, the product's respiration and the transfer of gases through the packaging, leading to an atmosphere richer in CO_2 and poorer O_2. This environment can potentially reduce respiration rate, ethylene sensitivity and production, decay, physiological changes and oxidation, thereby enhancing their shelf-life. Thus, the respiration rate of the selected product is crucial to designing a successful modified atmosphere system. In this paper, principles of the respiration process, practical methods for measuring respiration rates, factors affecting the respiration rate and respiratory quotient, modeling the respiration rate and published work on the respiration rate of various fruits and vegetables are discussed.

Keywords: Respiration rate, O_2 consumption, CO_2 evolution, temperature effect, respiratory kinetics

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INTRODUCTION

Fruits and vegetables are perishable and commonly have a short shelf life. They begin to lose their freshness shortly after being plucked from the tree. The metabolic activities even after harvest are the main reason for losing freshness. Fruits and vegetables go through three developmental stages: maturation, ripening and senescence. During these developmental stages, some changes may occur chemically and physically, leading to loss of optimal eating quality if the crop is detached from the parent crop. A critical basic fact in postharvest handling is that the crops are still living structures upon harvest. Hence, the metabolic activities performed when attached to the parent crop continue. Among metabolic activities, respiration is the key process that brings some physiological disorders such as ripening, senescence, browning, molding, degradation of chlorophyll, decay and subsequent deterioration in their regular course of time (Raghavan and Gariepy, 1985; Kader et al., 1989).

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Respiration is a metabolic process that provides the energy for plant biochemical processes. During respiration, various substrates used in important synthetic metabolic pathways in the plant are formed. Glycolysis, tricarboxylic acid cycle and electron transport system are the metabolic pathways of aerobic respiration (Wills et al., 1989; Kays, 1991). The physiological disorders can be minimized by controlling the respiration rate through which can extend shelf-life. The respiration rate can be restricted by adequately controlling temperature, relative humidity and modification of natural atmospheric conditions. The modification process often tries to reduce the level of O_2 and increase the level of CO_2 initially. It changes dynamically depending on the produce and permeability of the packaging materials, and it is termed the modified atmosphere (MA) (Fonseca et al., 2002). The term controlled atmosphere (CA) is defined by adjusting the O_2 and CO_2 levels within tight gas stores and constantly maintaining their optimum levels throughout the storage period suitable to the commodities (Kandasamy, 2017).

The CA storage/MA packaging of fresh produce relies on modification and controlling of the atmosphere inside the storage, achieved by the natural interplay between two processes, the respiration of the product and the transfer of gases through the packaging, that leads to an atmosphere richer in CO_2 and poorer in O_2. This atmosphere can potentially reduce respiration rate, ethylene sensitivity and production, decay and physiological changes (Kandasamy, 2017). Knowledge of respiration rate during the storage is important in evaluating the postharvest tools that preserve fruit quality and information for the development of new packages (Barbosa et al., 2018). Respiratory process modelling is an important step in designing and selecting packaging and storing systems of fruit and vegetable products, as is the case of modified atmosphere packaging (Ravindra and Goswami, 2008).

CAS and MAP should be carefully designed, as a system incorrectly designed may be ineffective. The design should take into consideration not only steady-state conditions but also the dynamic process. The CA storage method depends on the product's characteristics, mass, recommended atmosphere composition, the permeability of the packaging materials to gases, and the product's respiration rate as affected by different gas compositions and temperatures (Kandasamy and Mukherjee, 2019). The main objectives of this paper are to present in systematic way information available in the literature regarding respiration rate of fresh produce, mathematical modelling, general aspects of the respiration process, factors affecting the respiration rate, methods of measuring respiration rates and respiration rate models reported in the literature.

RESPIRATION PROCESS

Respiration is considered a metabolic process involving the consumption of oxygen (O_2) for oxidative break-down of starch, sugar and organic compounds into simple molecules such as carbon dioxide (CO_2), water and other intermediates with concurrent production energy form of heat. The organic substrates broken down in this process may include carbohydrates, lipids, and organic acids. The process consumes O_2 in a series of enzymatic reactions (Wills et al., 1989; Kader, 1992). Respiration is usually represented as oxidation of hexose sugars as follows:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Energy \qquad (1)$$

Respiration rate is generally expressed as the rate of O_2 consumption and CO_2 evolution per unit weight of product per unit time and as heat liberated and substrate loss, as indicated by mass loss. The other factor is that respiration involves the metabolism of different substrates, which differ in their degree of oxidation. Heat is liberated due to many interrelated metabolic processes that occur in the product simultaneously, some of which utilize respiratory energy. Respiration is necessary to maintain the vigour of the plant tissue and provide resistance against spoilage in the postharvest life of the produce. Respiration rate is an index of metabolic

turnover in the product and is believed to be proportional to the rate of deterioration. The higher the rate, the faster the deterioration rate because of the increase in the break-down of the organic compounds stored in the harvested product, leading to accelerated senescence, loss of food value, and reduced flavour (Phan et al., 1975; Kays, 1991).

FACTORS RESPONSIBLE FOR RESPIRATION

Type and maturity

The internal factors, type and maturity stage, affect the respiration rate of the commodity. The diversity of plant organs (roots, tubers, seeds, bulbs, fruits, sprouts, stems and leaves) have different metabolic activities and consequently different respiration rates. Even different varieties of the same product can exhibit different respiration rates (Song et al., 1992; Fonseca et al., 2002). In general, non-climacteric commodities have higher respiration rates in the early stages of development that steadily decline during maturation. The respiration rates of climacteric commodities also increase early in growth and decline until a rise that coincides with ripening (Fishman et al., 1996). Climacteric products exhibit a peak of respiration and ethylene (C_2H_4) production associated with senescence and ripening. Typically, climacteric changes are considered significant only long-term and not relevant to modified atmosphere storage. Due to elevated CO2 delayed climacteric rise in avocados and bananas and rose in apples due to reduced O_2 levels (Fonseca et al., 2002).

Wounding plant cells

The wounding may be due to mechanical damage or cutting of the product. Wounding plant cells and tissues causes the respiration rate to increase. Wounding stimulates ethylene production rate, respiration, deterioration, senescence and ripening of fruits and vegetables. The respiration rate may gradually increase over time until a maximum value is reached and then decrease to the matter before the wounding or to a higher value. The respiratory rate of apple slices was about 2–3 times that of the whole fruit (Lakakul et al., 1999).

Temperature

The temperature is the most important external factor influencing respiration. Biological reactions generally increase two or three-fold for every 10°C rises in temperature within the range of temperatures typically encountered in the distribution and marketing chain. At higher temperatures, enzymatic denaturation may occur and reduce respiration rates. A physiological injury may occur if temperatures are too low, leading to an increased respiration rate (Zagory and Kader, 1988). The effect of temperature on the respiration rate can be directly related to chemical reactions where the rate of reaction increases exponentially with an increase in temperature (Wills et al., 1989).

Relative humidity

The RH indicates that the amount of water vapour present in the air is a percentage of the maximum amount of water held in the air at a specified temperature. It plays a vital role in the quality of produce by influencing moisture loss. The moisture losses may cause the poor texture of the product. Studies have reported that about 5-10% of the product weight is lost as moisture in a wide range of products. The loss of moisture from the products is proportional to the partial water vapour pressure gradient between the saturated internal atmosphere of the products and the low saturated surrounding atmosphere. The partial water vapour pressure gradient is usually influenced by temperature. By increasing the temperature with constant

RH, an excellent water vapour gradient forces the water to diffuse out of the products (Grierson and Wardowski, 1978). The storage life of produces can be extended by 50% at a relative humidity of 90-100% (Raghavan et al., 1984). As noted, cherries and lemons had their shelf life extended by a week and a month respectively when stored in nearly saturated storage (Shewfelt, 1986). High RH storage sometimes induces pathogenic infection rather than advancing the storage life and splitting the tissues in the produce (Kays, 1991).

Atmospheric gas composition

The storage life of products is extended, modifying the temperature, relative humidity and gas composition. It is essential to maintain the desired O_2 and CO_2 levels throughout their storage period (Kandasamy et al., 2015). A major key element of respiration is O_2. The quality of commodities can be preserved longer if available O2 is restricted, which could be slowed down the rate of the respiration process. However, reducing the O_2 level beyond a critical point leads to an anaerobic process. It is based on the fact that respiration is a partly reversible chemical reaction in which O_2 is consumed, and CO_2 evolved along with water and energy in the form of heat (Burgheimer et al., 1967). Equation (1) suggested that if O_2 concentration is reduced and CO_2 increased, the respiration rate may be decreased, thereby extending the postharvest life of the produce. It is the basic process for establishing and maintaining optimal gas composition in storage systems (Burton, 1974).

Respiration, lowered by reducing available O_2 as a consequence of reduction of overall metabolic activities. The influence of CO_2 depends on type and developmental stage of the commodity. The respiration rates of most root and bulb-type vegetables are also stimulated by high CO_2 levels (Smock, 1979; Kader, 1987). The effects of decreased O_2 and increased CO_2 on respiration rate were stabilized. On the respiratory metabolism, the addition of 10% CO_2 has an equal effect as a 2% O_2. The combination of 2% O_2 and 10% CO_2 has approximately twice the impact. When O_2 levels are below 8%, fruits and vegetables reduce their production of ethylene and their sensitivity to ethylene. When exposed to O_2 levels below or CO_2 levels above their tolerance limits, various physiological disorders may occur (Kader, 1986). The gas concentrations may be altered either passively by the combined effects of the respiring produce and selective gas diffusion through a storage enclosure or by an active system where gas is pulled out of the storage chamber and replaced with the gas of desired concentration which is constantly monitored (Kandasamy, 2017).

METHODS OF RESPIRATION RATE MEASUREMENT

The respiration rate of fresh produce can be expressed as O_2 consumption rate and CO_2 production rate. It is estimated either by experimental methods or mathematical models. The usual practical methods for measuring respiration rate are (i) closed or static system**,** (ii) flowing or flushing system and (iii) permeable system.

Closed or static system

In the closed system (Fig. 1), a gas-tight container of known volume is filled with a known weight of the product and made tight (using a neoprene gasket and silicone grease) after equilibrating the temperature and humidity. The container contains ambient air as the initial atmosphere. The headspace gas is taken using a syringe through the silicon septum. The gas chromatograph measures changes in the concentration of O_2 and CO_2 over a certain period. The parameters quantified to determine the respiration rate and respiration quotient are (i) the mass of the product, (ii) free volume in the chamber, and (iii) the volume of O_2 and CO_2 at the respective time.

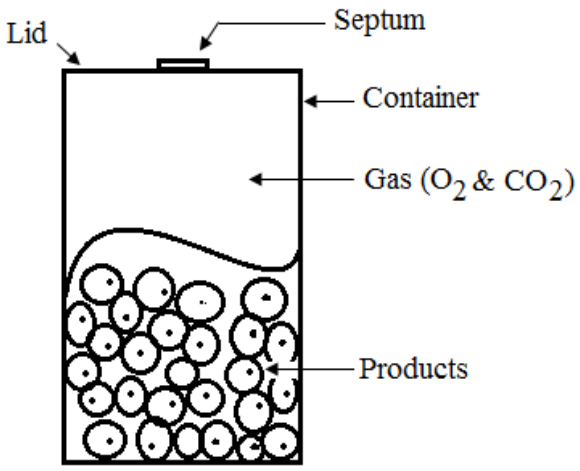

Fig. 1. Closed respiration meter

Respiration rate is determined by measuring CO_2 or O_2 concentration when the commodity is stored in a closed chamber (Lee et al., 1991; Ratti et al., 1996). The Equations (2) and (3) are used to estimate respiration rates as a function of O_2 and CO_2, respectively (Kandasamy et al., 2015).

$$R_{O_2} = -\frac{d[O_2]}{dt} \times \left(\frac{P\, M_a V_f}{100\, R\, T\, W_p}\right) \quad (2)$$

$$R_{CO_2} = \frac{d[CO_2]}{dt} \times \left(\frac{P\, M_a V_f}{100\, R\, T\, W_p}\right) \quad (3)$$

The negative sign in Eq. (1) signifies that the O_2 concentration in the container decreases with time. In the closed system, it is difficult to estimate the gas volume accurately. The O_2 depletion and CO_2 production during measurement may affect the respiration rate (Lee et al., 1991). The gas concentration is greatly influenced while modeling the respiration rate. The gas concentrations generally associated with the respiration rate measured are the initial values or the average values between the initial and final measurements.

Flowing or flushing system

The apparatus for measuring respiration rate in the flushing system (Fig. 2) consists of respiration chambers that store products. A gas mixing system contains cylinders of compressed air, carbon dioxide, oxygen, and nitrogen to prepare the gas mixtures of any required proportions of oxygen, carbon dioxide, and nitrogen. The premixed gas is flowing at constant, ate to separate respiration chambers through the flow distribution board. The distribution lines contain separate pre-calibrated capillary flow meters to regulate the gas flow rate into each respiration chamber. The composition of the gas mixture entering and leaving the respiration chambers should be monitored regularly for oxygen and carbon dioxide concentrations by withdrawing 10 ml gas samples with a hypodermic syringe and analyzing them in a gas chromatograph equipped with a thermal conductivity detector (Mannapperuma et al., 1991).

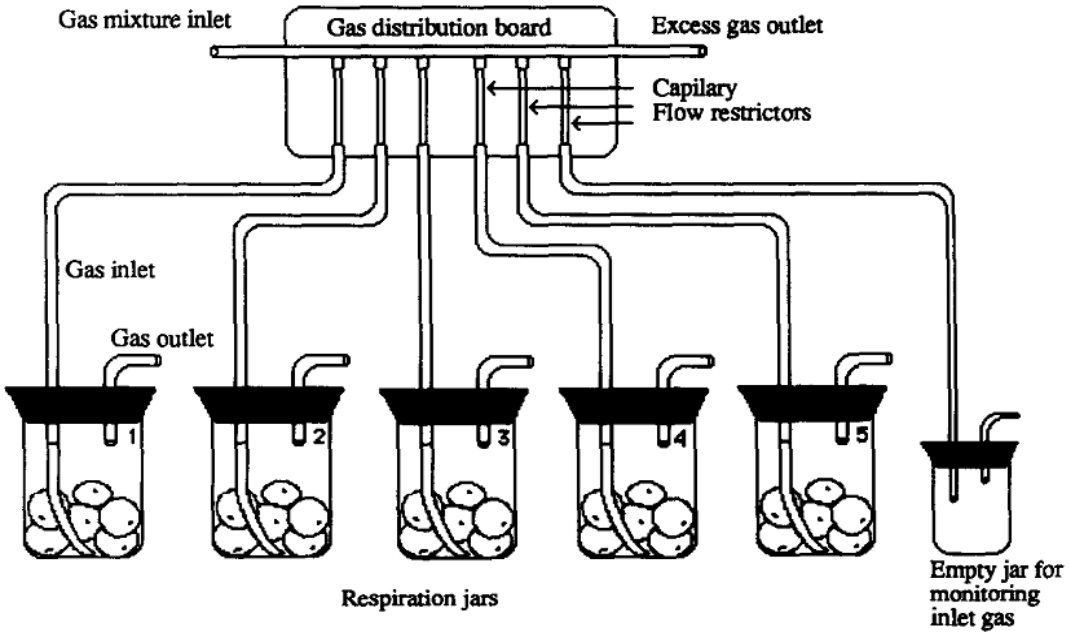

Fig. 2. Schematic diagram of measurement of respiration rate (Mannapperuma et al., 1991)

The respiration rates are calculated from the absolute differences in gas concentrations between the outlet and the inlet when the system reaches a steady-state. The following expressions (4) and (5) are used to estimate the respiration rate of the stored products concerning O_2 and CO_2, respectively (Lee et al., 1991; Talasila et al., 1992).

$$R_{O_2} = \frac{(y_{O_2}^{in} - y_{O_2}^{out})\ F}{100\ M_s} \quad (4)$$

$$R_{CO_2} = \frac{(y_{CO_2}^{out} - y_{CO_2}^{in})\ F}{100\ M_s} \quad (5)$$

Permeable system

In the porous system, a package of known dimensions and film permeability is filled with product. The steady-state concentrations of O_2 and CO_2 are determined, and a mass balance is performed on the system to estimate the respiration rate concerning O_2 and CO_2 using Eqs. (6) and (7), respectively (Beaudry, 1993; Cameron et al., 1995; Lee et al., 1991).

$$R_{O_2} = \frac{P_{O_2} A\,(y_{O_2}^{e} - y_{O_2})}{100\ L\ M_s} \quad (6)$$

$$R_{CO_2} = \frac{P_{CO_2} A\,(y_{CO_2} - y_{CO_2}^{e})}{100\ L\ M_s} \quad (7)$$

MEASUREMENT OF INTERNAL GAS CONCENTRATION

The method used to extract the internal atmosphere was a modified version of the vacuum extraction method (Mannapperuma et al., 1991). The average gas concentration inside the fruits can be determined by removing the internal atmosphere of the fruits, which are stored in a chamber of the controlled atmosphere, by applying a vacuum and analyzing the extracted gases. The apparatus used to measure the average gas concentration (Fig. 3) is a heavy-duty pressure vessel equipped with a pressure gauge, vacuum pump and a glass funnel with a gas sampling attachment. The vessel is filled with deaerated and distilled water.

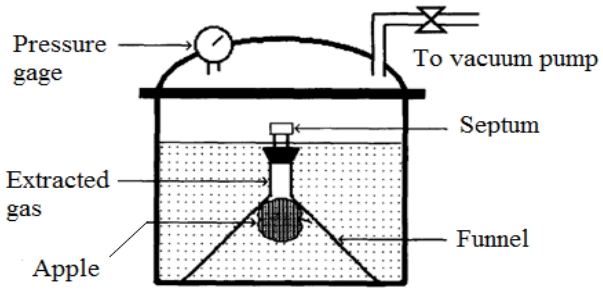

Fig. 3. Measurement of the internal gas concentration of fruits (Mannapperuma et al., 1991)

Before starting the experiment, ensuring that the fruits had already reached the steady-state internal concentrations corresponding to each external gas composition, the fruit taken for the investigation is placed under the inverted funnel. The container is then closed, and a vacuum pressure of 25 inches of mercury may be applied for four minutes. The gases to be analyzed for oxygen and carbon dioxide are collected at the top of the funnel.

MEASUREMENT OF GAS CONCENTRATION UNDER THE SKIN

The measurement method of gas concentration under the skin has been described by Mannapperuma et al. (1991). The apparatus (Fig. 4) is a specially constructed glass chamber with a U-tube and a gas sampling port. The upper rim of the device should contact the fruit surface, which is taken for the experiment. The clamps are used to hold the instrument and apple in place. The U-tube should be filled with water to seal the chamber from the environment. This water column also indicated the reliability of the seal between the chamber and the apple. Gas samples of 20 µl from the chamber may be analyzed for carbon dioxide and oxygen until the steady-state is detected.

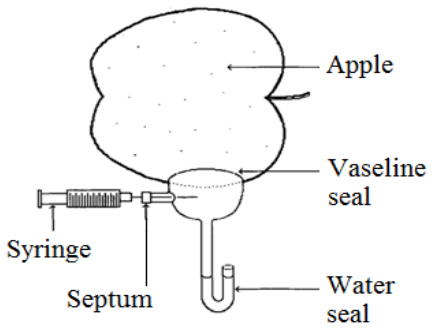

Fig. 4. Measurement of gas concentration under the skin (Mannapperuma et al., 1991)

RESPIRATORY QUOTIENT

Another important parameter associated with respiration is the respiration quotient (RQ). The RQ provides a general indication of what type of substrate is being used in respiration process. It is the ratio of CO_2 produced to O_2 consumed during the respiration cycle (Kader, 1987), which is expressed as follows:

$$RQ = \frac{M\,CO_2}{MO_2} \tag{8}$$

The RQ value varies with varying degrees of substrate oxidation. The RQ values for fresh produce usually range from 0.7 to 1.3 (Fonseca et al., 2002). When anaerobic respiration takes place, the RQ is more significant than 1.0. If the metabolic substrates are carbohydrates, it is usually assumed to be equal to 1.0. The RQ is always lower than unity if the substrate is a lipid. If the substrate is an acid, the RQ is higher than unity (Kader, 1987). The RQ helps select appropriate packaging materials when designing MAP systems, identify the vital heat in calculating refrigeration load, select fan size and location for optimal airflow within CA facilities, and formulate appropriate process control for ventilating storage facilities (Ravindra and Goswami, 2008).

MODELING OF RESPIRATION RATE KINETICS

Measurement of the respiration rate of produce can be a time-consuming process. Therefore, it is essential to find a rapid and precise method of predicting the respiration rate of a commodity under any given storage condition without requiring extensive experimentation (Kandasamy et al., 2015). Usually, the respiration process involves a series of enzymatic reactions through various metabolic pathways such as the tri-carboxylic acid cycle and the associated electron transport system (Phan et al., 1975). The respiration rate determination considers the cellular respiration process and the gas exchange process, such as the skin resistance to gas diffusion and the diffusion of gases inside the product (Wills et al., 1989).

Typically, the respiration process involves a series of enzymatic reactions through various metabolic pathways (Kader et al., 1989). Because of the complexity of the respiration process, the Michaelis–Menten equation based on enzyme kinetics with the uncompetitive type of inhibition, wherein CO_2 reacts with the enzyme-substrate complex, is used (Lee et al., 1991).

$$v_0 = \frac{V_m\,[S]}{K_m + [S]} \tag{9}$$

Based on Equation (3), they developed a model for predicting the respiration rate of fresh produce in the absence of CO_2. This model is valid only under aerobic conditions where sufficient O_2 is available for respiration. The dependence of respiration on O_2 concentration is expressed as follows (Kandasamy et al., 2015):

$$r = \frac{R_m\,[O_2]}{K_m + [O_2]} \tag{10}$$

Considering that CO_2 acts as a respiration inhibitor, the effect of CO_2 on the product respiration can be described by the uncompetitive inhibition (Ratti et al., 1996):

$$r = \frac{R_m\,[O_2]}{K_m + \left(1 + \frac{[CO_2]}{K_i}\right) \times [O_2]} \tag{11}$$

Eq. (5) is assumed to be valid as long as aerobic respiration occurs, i.e., sufficient O_2 is available to act as a substrate. Ratti et al. (1996) developed a similar model with some modifications ($K_1 = R_m$, $K_2 = K_m$ and $K_3 = 1/K_i$) for predicting fresh cauliflower's respiration rate as a function of O_2 and CO_2 concentrations.

$$r = \frac{K_1 \times C_{O_2}}{K_2 + (1 + K_3\, C_{CO_2}) \times C_{O_2}} \tag{12}$$

The model constants (K_1, K_2, and K_3) can be obtained by fitting the model (Eq. 12) to the experimental respiration data (Kandasamy et al., 2015).

The Arrhenius equation is also used to quantify the effect of temperature on respiration rate. The simultaneous use of this Equation to describe the influence of temperature on film permeability simplifies the mathematical modeling of MAP systems (Exama et al., 1993). The activation energy parameter (E) in non-activated processes loses its physical meaning and only characterizes the temperature dependence.

The effect of temperature can be expressed by the Michaelis constant K_i (where, i = 1, 2, 3) in Eq. (12). Vant-Hoff and Arrhenius described a similar relationship in their first theories of dependency of temperature on the rate constants such that the constants K_1, K_2 and K_3 can be expressed by Arrhenius relationship as follows (Cornish-Bowden, 1979):

$$\frac{d(lnK)}{dT} = \frac{E_a}{R\,T^2} \tag{13}$$

By integrating Eq. (13) with respect to T, obtained the following:

$$lnK = ln\beta - \left(\frac{E_a}{R\,T}\right) \tag{14}$$

After rearranging and taking exponential, Eq. (14) can be expressed as:

$$K = \beta exp\left(-\frac{E_a}{R\,T}\right) \tag{15}$$

At equilibrium, E_a/R_c is constant, which is denoted by b_i. The continuous K will be a function of temperature. Then Eq. (15) can be written as follows:

$$K_i = \beta_i exp\left(\frac{b_i}{T}\right) \tag{16}$$

The respiration rate model based on the Arrhenius relationship can be obtained by substituting the K_i value in Eq. (12):

$$r = \frac{\beta_1 exp(b_i/T) \times C_{O_2}}{\beta_2 exp(b_2/T) + \left[1 + \beta_3\, exp(b_3/T)\, C_{CO_2}\right] \times C_{O_2}} \tag{17}$$

The constants βi and bi (where i = 1, 2 and 3) can be obtained through non-linear regression analysis of the experimental data. The values of K_1, K_2 and K_3 can be calculated numerically. Based on the storage temperature and available O_2 and CO_2

concentrations, the respiration rate of individual fruits and vegetables can be derived by mathematical modeling. The value of activation energy ranges from 29 to 92.9 kJ/mol for common fruits and vegetables in the air (Exama et al., 1993).

STUDIES ON RESPIRATION RATE OF FRESH PRODUCE

Calegario et al. (2001) determined the respiration rate of tomato fruit (var. Santa Clara) using the continuous-flow method. They developed a conductometric detector to measure CO_2 and monitored it using a closed-loop system. They reported average respiration rates for the tomatoes of various stages of maturity ranged from 40 to 120 mgCO_2/kg.h.

Ravindra and Goswami (2008) estimated the respiration rate of mature green mango under aerobic conditions using the closed system method. They reported that the average experimental respiration rate of 6.28, 9.20, 11.22, 17.15, 22.04 and 31.11 ml/kg.h for O_2 concentration and 6.88, 9.0, 11.26, 17.31, 21.07 and 28.22 ml/kg.h for CO_2 concentration at 5, 10, 15, 20, 25 and 30ºC, respectively. They also estimated the respiration rate based on Michaelis–Menten equation, linear and non-leaner regression equation for the change in O_2 or CO_2 concentration with time.

Iqbal et al. (2009) measured the respiration rate of freshly shredded carrots at 0, 4, 8, 12, 16 and 20C under different gas compositions of O_2 and CO_2 using the closed system method. They observed that as the temperature increased from 0 to 20ºC, the values of RR varied from 5.2 ± 0.5 to 51 ± 1 ml/kg.h for ambient air. The extreme gas mix (2% O_2+16% CO_2) reduced O_2 consumption and CO_2 production rates by 30-45%. A Michaelis–Menten uncompetitive model best described the influence of gas composition.

Mangaraj and Goswami (2011) investigated the respiration rate of litchi fruits using the closed system method at different temperatures. They reported the respiration rate of 14.28, 30.3, 45.64, 62.5, 76.92, 90.9 and 125.55 ml/kg.has a function of O_2 and 13.33, 23.8, 33.33, 50.63, 62.16, 83.33 and 111.10 ml/kg.has a function of CO_2 at 0, 5, 10, 15, 20, 25 and 30ºC, respectively. They also proposed two different models based on regression analysis and enzyme kinetics with the help of respiration data and predicted respiration rate using the models.

Caleb et al. (2012) investigated the effect of temperature and storage time on the respiration rate (RO_2 and RCO_2) of 2 pomegranate cultivars (cv. Acco and Herskowitz) fresh arils. They reported that the RO_2 and RCO_2 were 3 to 4 folds significantly higher with increased temperature from 5 to 15ºC and were within the range of 2.51 to 7.59 ml/kg h and 2.72 to 9.01 ml/kg h, respectively, for both cultivars. RCO_2 increased from 8.4 to 25.96 ml/kg h at 15ºC, and from 2.9 to 2.05 ml/kg h at 5ºC from day 1 to 5. The respiratory quotient was 0.98 at a 95% significant level. The respiration rate was dependent on temperature and time and described with a combination of an Arrhenius-type and power equation model.

Singh et al. (2013) evaluated the respiration rate and respiratory quotient of mature tomato (*cv. Himsona*) fruit using the closed system method at various temperatures. They observed the respiration rate of 14.35, 15.04,19.95, 21.7 and 20.3 mlCO_2/kg-h at 10, 15, 20, 25 and 35°C, respectively. The respiration rate was higher at the beginning and gradually declined as the storage period prolonged. The RQ values varied from 0.55 to 1.10 with time under the experimental conditions.

Rahman et al. (2013) studied the effect of temperature (5, 10, 15, 20, 25 and 30ºC) on the respiration rate of fresh-cut papaya using a closed system method. They found that the RR increased from 0.021 to 0.289 mlO_2/kg hand from 0.063 to 0.393 mlCO_2/kg has a function of O_2 and CO_2 gas concentrations, respectively. They also developed a respiration rate model based

on Peleg's Equation to predict RRs of fresh-cut papaya. The model was in good agreement with the experimentally estimated RRs.

Aindongo et al. (2014) investigated the effects of storage temperature (5, 10, 15 and 22°C) on the respiration rate of pomegranate (var. Bhagwa) whole fruit aril-sacs and arils. They reported that the respiration rates as a function CO_2 and O_2 for whole fruit in the range of 2.66-22.97 and 3.71-33.3 ml/kg.h; for aril-sacs in the range of 2.95-27.66 and 5.49-48.44 ml/kg.h; for arils were 1.96-18.64 and 3.19-28.91 ml/kg.h, respectively. The respiration rate was reduced by about 74.5% by reducing the storage temperature from 22°C to 5°C. They also proposed a model based on the Arrhenius-type Equation relating to temperature and respiration rate.

Kandasamy et al. (2015) investigated a study on the respiration rate of tomatoes at 10, 20 and 30ºC using a closed system. They found that the RR of 60.08, 89.0 and 88.68 mgCO_2/kg.h at 10, 20 and 30ºC, respectively, at the beginning of the experiment and corresponding values were 1.75, 1.55 3.12 mgCO2/kg.h, respectively after 17 days. The RR decreased with a decrease in the O_2 and an increase in the CO_2 concentrations. They also observed significant fluctuations in RRs at the end of the experiment. The O_2 concentration reduced below 8%. The fast decline in the RR at high temperature could be attributed to the malfunctioning of the enzymes which catalyzes the respiration process.

Agudelo et al. (2016) studied the respiration rate of mango (cv. Tommy Atkins) using the closed system method at three temperatures (4, 20 and 35ºC). Three models, based on Michaelis-Menten's enzymatic kinetics, regression analysis and saturation equation were set to predict the respiration rate. They reported the respiration rate of 5.09, 59.21 and 110.76 mLCO_2/kg.h at 4, 20 and 35ºC, respectively. The difference in respiration rate is due to the reduction of temperature. They also reported the organoleptic and physiological characteristics of mango stored at 4°C had no significant change in odour, texture and flavour.

Patel et al. (2016) studied the effect of different storage conditions on the rate of respiration and heat of respiration of mango fruits (*cv*. Langdo) at 10, 15, 20, 25°C and ambient temperature using the closed system method. The reported the respiration rate of 61.44, 71.76, 80.03, 83.93, 100.42 mlCO_2/kg.h and heat of respiration of 7164.84, 8221.14, 9009.34, 9287.19, 10745.55 kcal/metric ton/day at 10, 15, 20, 25°C and ambient temperature, respectively at the beginning. They also demonstrated the rate of respiration and heat of respiration increased with an increase in temperature whereas decreased with time under steady-state conditions.

Barbosa et al. (2018) measured the respiration rate of papaya (cv. Golden) using the closed system method at ambient temperature (23°C). They reported that the respiration rate was decreased while decreasing O_2 and increasing CO_2 concentration; however, it raised over storage time. The respiration rate of 0.33 and 0.52 µmol/kg.s was reported at the beginning and after 13 days, respectively, with a 17% O_2+0.6% CO_2 gas combination. At 3% O_2+5% CO_2, the RR of 0.15 and 0.25 µmol/kg.s at the beginning and after 13 days, respectively. They also proposed a model based on the Michaelis–Menten equation with uncompetitive inhibition.

Kumar and Siddharth (2020) investigated the effect of different temperatures and storage time on respiration rate (RO_2 and RCO_2) of pomegranate cultivar (cv. 'Bhagwa') fresh arils. They observed that RO_2 and RCO_2 were within the range of 2.54-8.36 ml/kg.hand 2.76-10.04 ml/kg.h, respectively. Reducing the storage temperature of arils from 15 to 5°C decreased RO_2 and RCO_2 by about 67 and 70%, respectively. The dependence of RR on time and temperature is well described by a combination of the Arrhenius-type and power equation model.

CONCLUSION

Controlled atmosphere storage is one of the important techniques used to supplement the low-temperature preservation of fruits and vegetables. CA is primarily employed to reduce respiration rate and retard the ripening process, increasing host resistance to diseases. Commercially, CA is successful for the storage of many fruits and vegetables such as apples and pears. The success of CAS dramatically depends on the accuracy of the predictive respiration rate and its models. The empirical models have been developed due to the complexity of the respiration process. The models describe the respiration rate of produce, gas exchange between CA in the storage and ambient atmosphere. The models are an effective tool for selecting the appropriate initial gas mixture, properties of the packaging film, right storage temperature and maintain a self-controlled atmosphere. CA storage's marginal increases in storage life and quality are not enough for the added cost of implementing CA technology commercially for most fruits vegetables.

NOMENCLATURE

$[O_2]$	oxygen concentration (%)
$[CO_2]$	carbon dioxide concentration (%)
$d[O_2]$	change in concentration of O_2 with time
$d[CO_2]$	change in concentration of CO_2 with time
dt	difference in time between two gas measurements (h)
R_{O_2}	respiration rate as a function of oxygen (mgO_2/kg h)
R_{CO_2}	respiration rate as a function carbon dioxide ($mgCO_2$/kg h)
P	gas pressure (1 atm)
M_a	mean molecular mass of air (g/mol)
V_f	free volume of the container (L)
R	ideal gas constant (0.08206 L atm/mol K)
T	temperature of the gas (K)
W_p	weight of the stored product (kg)
V	free volume of the chamber (cc)
M_s	mass of the stored product (kg)
E_a	activation energy (Pa m^3/mol
P_c	permeability coefficient, m^2/s
Co_2	oxygen concentration inside the chamber (mg/l)
Cco_2	carbon dioxide concentration inside the chamber (mg/l)
Mco_2	mass of carbon dioxide evolved (mg)
Mo_2	mass of oxygen consumed (mg)
K_1	inhibition constant (mg/kg.h)
K_2	inhibition constant ($molO_2$/mol total)
K_m	Michaelis-Menton constant (% O_2)
r	respiration rate (ml/kg.h)
y	volumetric concentration (v/v)
A	surface area (m^2)
RQ	respiratory quotient
t	time (s)
L	thickness (m)
F	flow rate (m^3/s)
T	temperature (°C)
S	substrate concentration
β	integrating constant

Superscripts

e	external
in	internal
out	outlet

Subscripts

i	initial
f	final

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