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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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ABSTRACT

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 (8°=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/m²-day at 10–20 °C.

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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), Saudi 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 deteriorates 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 acuminate, AAA group) variety were procured from the experimental farm of Agriculture and Food Engineering Department, IIT kharagpur. 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 (Acoset, 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.

\[
TR = \frac{M - M_i}{t \times \frac{M}{1000}}
\]

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 \(^\circ\)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 rate of O\(_2\) consumption and CO\(_2\) evolution (Eq. (3)) (Song et al., 2002).

\[
\begin{align*}
C_6H_{12}O_6 + 6O_2 & = 6CO_2 + 6H_2O + 2,816,000J \quad (2) \\
Q_r & = \frac{1}{2} \left[ rO_2 + rCO_2 \right] \times \frac{2,814,000}{6} J \quad (3)
\end{align*}
\]

Where, \(Q_r\) is the respiratory heat generation J/mol; \(rO_2\) is the respiration rate of banana in terms of \(O_2\) consumption, and \(rCO_2\) 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.

\[
Q_r \times RR \times M + h_s \times A \times (T_s - T_{b,t}) = TR \times M \times \lambda + M \times C_{p,f} \times \frac{dT_{b,t}}{dt} \quad (4)
\]

Where, A is surface area of fruit, m\(^2\); \(T_s\) is the temperature (\(^\circ\)C) of the storage environment; \(T_{b,t}\) is the surface temperature (\(^\circ\)C) of the banana at any time, and was assumed to be initially at the wet bulb temperature of the storage environment; \(\lambda\) 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).

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

Where, Where, \(T_{w,t}\) is 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.

\[
\left[ M_s \left( \frac{RR \times Q_r - \lambda \times TR}{h \times A_b \times (T_s - T_{b,t})} \right) \right]_{\text{Day2}} + \left[ M_s \left( \frac{RR \times Q_r - \lambda \times TR}{h \times A_b \times (T_s - T_{b,t})} \right) \right]_{\text{Day1}} = e^{-h_b \times (T_s - T_{b,t})} \quad (6)
\]

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.
of TR of three variety of banana at each temperature.

\[ y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + \beta_4 x_1^2 + \beta_5 x_2^2 + \beta_6 x_1^2 x_2^2 \]  

(7)

Where, \( x_1 \) is temperature; \( x_2 \) is RH and \( x_3 \) is storage duration and \( \beta \) terms represent co-efficients.

Eqs. (6) and (7) were used to fit the experimental data obtained at the combinations of temperature and RH reported earlier, and the constant coefficients (\( T_{1,0} \) of heat balance model and \( \beta \) terms of regression model) were estimated by minimizing sum of square residual using solver tool of the Microsoft Excel, 2007 software. Experimental data were subjected to analysis of variance using Design Expert 7, software. When the significant difference was observed, mean treatments were compared using Turkey's test.

An additional set of similar experiment mentioned in Sections 2.1 and 2.2 was carried out at 15 °C and 70, 80 and 90% RH to determine respiration rate and TR in order to validate the developed model. The mean relative percentage deviation modulus was calculated to evaluate the goodness of fit of the predicted and experimental data.

### 3. Results and discussion

#### 3.1. Effect of storage temperature

The transpiration rate of banana increased with rise in temperature, decrease in RH and progress of storage duration (Table 2). Singapuri had significantly low (\( P < 0.05 \)) average value of 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 were least affected by variation in temperature and relative humidities.

The observed TR of banana was higher than transpiration rate of other commodities which do not have any protective covering. For example, Sousa-Gallagher et al. (2013) reported that TR of strawberries was in the range of 5–24 g/kg-day over temperature range of 5–15 °C and RH range of 76–96%. Similarly, Caleb et al., (2013) reported lower TR of non-climacteric pomegranate arils between 1.4–16.75 g/kg·day at a temperature range of 5–15 °C and 75–90% RH and also reported that highest water loss of the arils were at low temperature and low RH. This comparison shows that banana is highly transpiring fruit and stresses the importance of measurement of banana TR before engineering design of its MHP.

The interaction effect of storage temperature \( \times \) storage relative humidity (\( P < 0.05 \)) and storage temperature \( \times \) storage duration is significant (Fig. 1). The variation of RH causes greater variation in TR at higher temperature only for all the studied cultivars. Also at any temperature TR decreases with storage duration initially after which it increases (for Singapuri and Chapa) or remains constant (G9) variety.

When banana was stored at 30 °C and 70% RH mould growth was observed on the fruit surface after only four days of storage at 30 °C and 70% RH. Surprisingly, within four days banana did not ripen as indicated by the skin color (data not shown). The aforesaid storage condition was also found to support Botrytis decay resulting in excessive softening of the infected part of the fruit advancing with storage time, therefore the experiment was terminated after six days. Whereas, storage at 90% RH and 10 °C induced peel browning/blackening affecting overall visual acceptability of the banana. Contradictorily, at 20 °C and 80–90% RH no mould growth was observed till banana was fully ripened to yellow color following 7 days of storage. This indicates that in-pack RH of 80–90% may be favorable for MAP banana.

To prevent water condensation inside the packaging film at any temperature, it is required to match the water vapour transmission rate of the packaging film with banana transpiration rate at that temperature (Mahajan et al., 2008). Considering this, the design considerations for equilibrium humidity packaging of one kg Singapuri banana (approximately 8–10 fingers) is demonstrated at 10 °C.

The required packaging film area (\( A_f \)) was calculated by using banana finger dimenions from Table 1 as \( A_f = \pi \times (\text{width of one finger} \times \text{length of one finger}) \times (1 \text{kg/weight of each finger}). \) With this 20% extra area can be obtained providing enough space for sealing etc. Total area thus calculated was \( A_{\text{total}} = 936 \text{cm}^2 \).

The required water vapour transmission rate (WVTR) of the packaging film at any temperature was calculated as \( \text{WVTR} = \frac{A_{\text{total}} \times \text{TR of banana at that temperature}}{A_{\text{total}}} = 190.59 \text{g/m}^2 \text{-day}. \) In the similar way WVTR was determined for other cultivars of banana at three temperatures and presented in Table 3. The WVTR of the packaging films is different for each variety of bananas and is sensitive to fluctuation in temperature.

When the WVTR of the available film is lower than the WVTR, water vapour would condense inside MAP. To avoid inpackage condensation calculated mass of scrubber may be included in equilibrium humidity packaging. For example, packaging film with high WVTR of about 300 g/m²·day had been used by Mahajan et al. (2008) for mushrooms. Using film having WVTR of 300 g/m²·day for packaging one kg G9 banana at 10 °C for storage of 14 days, total mass of water accumulation (\( M_w \)) inside the designed packaging may be calculated as \( M_w = (\text{WVTR} - \text{WVTR available}) \times A_f \times \text{Storage duration} = 244.86 \text{g}. \)
Table 3  
The required water vapour transmission rate for design of equilibrium humidity packaging of one kg banana for Singapuri, G9 and Chapa cultivars at 10, 20 and 30 °C.

<table>
<thead>
<tr>
<th>Variety</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapuri</td>
<td>247</td>
<td>172</td>
<td>280</td>
</tr>
<tr>
<td>G9</td>
<td>618</td>
<td>436</td>
<td>818</td>
</tr>
<tr>
<td>Chapa</td>
<td>271</td>
<td>223</td>
<td>305</td>
</tr>
</tbody>
</table>

This mass of accumulated water must be absorbed by the selected moisture scrubber. Average absorption capacity of silica gel is 0.4 g water/g silica. Hence, 612.15 g silica is required for effective shelf-life of 1 kg G9 banana. This mass of required silica gel is very high for incorporating in MAP. Hence, moisture absorber having higher absorbing capacity e.g. clay and mesoporous materials (Eng-Poh and Mintova, 2008) may be used instead of silica gel.

3.2. Transpiration rate models and comparison

The regression equations for three cultivars of banana at 10, 20 and 30 °C are shown in Table 4. Linear relationship was suggested to predict TR as a function of storage RH and storage duration at 10 °C for the three cultivars, equations involving interaction terms of RH and storage duration and their quadratic terms were fitted at 20 and 30 °C. The co-efficient of determination (R²) of the regression equations at all the temperatures ranged from 0.14–0.76; with the lower values of R² indicating unsatisfactory fit of the predicted data to the observed data.

To predict TR of banana by energy balance model the necessary parameters including the respiration rate in terms of oxygen consumption, carbon dioxide evolution and the corresponding estimated respiratory heat generation are shown in Table 5. The respiration rate and consequently the generated respiratory heat followed the expected climatic pattern. The respiratory heat was highest for Singapuri cultivar (1.33–23.12 J/kg-h) compared to that of G9 (0.34–4.04 J/kg-h) and Chapa cultivars (0.57–18.40 J/kg-h) at all the studied temperatures.

The only unknown parameter in the energy balance model was the temperatures of banana surface at any storage temperature, humidity and storage duration. The estimated temperature at the banana surface was relatively less than the wet bulb temperature at 10 °C and was more than the wet bulb temperature at 20 and 30 °C for all the cultivars (Fig. 2a–c). This indicated that the developed energy balance model considered the evaporative cooling of the banana surface due to transpiration as well as rise in temperature of the banana surface due to heat of respiration. By analyzing the model it was found that respiratory heat contributed 3–30%, 0.01% and 0.1–0.03% of the total heat required for transpiration for singapuri, G9 and Chapa cultivars, respectively at the three studied temperatures. This indicated that majority of the heat required for transpiration was provided by heat transfer by convection from the surface.

The co-efficient of determination of the energy balance model was 0.71, 0.76, and 0.81 for the Singapuri cultivar; 0.81, 0.76, and 0.71 for G9 cultivar; and 0.61, 0.67, and 0.69 for Chapa cultivar at 10, 20 and 30 °C, respectively. As this model had higher co-efficient of determination, therefore it was selected over the regression model to predict TR of banana. This could be further confirmed from Fig. 3(a–c) which show the observed TR and predicted values.
Fig. 2. Relative variation in temperature of banana surface estimated from energy balance model from the wet bulb temperature for (a) Singapuri (b) G9 and (c) Chapa cultivars of banana at 10, 20 and 30 °C and 70, 80 and 90% storage RH.
Fig. 3. Observed and predicted transpiration rate of (a) Singapuri (b) G9, and (c) Chapa cultivars by regression model and heat balance model at 10, 20 and 30 °C and 70% RH on the 2nd day of storage and (d) during the storage duration for Singapuri cultivar at 10 °C and 70% RH.
Table 4
Regression equation to predict transpiration rate of three varieties of banana at 10, 20 and 30 °C with their corresponding co-efficient of regression (R²) values.

<table>
<thead>
<tr>
<th>Banana Variety</th>
<th>Temperature, °C</th>
<th>Regression Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapuri</td>
<td>10</td>
<td>TR = 63.40 – 0.31 * x₁ – 5.29 * x₂</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>TR = –196.88 + 9.33 * x₁ – 71.71 * x₂ + 0.32x₃ * x₂</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>TR = 405.33 – 5.68x₁ – 73.72 * x₂ + 0.06x₃ * x₂ + 0.03x₁² – 7.81 * x₂²</td>
<td>0.73</td>
</tr>
<tr>
<td>G9</td>
<td>10</td>
<td>TR = –105.63 + 1.86 * x₁ – 3.08 * x₂</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>TR = –927.99 + 24.62 * x₁ – 10.18x₂ – 0.16 * x₁ * x₂ – 0.15x₁² + 2.64 * x₂²</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>TR = 181.04 – 0.74 * x₁ + 0.67 * x₁</td>
<td>0.45</td>
</tr>
<tr>
<td>Chapa</td>
<td>10</td>
<td>TR = –59.72 + 1.23 * x₁ + 22.89 * x₂ – 0.31x₃ * x₂</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>TR = 118.40 – 1.24 * x₁ – 29.75 * x₂ + 0.39x₃ * x₂</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>TR = 1046.56 – 24.80 * x₁ – 12.97 * x₂ + 0.30x₃ * x₂ + 0.14 * x₁² – 1.20 * x₂²</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Table 5
Experimentally observed respiration rates and estimated respiratory heat of three cultivars of banana on the 2nd, 3rd and 6th day of storage at 10, 20 and 30 °C.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Temperature, °C</th>
<th>Storage time, days</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R₀₂ × 10⁻⁵</td>
<td>R₀₅ × 10⁻⁵</td>
<td>R₆₅ × 10⁻⁵</td>
<td>Q₀</td>
</tr>
<tr>
<td>Singapuri</td>
<td>2</td>
<td>0.85</td>
<td>0.3</td>
<td>1.21</td>
<td>2.71</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.18</td>
<td>0.37</td>
<td>1.18</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.18</td>
<td>0.55</td>
<td>1.54</td>
<td>1.74</td>
</tr>
<tr>
<td>G9</td>
<td>2</td>
<td>0.22</td>
<td>0.22</td>
<td>0.22</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.15</td>
<td>0.07</td>
<td>0.11</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.18</td>
<td>0.03</td>
<td>0.07</td>
<td>0.34</td>
</tr>
<tr>
<td>Chapa</td>
<td>2</td>
<td>0.61</td>
<td>0.44</td>
<td>0.53</td>
<td>2.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.16</td>
<td>0.11</td>
<td>0.13</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.14</td>
<td>0.01</td>
<td>0.12</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Where R₀₂ and R₀₅ are respiration rate of banana in kg mol/kg-day and Q₀ is respiration heat in J/kg-day.

Fig. 4. Transpiration rate of banana of Singapuri cultivar observed and predicted by energy balance model at 15 °C on 2nd day of storage at different RH (a) and 90% RH (b).

of TR of banana by regression model and energy balance model at all the temperatures. The energy balance model also predicted TR of banana with respect to time. An example of such TR prediction with respect to storage duration for Singapuri cultivar at 10 °C and 70% RH is shown in Fig. 3(d). To predict TR of banana at any unknown temperature and relative humidity the corresponding banana surface temperature (Tᵢ) is required. This temperature was found to depend linearly on the storage wet bulb temperature (y₁) and storage duration (y₂). Such regression equations for three banana cultivars and their corresponding co-efficient of determinations are shown in Table 6. These equations may be combined with the energy balance model to predict the TR of the selected banana cultivars at any storage temperature, relative humidity and storage duration.

Transpiration rate of banana of Singapuri cultivar observed at 15 °C and different storage RH are presented in Fig. 4(a) while the predicted value at 15 °C and 70% RH as a function of storage duration is shown in Fig. 4(b). For these two predictions the mean relative percentage deviation modulus is 10.27% and 18.35%, respectively.

4. Conclusion

Transpiration rate of three variety of banana in the temperature range of 10–30 °C varied from 17 to 26, 35–45, 30–33 g/kg-hr for Singapuri, G9 and Chapa cultivars, respectively. TR increased...
with rise in storage temperature and decreased with rise in storage humidity and progress of storage time. Maximum in-package storage temperature and RH for minimum transpiration and quality deterioration may be 20 °C and 90% RH. Unsteady state energy balance model fitted the TR data of banana at all RH and temperatures. The coefficient of determination of the model was 0.61–0.81 which provided a better fit of the experimental data than regression equation. Surface temperature of banana was less than storage environment temperature at a particular RH. Convective heat transfer between the storage environment and banana surface provided majority of the heat energy required for water evaporation. The required water vapour transmission rate for designing equilibrium humidity packaging of three variety of banana ranged from 172 to 618 g/m²/day at 10–20 °C.

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