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A mathematical expression for prediction of sugar loss in fresh produce during its storage by using a respiratory model

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Abstract—Fruits and vegetables respire even after harvest. In respiration process the sugars and/or acids are consumed as substrates. The sugars contribute almost 90% in CO_2 production of respiration. Uchino et al. 2004 developed respiration rate equation, which has been used to obtain a mathematical expression for sugar consumption/losses during storage of fruits by knowing the constants from experiment. One can predict the sugar losses during storage using the equation. The expression developed has been validated with data reported in the literature.

Keywords— respiration rate, sugar, shredded cabbage, broccoli, temperature, mathematical expression

I. INTRODUCTION

Fruits and vegetable continue metabolic activities such as the respiration even after harvest. In the respiration, which is an oxidative metabolism mainly, reserves of sugars and fatty acids are utilized. The process of respiration can be represented by a simplified chemical reaction (Lee et al. 1991)

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

The respiration and consumption of respiratory substrates are interrelated. The main substrates that are consumed in respiration are sugars and/or acids. The initial decrease in reducing sugars of bamboo shoots during storage was considered due to consumption during respiration [Lu and Xu (2004)]. It was mentioned by Bolin and Huxsoll (1991) that the decrease in soluble solids of cut lettuce was caused by carbohydrate utilization via respiration.

If the relationship between respiration and consumption of the substrates is quantitatively clarified, quality loss of fresh-cut produce could be quantitatively predicted by using respiratory models. Therefore, a mathematical relationship between respiration and consumption of sugars has been derived by using model of Uchino el al. (2004) (equation 2) for respiration rate of fresh produce which is dependent on temperature and time.

II. MATHEMATICAL MODEL DERVATION:

Uchino el al. (2004) model for respiration rate of fresh produce is given below

$$R_C = K_1 \exp\left(\frac{-E_a}{RT}\right)\{1 + K_2 \exp(-k_d t)\} \qquad (2)$$

where K_1 and K_2 are parameters in mmol kg $^{-1}$ h^{-1} and dimensionless, respectively. E_a is the apparent activation energy (Jmol^{-1}), k_d the rate constant for decomposition of enzyme (h^{-1}), *R is* the ideal gas constant (Jmol^{-1} K^{-1}), and *T* is the absolute temperature (K).

The respiration rate is actually production rate of CO_2.

$$R_C = \frac{d\,[CO_2]}{d\,t} \qquad (3)$$

From Equations 2 and 3

$$\frac{d\,[CO_2]}{d\,t} = K_1 \exp\left(\frac{-E_a}{RT}\right)\{1 + K_2 \exp(-k_d t)\} \qquad (4)$$

Integration of equation gives moles of CO_2 produced during initial t_i time to any time t

$$[CO_2] = K_1 \exp\left(\frac{-E_a}{RT}\right)\left[(t - t_i) + \frac{K_2}{k_d}\{\exp(-k_d t_i) - \exp(-k_d t)\}\right] \qquad (5)$$

Equation 5 reduces for observation for time 0 to t

$$[CO_2] = K_1 \exp\left(\frac{-E_a}{RT}\right)\left[t + \frac{K_2}{k_d}\{1 - \exp(-k_d t)\}\right] \qquad (6)$$

From stoichiomatery of reaction equation 1 from one mole of hexose (glucose or fructose), six moles of CO_2 are produced. Therefore, consumption of sugar will be

$$\begin{bmatrix} moles\ loss\ due\ to\ respiration \\ equivalent\ to\ glu\cos e \end{bmatrix} = \frac{1}{6} \times \left[Moles\ of\ CO_2\ produced \right]$$

Therefore, consumption of mass in gm of sugars as glucose will be

$$\begin{bmatrix} mass\ loss\ of\ sugars\ due\ to \\ respiration\ equivalent\ to\ glu\cos e \end{bmatrix} = \frac{180}{6} \times \left[Moles\ of\ CO_2\ produced \right]$$

Loss of mass in gm of total sugars as glucose from fresh produce stored at temperature T Kelvin is given by

$$S_L = 30 \times K_1 \exp\left(\frac{-E_a}{RT}\right)\left[t + \frac{K_2}{k_d}\{1 - \exp(-k_d t)\}\right] \qquad (7)$$

Where CO_2 is measured in moles. Hisaka (1989) reported that ~90% of CO_2 produced from spinach was derived from sugar. It was assumed that 90% CO_2 emitted from shredded cabbage was also due to oxidation of sugar for respiration. Thus, only 90% CO_2 contributed to reduction of sugar the expression results in actual loss of sugars will be given by

$$S_L = 27 \times K_1 \exp\left(\frac{-E_a}{RT}\right)\left[t + \frac{K_2}{k_d}\{1 - \exp(-k_d t)\}\right] \qquad (8)$$

However, for a different temperatures and different time durations expression will be

$$S_L = 27 \times K_1 \exp\left(\frac{-E_a}{RT}\right)\left[(t - t_i) + \frac{K_2}{k_d}\{\exp(-k_d t_i) - \exp(-k_d t)\}\right] \qquad (9)$$

The total remaining sugar in any sample after a storage time t is given by

$$\begin{bmatrix} \text{The total remaining sugar in a} \\ \text{sample after storage of time t} \end{bmatrix} = \left[\text{Initially sugar present}\right] - \left[\text{sugar loss/consumed in time t}\right]$$

The expression (Equations 8 and 9) obtained is simple to use. For using equations 8 and 9, the values of K_1, K_2, E_a and k_d in equation 2, are to be determined from respiration rate data for a particular fresh produce. These values vary for intact and partially processed sliced, shredded and/or peeled fruits and vegetables of same variety or cultivar as partial processing lead severe stress on tissues and hence respiration rate increases.

Equation 9 is useful in estimating the sugar losses at different storage periods. It is required because, before consumption fresh produce are stored during transportation, retailing and at consumer level at different temperatures and different durations. The equation 9 may find use in predicting useful self life recommendation to consumer.

III. RESULTS AND DISCUSSIONS:

The respiration rates and sugar content are reported with storage for shredded cabbage (*Brassica oleracea var. capitata* cv. Teruyoshi) by Nei et al. (2006) and for broccoli florets (*Brassica oleracea var. italica* cv. Piracicaba Precoce) by Finger et al. (1999); the same data has been utilized to verify the proposed Equation 8.

The values of parameters K_1, K_2, E_a and k_d reported by Nei et al. (2006) for shredded cabbage are used as such. For broccoli florets the values were calculated from respiration rate data reported by Finger et al. (1999); the respiration rate for more than 24 hours were not considered as respiratory activity changed its pattern after this time during the storage condition in the reported data probably due to change of substrate. Also sugar reported was based on dry weight, after drying the samples in oven at 70 ^oC therefore authors of present paper assumed dry weight of broccoli florets equal to 15% which is justified as it contains equilibrium moisture and dry matter. The SOLVER addin of MS EXCEL sheet was used to estimate the values of constants. For initial guess the values of constants reported for broccoli cv parsol, by Uchino et al. (2004) were used. The values of the constants for the two shredded cabbage and broccoli florets are given in Table 1. Nei et al. (2006) found that the glucose and fructose were the main sugars contained in shredded cabbage; sucrose contents were markedly lower, similar is expected in broccoli. Changes in total sugar contents experimental as well as predicted, from the constants obtained from respiratory data for shredded cabbage at storage temperatures 5°C and 20 °C and for broccoli florets at storage temperature 25°C are shown in Figure 1 in Figure 2 respectively.

The observed values of sugar remained in shredded cabbage and broccoli samples and the values predicted from proposed equation with storage time are given in Figure 1 and Figure 2 respectively. It is evident from the figures that the predicted values are close to the observed values within experimental limitation. The reason for slight variation in experimental and predicted values may be due to the fact that in addition to sugars various other substrates also contribute to respiratory production of CO_2, however, it is notable that in the equation 8 it has been assumed that 90% CO_2 emitted from shredded cabbage was due to oxidation of sugar for respiration.

Thus, it is found that with the developed mathematical expression sugar consumption or remaining sugar in sample during storage of fresh produce at a temperature could be predicted satisfactorily. The parameters K_1, K_2, E_a and k_d of respiration equation (2) used in above expression may be determined from experimental data of its respiration rate for a produce.

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Table1: values of different parameters for RR

	K_1 (mmol kg $^{-1}$ h $^{-1}$)	K_2	E_a (Jmol $^{-1}$)	k_d (h $^{-1}$)	Reference
Shredded cabbage	1.44×10^{8}	0.241	4.06×10^{4}	9.88×10^{-2}	Nei et al. (2006)
Broccoli florets	1.59×10^{5}	1.044	2.54×10^{4}	0.1996	Finger et al. (1999)

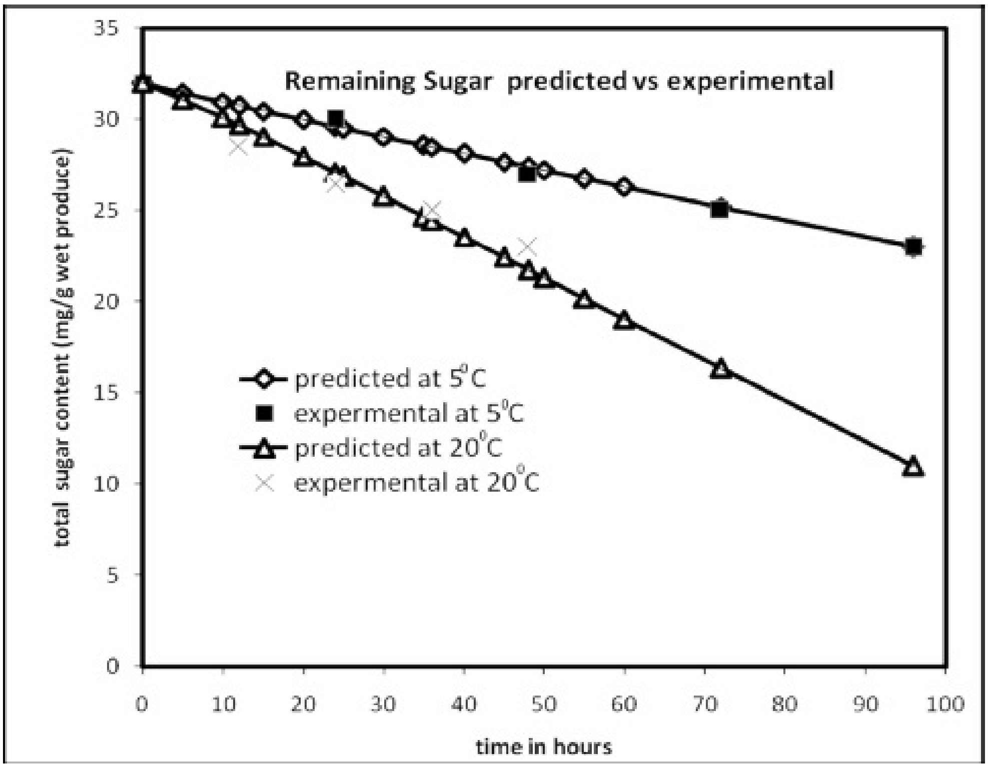

Figure 1: **Comparison of remaining sugar predicted from proposed expression and experimental data (Nei et al.2006) for shredded cabbage**

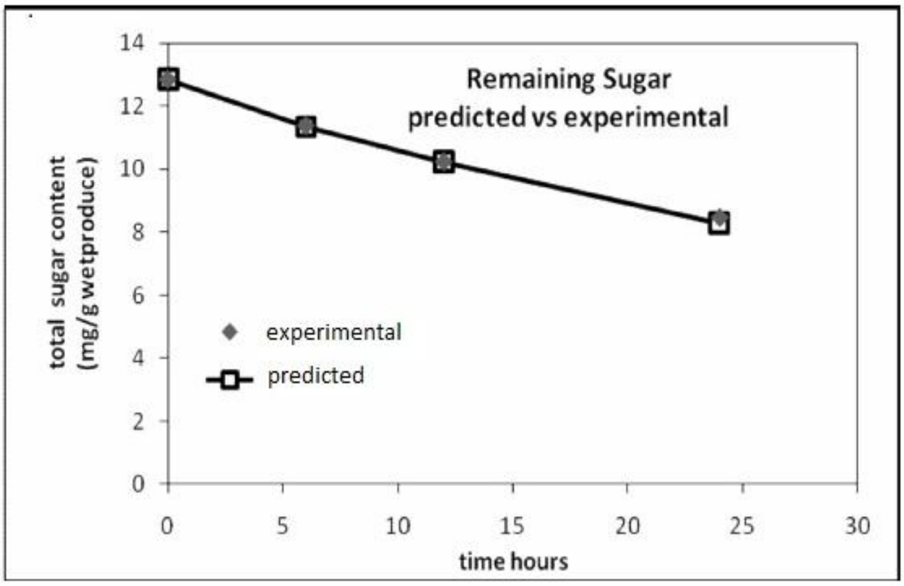

Figure 2: **Comparison of remaining sugar predicted from proposed expression and experimental data (Finger et al. 1999) for broccoli florets**