ABSTRACT This study was aimed to study the dehydration kinetics of mango kernel with specific reference to sample thickness, drying temperature and mango varieties. It was performed prior to the preparation of flour from mango kernel. Kernels of four mango varieties (Boishakhi, Amrapali, Fazli and Ashwina) were separated manually and dried at 65°C by slicing into 4, 6 and 8 mm thickness to know the thickness effect on drying kinetics. Again, 6 mm thick slices of kernels were dried at 55, 60 and 65°C to know the temperature effect. Kinetics analysis resulted that the drying rate decreased with the increase of thickness and decreasing of temperature. Ashwina’s kernels having the highest initial moisture content (M0) had the highest drying rate constant (m), while the lowest m was noticed for Boishakhi’s kernels having the lowest M0. The values of the power law index (n) of the drying model were 0.83, 0.32, 0.31 and 0.70 for kernels of Boishakhi, Amrapali, Fazli and Ashwina mango, respectively. The activation energy of water diffusion was in the range of 7.002-7.515 KCal/g-mole. Conclusively, this study revealed that moisture diffusivity and drying rate are greatly influenced by drying parameters and kernel varieties.

KEYWORDS Mango kernel, Hot air drying, Rate constant, Activation energy

1. Introduction
Mango (Mangifera indica L.), having a delicious taste, captivating flavour with multifarious color and excellent nutrients, is one of the most common, essential and popular fruits in Bangladesh. In 2014-15, total mango production in Bangladesh was 10,18,112 metric tons from 61,997 acres of land, and it was the 7th highest production all over the world (BBS, 2015). Peel, pulp and seed are the main parts of a mango, where the seed is formed with seed coat and kernel. According to Das et al., 2018, a full mango contains around 9.80-14.30% peel, 66.10-72.40% pulp, 7.50-9.30% seed coat and 8.4-12.4% kernels. Pulp is the main consuming part of mangoes, whereas other parts (kernel, peel and seed coat) are discarded as waste material. Mango kernel has been identified as a good source of nutrients (Ribeiro and Schieber, 2010), especially carbohydrates, protein, lipids, fibre, minerals, antioxidants etc. (O’Shea et al., 2012; Khammuang and Sarnthima, 2011), and the food industry can use these nutrients. Researchers have identified good effect of mango kernel flour on the substitution of wheat flour to produce different food items in terms of nutritional improvement. A study carried out by Das et al. (2019) on the preparation and utilization of mango kernel flour in composite cake and revealed that mango kernel flour incorporated cakes increased the overall energy, fat, fibre and minerals content. In addition to that, Bandyopadhyay et al. (2014) studied the potentiality of mango kernel flour in composite flour bread quality. They found that it has good functional and chemical ability while processing bread. Moreover, Ashoush and Gadallah (2011) reported that
mango kernel flour increased the nutritional and phytochemical properties of biscuits.

Drying is widely used to preserve food, refers to the removal of moisture from the product to prevent the growth of microorganisms responsible for spoilage of the particular foods. This method is also used to prepare powder or flour from raw materials. All the dried foods are considered more acceptable to their use when a good color, flavour, texture and nutritional value is resumed after rehydration of the dried items. (Sultana, 2013). So, drying conditions (temperature, airflow, thickness etc.) must be carefully chosen to do as little injury to these qualities as possible.

Considering the above conditions, this study was performed to dry the kernels of different mango varieties as a part of the study of processing mango kernel flour and food products from this flour. The specific aims were set to study mango kernel’s mechanical drying behaviour with particular reference to thickness and temperature and mango varieties and to know the activation energy for drying different mango kernels.

2.Material and methods

2.1 Preparation of kernel

Four different mango varieties were purchased from the growers of the mango orchards of Chapai Nawabganj, Rajshahi, Bangladesh, during mango ripening season (May-August). Collected mango varieties were locally known as Boishakhi- early variety, Amrapali- mid-time variety, Fazli- late variety and Ashwina-late variety. Mangoes were pulped, and kernels were removed manually from seeds.

2.2 Mechanical drying of mango kernel

Different mango kernels were dried mechanically using a cabinet dryer (1816, Modern Laboratory Equipment Co., Inc., New York, USA)). Hot air was blown into the drying chambers, and kernels were dried due to this hot air. Mango kernels were analyzed for their initial moisture content by adopting AOAC (2012) prior to drying. To know the effect of slice thickness and drying temperature on drying behavior, mango kernels were sliced into three different thickness as 4, 6 and 8 mm and dried at three different temperature (55, 60, 65°C) up to 5 hr. The air velocity of the drying chamber was constant at 0.6 m/s. The loss of weight during drying was recorded and the moisture content of the samples at different interval was calculated gravimetrically from initial known moisture content.

2.3 Modeling of drying data

Fick’s second law of diffusion is generally used to describe the mass transfer phenomena during the drying of food materials, and the equation is as follows:

\[ \frac{dM}{dt} = \nabla^2 D_m M \] ............................. (1)

where \( M \) indicates the moisture content of the sample on dry weight basis (db), \( t \) is the time, and \( D_m \) is effective diffusion coefficient.

For a food material having infinite geometry, this unsteady-state diffusion Equation 1 can be solved to the following form considering uniform initial moisture distribution throughout the sample (dried from one major face, with thickness \( l \)) and negligible external resistance to heat transfer (Islam, 1980 and Crank, 1975).

\[ MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{\sin(\pi n l)}{n^2} \exp\left(-\frac{2n^2 l^2 D_0}{\pi^2}ight) \] ............................. (2)

where, \( MR \) is moisture ratio, \( M_t \) is the moisture content at any time in db, \( M_0 \) is moisture content at the starting time of drying in db, and \( M_e \) is the equilibrium moisture content in db. While the \( M_e \) values become lower and the MR value comes to <0.6, the Equation 2 is reduced to:

\[ \frac{M_t}{M_e} = \frac{8}{\pi^2} e^{-\frac{2D_0}{\pi^2} l^2 t} = \frac{8}{\pi^2} e^{-mt} \] ............................. (3);

where, \( m = \frac{2D_0}{\pi^2} \) drying rate constant in per unit time. The Equation (3) can be rearranged to

\[ \ln MR = \ln \frac{8}{\pi^2} - mt \] ............................. (4)

The value of drying rate constant, \( m \) can be obtained from the slope of \( \ln (MR) \) vs time \( t \) plot in a semilog coordinate. De has an Arrhenius type relation with drying temperature. The relationship is as follows (Okos et al, 2007 and Islam, 1980):

\[ \frac{d\ln D_0}{dT_{abs}} = \frac{E_a}{RT_{abs}^2} \] or\[ \ln D_0 = \ln D_{0} - \frac{E_a}{RT_{abs}} \] ............................. (5)

Or, \( m = A (l)-n \)

Or, \( \log m = \log A - \log(l) \) ............................. (7)

Where, \( A = \pi^2 D_0 \) and \( n = 2 \). For negligible external resistance to mass transfer and simultaneous heat and mass transfer, the value of power-law index should be 2, but experimentally \( n \) value is generally found to be < 2 (Islam, 1980).

3. Results and Discussion

3.1 Effect of thickness on drying time and drying rate constant

To observe the influence of thickness on drying time and drying rate constant 4, 6 and 8 mm thick kernel slices of Boishakhi, Amrapali, Fazli and Ashwina mango were dried at a constant air dry bulb temperature of 65°C. The results were analysed by using semi theoretical equation (Equation 4) and are depicted in Figure 1 whereas the developed regression equations are shown in Table 1.

The drying rate constants for 4, 6 and 8 mm thick slices of four different mango kernels were 0.738, 0.324 and 0.208 per hr for Boishakhi; 0.397, 0.377 and 0.316 for Amrapali kernel; 0.486, 0.427 and 0.359 for Fazli kernel; and 0.592, 0.502 and 0.362 for Ashwina kernels, respectively. The earliest mango variety’s kernel required 3.75 hr, whereas 5.66, 5.32 and 4.29 hr required for Boishakhi, 0.397, 0.377 and 0.316 for Amrapali kernel; 0.486, 0.427 and 0.359 for Fazli kernel; and 0.592, 0.502 and 0.362 for Ashwina kernels, respectively.
Table 1 Drying parameters of dried mango kernels’ slices influenced by thickness.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial moisture content (wb)</th>
<th>Thickness (mm)</th>
<th>Regression equation</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boishaki</td>
<td>48.79</td>
<td>4</td>
<td>$y=0.8505e^{-0.378x}$</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>$y=0.9084e^{-0.324x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>$y=0.9145e^{-0.208x}$</td>
<td></td>
</tr>
<tr>
<td>Amrapali</td>
<td>52.35</td>
<td>4</td>
<td>$y=0.8263e^{-0.397x}$</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>$y=1.0309e^{-0.377x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>$y=1.0162e^{-0.316x}$</td>
<td></td>
</tr>
<tr>
<td>Fazli</td>
<td>62.76</td>
<td>4</td>
<td>$y=0.8026e^{-0.466x}$</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>$y=1.0006e^{-0.427x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>$y=1.0172e^{-0.359x}$</td>
<td></td>
</tr>
<tr>
<td>Ashwina</td>
<td>65.67</td>
<td>4</td>
<td>$y=0.9362e^{-0.597x}$</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>$y=0.9668e^{-0.502x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>$y=0.9718e^{-0.362x}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Drying parameters of dried mango kernels’ slices influenced by temperature.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Temperature (˚C)</th>
<th>Regression equation</th>
<th>Ea (KCal/g-mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boishaki</td>
<td>55</td>
<td>$y=0.9649e^{-0.236x}$</td>
<td>7.002</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>$y=0.9336e^{-0.283x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>$y=0.9084e^{-0.324x}$</td>
<td></td>
</tr>
<tr>
<td>Amrapali</td>
<td>55</td>
<td>$y=1.0209e^{-0.274x}$</td>
<td>7.052</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>$y=1.0336e^{-0.329x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>$y=1.0309e^{-0.377x}$</td>
<td></td>
</tr>
<tr>
<td>Fazli</td>
<td>55</td>
<td>$y=0.9813e^{-0.308x}$</td>
<td>7.212</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>$y=0.9783e^{-0.365x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>$y=1.0006e^{-0.427x}$</td>
<td></td>
</tr>
<tr>
<td>Ashwina</td>
<td>55</td>
<td>$y=0.9981e^{-0.357x}$</td>
<td>7.515</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>$y=0.9858e^{-0.411x}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>$y=0.9668e^{-0.502x}$</td>
<td></td>
</tr>
</tbody>
</table>
drying rate constant values of 0.208-0.378/hr and the latest variety’s kernel. Initial moisture values were obtained from our previous research-Das et al. (2018). Ashwina (initial moisture content: 65.67%) had the highest drying rate constant values of 0.362-0.597/hr for each thickness.

The values of rate constant for 3 different thickness (4, 6 and 8 mm) as found from the slope of regression lines s were plotted on a log-log coordinates (Figure 2) as per Equation 7 and the following power-law equations (8-11) were developed.

\[ m = 1.2605l^{-0.83} \quad \text{[For Boishakhi kernel, } R^2 = 0.8691]\]
\[ m = 0.6292l^{-0.32} \quad \text{[For Amrapali kernel, } R^2 = 0.8457]\]
\[ m = 0.7508l^{-0.31} \quad \text{[For Fazli kernel, } R^2 = 0.999]\]
\[ m = 1.6333l^{-0.70} \quad \text{[For Ashwina kernel, } R^2 = 0.9272]\]

From the above equation, it is seen that the value of index ‘n’ of the power-law equations is 0.83, 0.32, 0.31 and 0.70 for Boishakhi, Amrapali, Fazli and Ashwina kernels, respectively, instead of 2 as predicted by theoretical drying Equation 7. The values indicate that there was a presence of significant external resistance to mass transfer.

Ayesha et al. (2012) found the value of ‘n’ for drying of local variety potato (Lalpakri) at 50°C as 0.459, whereas ‘n’ value of 1.3603 was obtained by Sultana (2013) for carrot dried at 55°C. Ayesha et al. (2012a) found the value of exponent ‘n’ as 0.261 at 50°C for drying potato slices with 3, 5 and 7 mm thickness. Iqbal and Islam (2005) studied the drying behaviour of cauliflower and cucumber and found the n values as 0.287 for cauliflower and 0.4105 for cucumber. On the other hand, Islam (1980) reported that the ‘n’ value as high as 1.70 for dehydration of potato slices with an increased air flow rate of 2.5 m/s. The values of n is mainly differed due to airflow rate, product thickness, chemical composition, structure and simultaneous heat and mass transfer phenomena (Islam, 1980).

### 3.2 Effect of temperature on drying time and drying rate constant

In order to study the influence of air temperature on drying characteristics, 6 mm thick slices of four mango kernels were subjected to dry at three different air dry bulb temperatures of 55, 60 and 65°C. The Equation 5 was used to analyse the obtained data and regression lines were drawn (Figure 3) and equations...
were developed as shown in Table 2 by plotting the MR values against time on semi-log coordinate. From Figure 3 and Table 2, it is seen that temperature had a significant influence on drying time and drying rate constant. The drying rate constant was increased with the increase of the drying temperature. To attain MR=0.1 by 6 mm thick kernels, dried at 65°C required the lowest time, which was followed by 60°C and 55°C. On the other hand, the different kernel variety resulted in a great variation in drying time and drying rate at any specific temperature. It was thus observed that at each drying temperature, Boishakhi kernels required the highest drying time compared to Amrapali, Fazli and Ashwina kernels at the constant air velocity and thickness. Islam (1980) marked that optimum temperature during drying should be selected carefully considering the product quality and drying time. Thus, this study revealed that drying mango kernels can reduce the time to get dried mango kernels at a high temperature.

3.3 Activation energy

The activation energy (Ea) of moisture diffusion during drying of the mango kernels were determined from regression lines (Equation 12-15) as shown in Figure 4, and the results are depicted in Table 2.

\[
\text{De} = 0.1118e^{-3524/\text{Tabs}} \quad (12) \quad \text{[For Boishakhi kernel, R² = 0.9949]}
\]

\[
\text{De} = 0.1399e^{-3549/\text{Tabs}} \quad (13) \quad \text{[For Amrapali kernel, R² = 0.9949]}
\]

\[
\text{De} = 0.2003e^{-3630/\text{Tabs}} \quad (14) \quad \text{[For Fazli kernel, R² = 0.9935]}
\]

\[
\text{De} = 0.3643e^{-3782/\text{Tabs}} \quad (15) \quad \text{[For Ashwina kernel, R² = 0.9912]}
\]

From the above equations, the Ea values for Boishakhi, Amrapali, Fazli and Ashwina mango kernels were found to be 7.002, 7.052, 7.212 and 7.515 KCal/g-mole, respectively. Sultana (2013) reported the Ea as 16.3 kcal/g-mole for carrot, while Ayesha et al. (2012a) found the Ea value for potato (Diamont variety) as 7.98 Kcal/g-mole. Khan et al. (2019) found the activation energy value for drying of mango pulp as 2.843 Kcal/g-mole for 5mm thick mango pulp dried at a temperature of 55, 60 and 65°C. The factors which may influence the activation energy in food product involves water activity, moisture content, pH, the temperature of drying, structure and growing season of that raw food (Villota and Hawkes, 2007; Islam, 1980; Iqbal and Islam, 2005).

Conclusion

Mango kernel, a by-product of the mango industry, can be processed into flour and could be a good replacer of wheat flour in bakery food. Mechanical drying prior to preparation of flour from mango kernel was performed in this study for kernels of four different mango varieties. Drying analysis revealed that the kernel of the late ripen mango variety dried faster than the earlier varieties. In addition, higher initial moisture content and higher temperature of drying resulted in increasing the drying rate and activation energy, though drying rate decreased with the increase of thickness. Further study on nutritional and physical parameters changes due to changing of drying attributes should be performed for the best recommendation.

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Conflict of interest

There are no conflicts of interest to declare by any of the authors of this study.

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