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Measurement and modelling the effect of temperature, relative humidity and storage duration on the transpiration rate of three banana cultivars

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A B S T R A C T

Transpiration rate (TR) of three cultivars of banana (triplicates of each experimental run, 2 nos. present in each run) was measured at different temperatures (10, 20 and 30 °C) and relative humidity (RH) (70, 80 and 90%) and storage time (2, 3 and 6 days). Models based on unsteady state energy balance equation and regression equation was fitted to the TR data. Best fitting model was validated at 15 °C and 70, 80 and 90% RH and on 2nd, 3rd and 6th day of storage. Using the TR data design parameters for equilibrium humidity packaging for three banana varieties had been estimated. While the TR of banana increased with rise in temperature, it decreased with rise in storage RH and with progress of storage duration. Banana Cv. Singapuri had significantly low ($P < 0.05$) average TR (21.69 g/kg-day), while the average TR of G9 (34.96 g/kg-day) and Chapa (29.53 g/kg-day) cultivars were similar ($P > 0.05$), and these two varieties (G9 and Chapa) were least affected by variation in temperature and relative humidities. The energy balance model ($R^2 = 0.61–0.81$) fitted the TR data better than the regression model at all RH and temperature studied. Temperature of the banana surface was determined from the model and was found to be greater than the wet bulb temperature of banana. Heat transfer from banana surface by convection was found to provide approximately 70% of the heat required for transpiration. At 15 °C, the predicted TR was plotted against the experimental data corresponding to storage RH, and duration. For these two predictions the mean relative percentage deviation modulus was 10.27% and 18.35%, respectively. The required water vapour transmission rate for designing equilibrium humidity packaging of three variety of banana ranged from 172 to 618 g/m^{2}day at 10–20 °C.

1. Introduction

India with annual production of 29.72 million metric tonn (MMT) is the leading producer of banana in the world contributing 27.8% of total world production. Also, the production increased at 2.08% average rate per year for the last five years (Indian Horticulture Database, 2014). Of the total production in India, only 0.12% is exported to more than nine countries of the world including USA (14000 MT), Soudi Arabia (4809 MT), Oman (3521 MT) etc. earning an export value of about 1.56 billion Indian rupee (APEDA, 2015).

The shelf-life of banana is limited due to its climacteric nature. Storage under modified atmosphere or humidity packaging (MAP/MHP) extends shelf-life of banana without use of any chemical preservatives (Chauhan et al., 2006). To design MHP for banana it is essential to have the information about rate of water evaporation from banana surface, which should be balanced with the water vapour transmission rate of the packaging film constituting the MHP. Otherwise, water vapour will condense on the walls of the package and enhance bacterial and mould growth on the commodity. On the other hand extremely low in-package humidity results in weight loss of banana. Where fruit is sold on a weight basis, loss of water is equivalent to economic loss. Water loss also detoriates visual acceptability and had been reported to causes plantain cultivars of banana to lose its firmness, the peel becomes soft and shriveled, and ripening period reduces (Mu-bo et al., 2015). Therefore, study of the transpiration rate (TR), which is the rate of water evaporated from banana surface per unit mass per unit time of

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banana is highly important in MHP design study. Water loss had been described as the most important factor effecting shelf life of pepper cultivars in MAP by Lownds et al. (1994).

Mathematical models are used to predict TR of a commodity at any time and any temperature. In the literature there are several models for estimating TR of different commodities but they have limited applications due to their specific assumptions. For ex., Kang and Lee (1998) estimated TR of apple by using respiratory heat as the latent heat required for water evaporation under saturated storage conditions in controlled atmosphere. Their model assumed a steady state condition and did not consider any change in temperature on the fruit surface due to energy transfer. Modified model was used for blueberries by Song et al. (2002) who used the overall energy balance equation inside MAP to estimate rate of water evaporation but convection heat transfer inside the pack was not considered.

Model based on Fick's law of diffusion was developed by Mahajan et al. (2008) who included temperature term to predict transpiration rate of mushrooms at any temperature. Sousa-Gallagher et al. (2013) used the model developed by Mahajan et al. (2008) to estimate water vapour transmission rate of polymer film required for MA storage of strawberries. Sastry and Buffington (1983) described water loss from tomato using mass transfer equation, which required information about water vapour diffusivity, characteristic dimension, air viscosity and air density.

In all the models TR has been considered constant and the effect of time has not been considered. Also, it appears that no model is present to detect the TR of banana considering unsteady state energy balance equation. The aim of this work was to (i) measure the TR of three cultivars of banana at different temperatures, relative humidity conditions and storage durations and (ii) develop model based on unsteady state energy equation and regression equation to predict TR of banana at any storage duration.

2. Materials and methods

2.1. Transpiration rate measurement

Banana of 'Singapuri' (Musa spp.) and 'Chapa' (Musa spp.) variety were purchased from the local market of Kharagpur (India) on the same day of their harvest whereas that of Grand Naini (G9) (Musa acuminata, AAA group) variety were procured from the experimental farm of Agriculture and Food Engineering Departmet, IIT khargpur. The banana bunches were quickly brought to the Food Chemistry and Technology Laboratory, Indian Institute of Technology, Kharagpur and washed with tap water followed by surface wiping with blotting paper and drying in ambient air.

Sorting of the fruits of each variety was done based on uniformity of weight, length and surface greenness (a* value) mentioned in Table 1. The initial weight of banana was measured using an electronic balance (Afcoset, GmbH); length, breadth and diameter were measured with a vernier calliper (Mitutoyo, Japan) and peel outer surface color was measured with colorimeter (Konica Minolta, CM-5).

To evaluate the TR of banana, a weight loss technique was used. Two bananas were stored inside an environmental test chamber (Remi Instruments) at thermostatically controlled temperature and relative humidity (RH) conditions; taken out at specific time interval and weight loss was measured. TR was calculated from the changes in weight of banana over time from Eq. (1). Temperature and RH inside the environment chamber were monitored continuously using temperature and RH probe and data displayed on the instrument display screen.

$$TR = \frac{M - M_i}{t \times \frac{M_i}{1000}} \tag{1}$$

Where, TR is the transpiration rate in g/kg day; M_i is the initial weight (g), and M is the weight of banana (g) at time t (day). Experiments were performed according to a full factorial design, considering 4 factors at three levels (3^4), i.e., banana variety (Singapuri, G9 and Chapa), temperature (10, 20 and 30 °C), RH (70%, 80% and 90%) and storage period (2, 3 and 6 days). Experiments were replicated three times.

2.2. Measurement of respiration heat

Respiration may be assumed as oxidation of glucose (Eq. (2)) and expressed as average of rate of O_2 consumption and CO_2 evolution (Eq. (3)) (Song et al., 2002).

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + 2,816,000\,J \uparrow \tag{2}$$

$$Q_s = \frac{1}{2}\left[r_{O_2} + r_{CO_2}\right] \times \frac{2,814,000}{6} J \tag{3}$$

Where, Q_s is the respiratory heat generation J/mol; r_{O_2} is the respiration rate of banana in terms of O_2 consumption, and r_{CO_2} is the respiration rate of banana in terms of CO_2 evolution in kg-mol/kg-day, measured by closed system method (Mangaraj and Goswami, 2011). The change in% O_2 and% CO_2 with time on the headspace of the 1.8 L jar containing banana at any temperature was determined by a head space analyzer (Systech Illinois, 6600).

2.3. Development of transpiration rate model

2.3.1. Energy balance model

An energy balance was done on the evaporating surface of the fruit (Eq. (4)) as used by Kang and Lee (1998) and Song et al. (2002). It was assumed that the respiratory heat was the only source of internal heat and the head space was assumed to be small and was at thermal equilibrium with the storage environment. Banana fruit was assumed to be cylindrical in geometry.

$$Q_s \times RR \times M + h_s \times A \times (T_s - T_{b,t}) = TR \times M \times \lambda + M \times C_{p,f} \times \frac{dT_{b,t}}{dt} \tag{4}$$

Where, A is surface area of fruit, m^2; T_s is the temperature (°C) of the storage environment; T_b is the surface temperature (°C) of the banana at any time, and was assumed to be initially at the wet bulb temperature of the storage environment; λ is the latent heat of evaporation of water in kJ/kg at T_s; $C_{p,f}$ is the specific heat of the fruit 3.35 kJ/kg °C (The engineering tool box website, 2016); dt is the time interval; h_s is the convective heat transfer co-efficient and is calculated by Eq. (5) by assuming natural convection and laminar flow past a cylinder (Kang and Lee, 1998).

$$h_s = 1.32 \times 3600 \times 24 \times \sqrt[4]{\frac{(T_s - T_{b,t})}{d}} \tag{5}$$

Where, Where, $T_{w,t}$ = wet bulb temperature of the banana surface, d is characteristic dimension of the fruit in m and was calculated by dividing volume by surface area of banana (Table 1). By integrating the energy balance model with time Eq. (6) was obtained.

$$\frac{\left[M_b(RR \times Q_r - \lambda \times TR) + (h \times A_b \times (T_s - T_{b,t}))\right]_{\text{Day 2}}}{\left[M_b(RR \times Q_r - \lambda \times TR) + (h \times A_b \times (T_s - T_{b,t}))\right]_{\text{Day 1}}} = e^{\frac{-h \times A_b \times (t_2 - t_1)}{M \times C_p}} \tag{6}$$

2.3.2. Regression model

Regression model Eq. (7) including the effect of time, RH, their interaction and quadratic terms was fitted to the experimental data