AJFAND ONLINE
African Journal of Food, Agriculture, Nutrition and Development
Scholarly, Peer Reviewed
ISSN 1684 5374
Volume 12 No. 7
December 2012
Published by African Scholarly Science Communications Trust

A COMPARISON OF THE KINETICS OF MANGO DRYING IN OPEN-AIR, SOLAR, AND FORCED-AIR DRYERS

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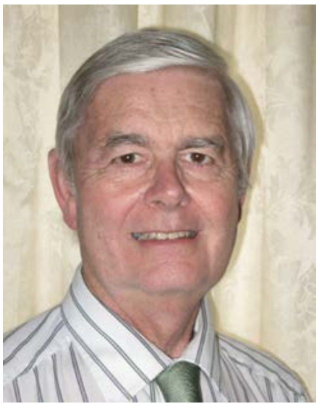

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ABSTRACT

Mangoes are under-utilized fruits that grow naturally in many sub-Saharan African countries. At the present time most mangoes are sold fresh in local markets. There is little done to preserve them for use during the off-season. Drying is one way in which the economic potential of mangoes could be exploited. This study was undertaken to investigate and compare the kinetics of mango drying using three basic drying methods: open-air drying on wire mesh racks; solar drying in a prototype dryer equipped with solar-powered exhaust fans; and forced-air drying in an Armfield Model UOP8 laboratory-scale tray dryer. Results could then be used to determine appropriate drying techniques for mango processing in sub-Saharan Africa on both local and commercial scales. Of these methods, forced air drying was found to provide the best overall results, based on water removal rates and general control over the drying process. Solar drying, while viewed as a promising technology for application in developing countries, was considerably slower than forced- air drying and is severely restricted by climatic conditions. A similar situation was observed for open-air drying, which was the slowest drying method of the three. Based upon mathematical models developed for each drying method, 11.6 hours was predicted as being required for mangoes in the forced-air dryer to a final moisture content of 10% (wet basis). Sixteen (16) hours and 24 hours of exposure to appropriate drying conditions were predicted as being required for solar drying and open-air drying, respectively. This could take three or four days to achieve under actual operating conditions. These times were supported by experimentally determined values. The impact of air temperature and linear air velocity on the drying kinetics of sliced mangoes were also investigated using the forced-air dryer. A linear velocity of 0.5 m/s was found to be sufficient for satisfactory drying of the mango slices when combined with an air temperature in the range of 50EC to 60EC. It is recommended that forced-air drying be utilized whenever possible for the drying of mango slices for both food safety and food quality reasons.

Key words: mangoes, drying kinetics, solar drying

INTRODUCTION

Mango trees (*Mangifera sp.*) are found in many countries of sub-Saharan Africa as well as other regions around the world with suitably temperate climates. Mangoes are an important commercial crop on a global basis, both in fresh and dried form. However, there has been little or no actual commercialization beyond sales of fresh mangoes at local markets in most sub-Saharan countries. During the times that mangoes ripen, prices tend to be relatively low with a gradual rise towards the end of the season. Often, mangoes literally spoil at road-side stands or rot where they fell from the trees due to a lack of consumer demand [1]. From personal observations on several assignments in sub-Saharan Africa, it was also apparent that potential opportunities were being missed to preserve the mangoes for use during the off-season. Only a limited amount of mangoes were made into chutney and other preserved products.

Countries in South East Asia have had considerable success both in domestic marketing and the export of dried mangoes as a value-added product. In some cases, sulphites are used to stabilize colour. Sugar may also be added to improve the product texture and taste [2]. In 2008, the United States of America imported an estimated 3,481 tonnes of dried mangoes of which 45% was sourced from the Philippines and 31% from Thailand [3]. A 2007 study acknowledged that the European market for dried fruits such as mangoes was small, but growing [4]. It recommended that exporters in Uganda target small niche markets for organic dried mangoes in Germany and the United Kingdom. Pakistan, a major source of mangoes, has also recognized the economic potential of value-added mango products. A 2010 pre-feasibility report on mango pulping and dried mango products in Pakistan indicated a demand for dried mango slices and mango leather as well as chutneys, pickles, and juices [5].

Previous studies have compared the drying of cassava, banana, and mango under natural solar drying conditions [6]. Such drying is both inefficient and unsanitary since there is an absence of an enclosed drying chamber to protect the product and enhance the rate of drying. The level of maturity of mangoes has been shown to be a significant factor in the drying of mango slices in addition to temperature and air velocity [7].The kinetics of thin-layer indirect solar drying have also been modelled [8].

This study was undertaken to investigate and compare the kinetics of mango drying using three basic drying methods: open-air drying, solar drying, and forced-air drying. Results could then be used to determine appropriate drying techniques for mango processing in sub-Saharan Africa on both local and commercial scales.

MATERIALS AND METHODS

Three basic methods for drying mangoes were investigated. All experiments were done in the Kemptville, Ontario area of Canada, approximately 50 km south of Ottawa (45E North latitude, 73E West longitude). Unlike many locations at lower latitudes, the amount of sunlight in Canada during the warmest months of June, July, August, and early September is well over twelve hours per day. Temperatures frequently reach 28EC to 30EC. These temperatures coupled with clear skies are ideally suited for solar drying. Afternoon rains are not as prevalent as they are in many tropical locations.

Over the course of this two-year study, red mangoes were purchased from local supermarkets which sourced them from South America - primarily Ecuador and Brazil. No variety names were provided. The mangoes were washed and peeled prior to being cut into slices of approximately 5 mm thickness. The degree of ripeness of the mangoes depended upon availability with the texture of the flesh ranging from firm to slightly soft.

Moisture contents of fresh and dried mango samples were determined using a Sartorius Model MA 50 Electronic Moisture Analyzer at 105°C with the recommended factory settings.

Open-Air Drying

Open-air drying experiments were conducted by placing mango slices (5 mm thick) on wire mesh racks similar to those used for cooling purposes in baking applications. Two such racks were used for each set of drying experiments. The racks were placed on a white plastic table-top and set out in the open sun away from any structures that would disrupt the natural air flow patterns. Wire supports kept them approximately 10 cm above the surface of the table.

The racks and their contents were weighed at the start of each drying trial and at regular intervals during the course of the drying process. Air temperatures were taken using a digital thermometer (Traceable7 Relative Humidity and Temperature Meter, Fisher Scientific: Catalogue # 11-661-13). This device also featured a built-in hygrometer to monitor the relative humidity of the ambient air. Velocities of the ambient air were measured using a vaned anemometer capable of measuring to the nearest hundredth of a metre per second (Vaned Anemometer, Airflow Developments: Model LCA30-VT). Sunlight intensity was measured using a digital dual range light meter (Traceable7 Dual Range Light Meter, Fisher Scientific: Catalogue # 06-662-73). Following completion of each test, moisture levels were determined using the Sartorius moisture balance.

Solar Drying:

Solar drying trials were conducted using a prototype dryer designed and fabricated by the author. Similarly designed units had been used successfully for solar drying studies of various food products (including tomatoes, mangoes, bananas, green peppers, carrots, and pitahaya) in Equatorial Guinea and Honduras prior to this study. Due to their importance as a commercial crop, much of the previous solar drying work was focussed primarily on tomatoes [9].

The unit was equipped with two solar-powered fans (Advanced Energy Solution: Solar Vent Fan) to draw air through a black metal heat collector. These fans appear as the two circular devices at the top of the dryer as shown in Figure 1 and were rated at a maximum capacity of approximately 900 litres of air per minute (32 cubic feet per minute). Additional air circulation was provided by a solar-powered fan located inside the drying chamber. The internal fan provided air flow across the surface of the mangoes to disrupt the stagnant boundary layer of air, which can reduce the drying efficiency of solar dryers with low linear air velocities.

On earlier prototypes used for international assignments, a plexiglass panel on the front of the dryer allowed the samples inside the dryer to be seen. This was replaced with 5 mm thick glass for later trials in Canada when breakage during travel was not a concern.

The drying chamber was lined with 20 gauge sheet metal. The heat collector was constructed of a similar material. All metal surfaces were painted matte black to enhance heat absorption.

Figure 1: Prototype solar dryer showing black heat collector (foreground) and solar-powered exhaust fans (top front of dryer).

Mango slices (5 mm thick) were placed on a wire mesh rack suspended by two metal rods linked to a weighing assembly on top of the drying chamber. This allowed weights of the material in the dryer to be taken without having to physically open the drying chamber and remove the samples. In such a way, the continuity of the drying process could be assured without interruption.

Temperatures and relative humidities outside the dryer were monitored using a digital thermometer similar to that used in the open-air drying experiments. Temperatures inside the dryer were monitored with a digital thermometer equipped with a remote sensor and featuring a minimum and maximum temperature memory (Traceable7 Memory Monitoring Thermometer, Fisher Scientific: Catalogue #15-077-8D).

Air velocities inside the solar dryer were measured using a hot-wire anemometer probe (Traceable7 Hot Wire Anemometer / Thermometer, Fisher Scientific: Catalogue #06-662-73) inserted through a small hole in the side of the drying chamber. Sunlight intensities were monitored with the same device used for the open-air drying experiments.

The solar dryer itself was mounted on a rotating platform which permitted it to be continuously directed towards the sun as the day progressed and the sun transited the sky.

Forced-Air Drying:

An Armfield Model UOP8-MK1 laboratory-scale tray dryer (Armfield Limited, Ringwood, England) was used for this portion of the study [10]. Slices of mangoes (5 mm thick) were placed on a wire mesh rack suspended from a linkage to a balance on top of the dryer. Temperatures inside and outside the dryer were monitored using digital thermometers similar to those in the other experiments. Both the temperature of the air and the air velocity could be adjusted by controls on the dryer. An air distribution plate was placed in the dryer upstream of the samples being dried. Its purpose was to provide back-pressure and reduce the linear air velocity to levels below which the variable speed fan could deliver without such a device in place.

Linear air velocities were measured using the same vaned anemometer as was used for the open-air drying experiment.

Temperature and sample weight readings were collected at one minute intervals over the course of each drying run using time-lapse video photography of the digital displays on the electronic thermometer and balance. Data from each 15 minute interval were used in the mathematical treatments and graphing.

Mathematical Treatment of Data:
Raw data collected from all runs were entered into Microsoft Excel7 spreadsheet files. Based on the initial moisture of the mangoes and the starting weight of each sample, the weight of dry solids could be calculated. Using this value and the weight of the samples in the dryer, the wet basis moisture (% water) and dry basis moisture (grams of water per gram of dry solids) could be calculated at any time. Graphs generated within the spreadsheet program, allowed trendlines to be obtained which established correlations between moisture content on a dry basis and drying time under various drying conditions.

Using an exponential trendline and forcing the intercept to be equal to the initial dry basis moisture of the mango sample provided an equation of the form:

$$M = M_o \exp^{-c\,t} \qquad \text{Equation 1}$$

where: M = dry basis moisture content at any time t

M_o = initial dry basis moisture content of sample

c = drying rate coefficient (reciprocal hours)

t = time (hours)

In order to directly compare the drying of mango samples with different initial moisture contents, moisture ratios were calculated based on the dry basis moisture at any time, t, divided by the initial dry basis moisture.

$$\text{Moisture Ratio} = M / M_o \qquad \text{Equation 2}$$

where: M = dry basis moisture content at any time t

M_o = initial dry basis moisture content of sample

Through this approach, the exponential trendline described in equation 1 would become:

$$\text{Moisture Ratio} = M / M_o = \exp^{-c\,t} \qquad \text{Equation 3}$$

By definition, the moisture ratio at time t = 0 would be 1.00

RESULTS

Forced-Air Drying of Mangoes:

There are several well-known factors which have an impact on the rate of water removal in forced-air dryers. These include the temperature and linear velocity of the drying air, as well as the thickness of the material being dried, and the time during which the drying is allowed to proceed. As part of this study, the impact of temperature and air velocity on the drying of mangoes in the Armfield laboratory-scale forced-air tray dryer was investigated. The thickness of the mango slices was maintained at 5 mm in all cases.

Figure 2 shows the effect of temperature on the drying of mango slices. Samples were placed in the Armfield tray dryer with an air velocity of 0.5 m/s. The temperatures were chosen as being representative of those that would provide suitable product quality in industrial drying processes (that is, 50EC to 60EC) or were achievable in small-scale solar drying operations (that is., 44EC to 50EC). Three trial runs were conducted for each of the three heat treatments (that is, 44°C, 50°C, and 60°C). Average moisture ratios for each of the three temperatures were plotted versus time as shown in Figure 2. Moisture ratios from a single test run at a temperature of 21EC have also been included. These room temperature results are for comparative purposes only, to illustrate the impact of air drying with no additional heat applied. They have not been used for any statistical comparison.

Plotting exponential trendlines (not shown) for each of the four temperature curves provided equations of the form shown in Equation 3 (using a Microsoft Excel 2010Spreadsheet program). These equations appear in Figure 2 along with the corresponding R^2 values.

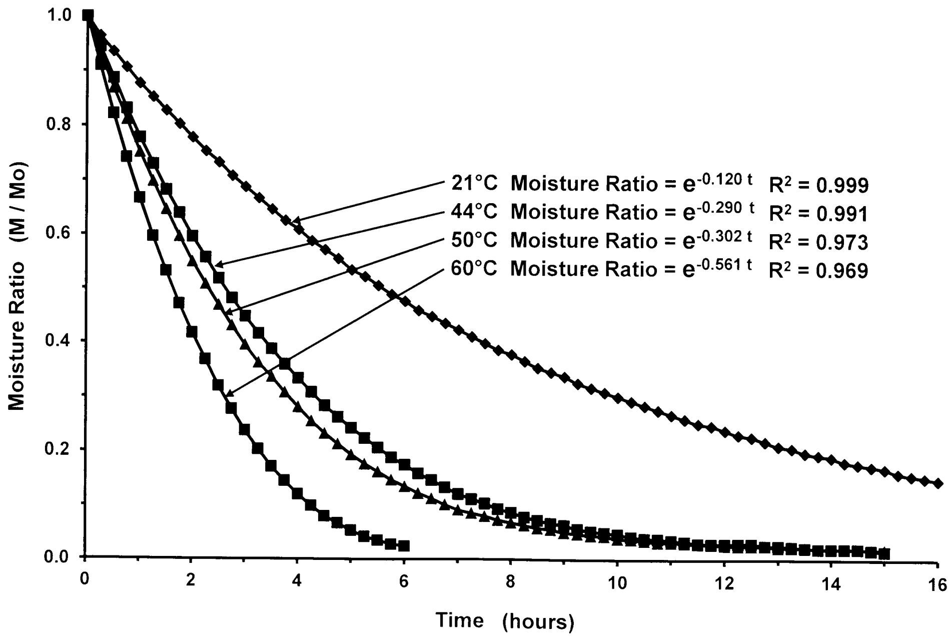

Figure 2: The effect of air temperature on the drying of 5 mm thick mango slices in a forced-air tray dryer. (Air velocity = 0.5 m/s)

Temperature had a strong impact on the rate of drying of the mango slices as can be seen from the steeper slopes of the drying curves at higher temperatures than at lower temperatures. Increasing magnitudes of c in the equations for each curve quantify the effects, with the negative sign indicating the fact that moisture is being removed from the samples. While this trend is not unexpected, its quantification is essential for a thorough treatment of the subject.

An analysis of variance (ANOVA) was performed on the curves for the three elevated temperatures in Figure 2 using SPSS 19.0.0 (IBM SPSS Statistics, Chicago, Illinois, USA). Differences were determined using the Duncan test. The curves at 44°C and

50°C were found to be not statistically different (p = 0.05). However, there was a statistical difference (p = 0.05) between drying at 50°C and 60°C.

Based upon an initial moisture content of 85% for mangoes (that is-, dry basis moisture = 5.7 g of water per g dry solids) and a desired final wet basis moisture of 10% (that is, 0.11 g water per g dry solids), the resultant moisture ratio (M / M_o) would be approximately 0.02. Using this moisture ratio, the time required for drying can be calculated for each temperature based on the equations shown in Figure 2. The time required to dry mangoes from an initial moisture of 85% (wet basis) to a final wet basis moisture of 10%, would be approximately 8.8 hours at 60°C, and would range from approximately 11.6 hours to approximately 13.2 hours at 50° C and 44°C, respectively. As an aside, at 21°C, over 32 hours of drying time would be required to reach the final desired moisture content; which is clearly not feasible in a commercial operation. The 2.8 hour increase in drying time when reducing the temperature from 60°C to 50°C, represents a 32% increase in drying time between the two temperatures. Attempting to dry mangoes with air at 44°C gives an increase in drying time of 50% compared to drying at 60°C. These time differences can have a significant impact on processing logistics, production capacity, and labour, plus other associated costs within a commercial drying operation.

Figure 3 shows the effect of air velocity on the drying of mango slices using the Armfield tray dryer at 50EC. 0.2 m/s was chosen as being representative of air velocities observed in the prototype solar dryer. The 0.5 m/s air velocity was based on experience gained during previous drying studies based on mangoes and apples [11]. This air speed was found to be appropriate in the drying of other materials and was sufficient to sweep away the stagnant boundary layer at the surface of the materials being dried. Flowrates above 0.5 m/s showed little additional impact on the water removal rate.

Three tests were conducted for each linear air velocity at a temperature of 50°C. The average moisture ratios for each velocity were then plotted versus time. Exponential equations for the two air velocity curves and their respective R^2 values are shown in Figure 3. Based on an analysis of variance (ANOVA), the drying curves at 0.2 m/s and 0.5 m/s air velocity were found to be statistically different (p = 0.05).

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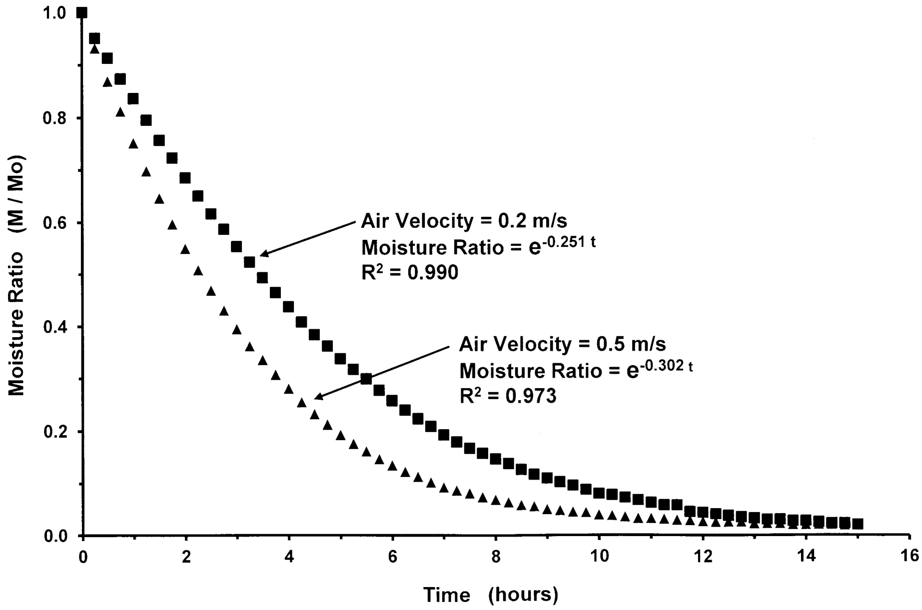

Figure 3: The effect of linear air velocity on the drying of 5 mm thick mango slices in a forced-air tray dryer. (Air temperature = 50EC)

Using a final moisture ratio of 0.02, as was done previously, and applying the equations shown in Figure 3, it would take approximately 11.6 hours to dry the mangoes at 50°C and an air velocity of 0.5 m/s, as calculated previously. With an air velocity of 0.2 m/s, at the same temperature, the required time would be approximately 15.6 hours. This 4 hour difference represents an increase of more than 34% between the higher linear air velocity and the lower velocity. Based on this calculation, the potential impact of air velocity on the time taken to effectively dry mango slices in a commercial process is fairly evident.

Open-Air Drying of Mangoes

Open-air drying tests were conducted on five separate dates. On each day, the weights of duplicate samples of mango slices (5 mm thick) were monitored throughout the drying process, and the dry basis moistures and moisture ratios at each time were calculated. The average moisture ratio was then calculated for each time on that date. Average moisture ratios obtained for each of the five days are plotted versus time in Figure 4. The equation for the overall average moisture ratio as a function of time for all five dates is included in this figure.

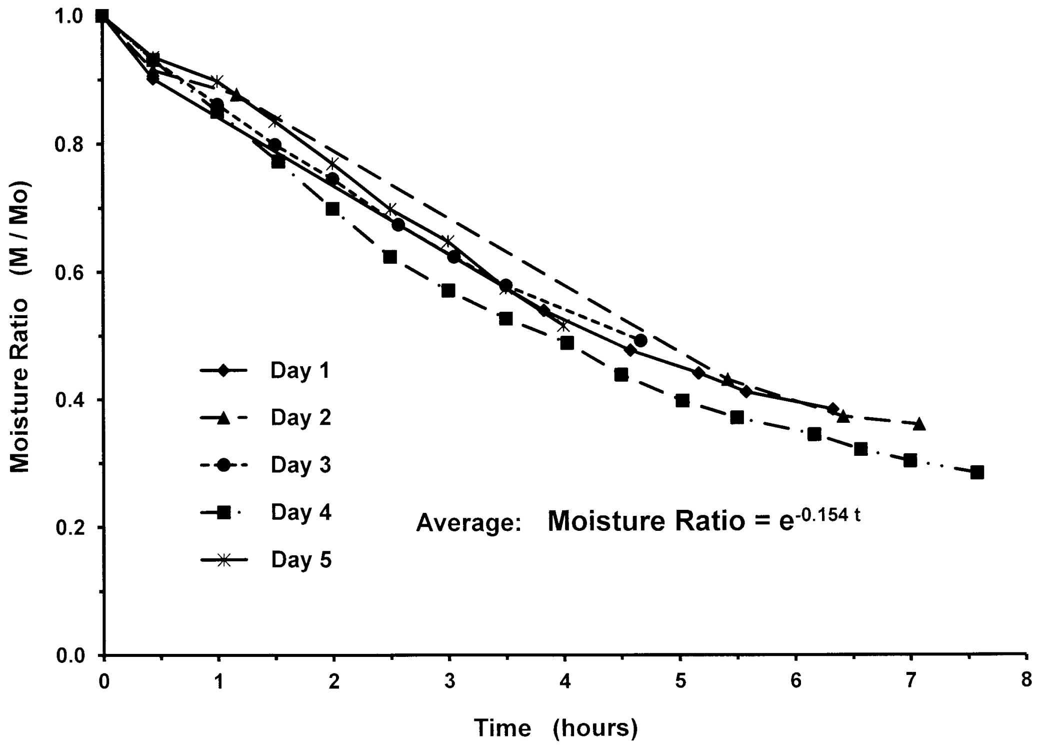

Figure 4: Moisture ratio versus time for the open-air drying of mango slices

Wind velocities were light during the days the tests were done. Typically, they ranged calm levels with no detectable wind to 3 m/s (approximately 11 km/h) throughout the duration of most tests. Average ambient temperatures ranged from 24.9EC to 27.5EC, while relative humidities averaged between 45% and 50%.

The average value of the coefficient Ac@ (that is, the drying rate coefficient expressed in reciprocal hours) was -0.154 h^{-1}. There was close agreement between the two runs done on Day 2. The two runs conducted on Day 3 were also in close agreement with each other as were the two runs done on Day 5. However, the two test runs from Day 1 showed less consistency with each other, as was also the case with the two runs done on Day 4. This is typical of drying runs conducted where there is little or no control over the conditions under which the drying takes place. It also points out the degree of variability that can be anticipated in open-air drying.

Solar Drying of Mangoes

Solar drying runs were limited by weather conditions and available sunlight, as were the open-air drying runs. Moisture ratios have been plotted versus time in Figure 5 for five separate occasions. In general, only six to eight hours of drying could be done in any one drying session.

Light intensity values averaged from 70,400 lux to 110,100 lux. As expected, days with higher sunlight intensities gave higher internal dryer temperatures (ca. 43EC on

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African Journal of Food, Agriculture, Nutrition and Development
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average) and higher drying rates (c = - 0.290 h^{-1}) than days with lower sunlight intensities (ca. 40EC with c = -0.194 h^{-1}). The average value of c was -0.238 h^{-1}.

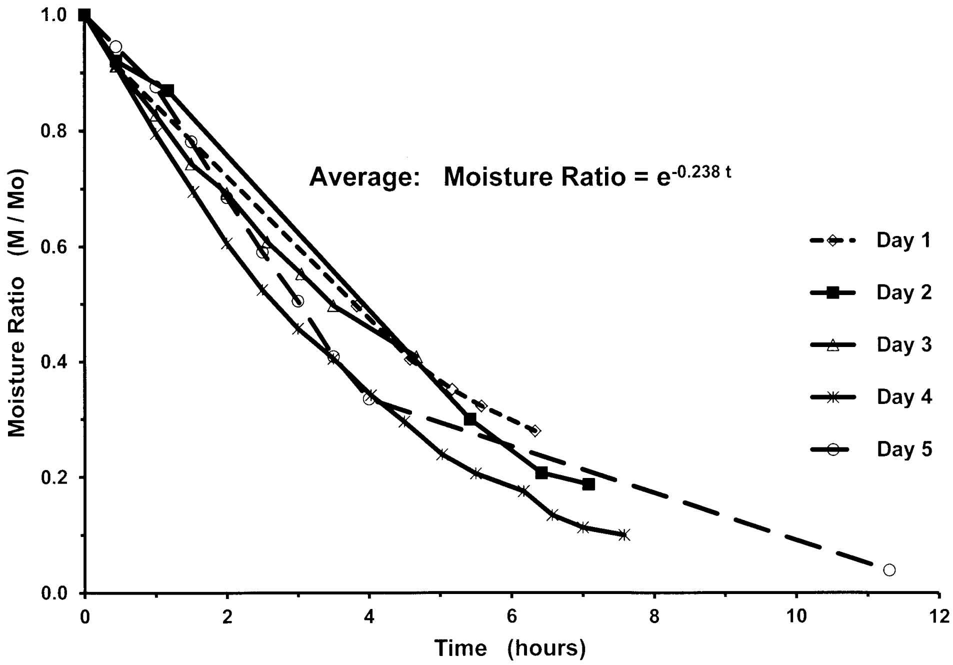

Figure 5: Moisture ratio versus time for the solar drying of mango slices

Day 5 was an exception day for drying. A suitable amount of sunlight was available from morning until early evening, which gave over eleven hours of drying time. It should be noted that these five solar drying runs correspond to the same dates on which the five sets of open-air drying runs were conducted.

Internal dryer temperatures averaged less than the 44EC used in investigating the effects of temperature on the drying rate of mangoes. However, these averages include temperatures earlier in the day at the beginning of the runs and later in the runs when the intensity of the sun was not as great. During the peak drying periods, temperatures were found to be at or above 44EC, thereby justifying its use as a representative drying temperature. These conditions were achieved in earlier solar drying trials in Equatorial Guinea [12], so are representative of those encountered in Sub-Saharan Africa.

DISCUSSION

Comparison of Drying Kinetics

In order to obtain a representative comparison of the kinetics of the three drying methods, the following equations were used:

Forced-Air Drying:	Moisture Ratio = $e^{-0.302 t}$	Equation 4
Solar Drying:	Moisture Ratio = $e^{-0.238 t}$	Equation 5

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Open-Air Drying: Moisture Ratio = $e^{-0.154\,t}$ Equation 6

Equation 4 represents the kinetics of the forced-air dryer when operating at 50EC with an air velocity of 0.5 m/s. Equations 5 and 6 are for the solar dryer and open air drying methods using the average values of c as previously determined.

The majority of the mangoes used in the tests had initial moisture contents of 85% (wet basis) or 5.7 grams of water per gram of dry solids (dry basis moisture). 10% moisture (wet basis) or 0.11 grams of water per gram of dry solids (dry basis moisture) is considered to be a desirable final moisture for many fruits and vegetables since it does not support microbial growth. Using a starting moisture content of 5.7 grams of water per gram of dry solids and a final moisture content of 0.11 grams of water per gram of dry solids gives a final target moisture ratio of 0.02.

Equations 4 through 6 are plotted in Figure 6. All curves were found to be significantly different based on analysis of variance (ANOVA, $p = 0.05$). As can be seen, the forced-air dryer offers the fastest means of achieving the desired final moisture for the dried mangoes. It takes approximately 11 hours to accomplish this at 50EC and 0.5 m/s air velocity. In an average solar drying run, it takes approximately 16 hours to reach the 10% wet basis moisture target. Open-air drying is the slowest of the three drying methods, taking over 24 hours to arrive at the target moisture level.

Figure 6 provides a degree of insight regarding the use of solar dryers and open-air drying. If there were six hours of drying time suitable for solar drying or open-air drying each day, then creating a break at each six-hour interval could be useful in predicting the drying kinetics under those conditions. Dividing lines at 6 and 12 hours indicate solar drying will not provide a suitably dried mango product until the third day of drying. In comparison, open-air drying must be allowed to continue for four days or more to obtain the desired final mango moisture content.

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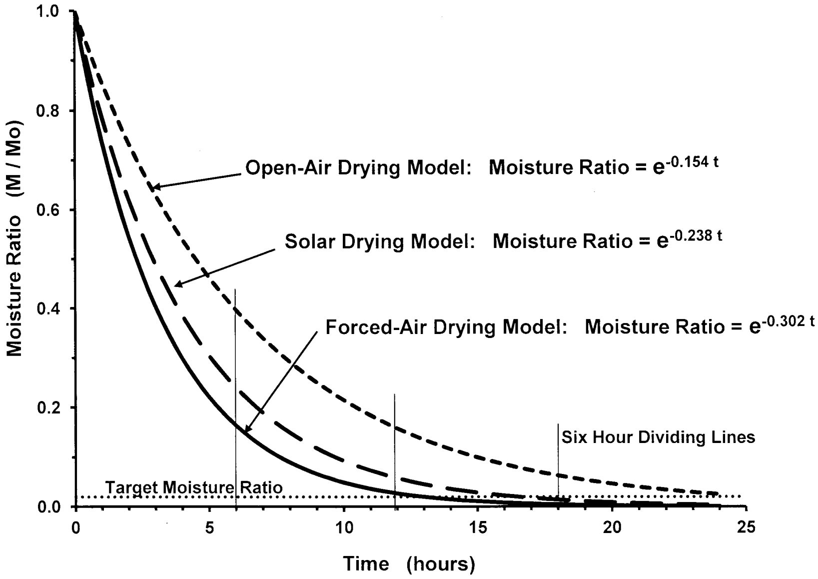

Figure 6: Comparison of mathematical models for the drying of mango slices under open-air, solar, and forced-air drying conditions

Figure 7 was prepared by taking the curves for solar drying and open-air drying from Figure 6 and inserting an 18 hour non-drying period between each six hour drying segment. This illustrates the time taken to appropriately dry the mango slices more clearly than Figure 6. The horizontal line at the bottom of the graph represents the target moisture ratio of 0.02 for cases where the initial moisture content of the mangoes is 85% on a wet basis, as explained previously. It should be kept in mind that the same amount of drying could be done in about 11 hours with a forced-air dryer.

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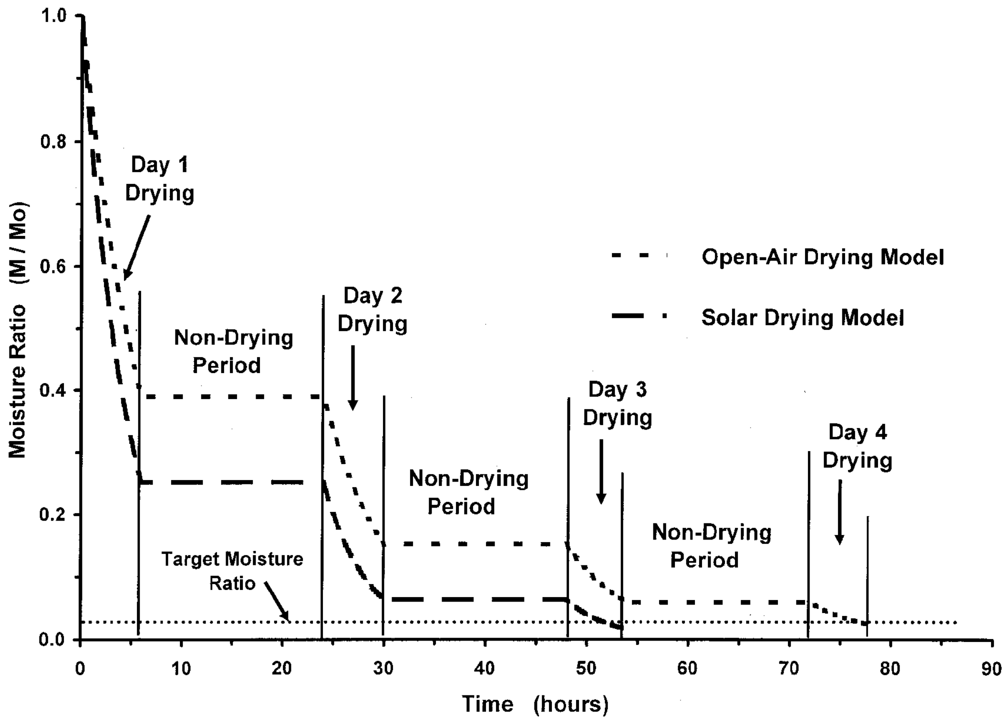

Figure 7: Using the mathematical models of open-air and solar drying to show the overall drying time required based on six hours drying per day

Figure 7 also provides the opportunity to consider potential problems that could arise during such prolonged time periods. At the end of the first six hours of drying, the moisture content of the solar-dried and air-dried mango slices is predicted to be approximately 1.44 g water per gram of dry solids (ca. 59% wet basis) and 2.59 g water per gram of dry solids (ca. 72% wet basis), respectively. There is still sufficient moisture in these samples to promote microbial growth during the 18 hours of non-drying before the next drying segment begins. Ample opportunity also exists for insect and rodent attack or infestation during the process which is not as likely during the much shorter and more controlled forced-air drying process. During particularly moist periods of overnight or early morning rain, partially dried foods can take up moisture from the air if they are not protected from the ambient air. Under such conditions of high moisture and warmth, mold growth can occur within the first 24 hours of processing [12]. Even during the day, insects are a significant problem with open-air drying.

For cases where the initial moisture (M_o) is known and it is desired to predict the dry basis moisture (M) at any time t, equations 4 through 6 may be written in the same form as equation 1. This gives:

Forced-Air Drying:	$M = M_o\, e^{-0.302\,t}$	Equation 7
Solar Drying:	$M = M_o\, e^{-0.238\,t}$	Equation 8
Open-Air Drying:	$M = M_o\, e^{-0.154\,t}$	Equation 9

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CONCLUSIONS AND RECOMMENDATIONS

For each of the drying methods assessed, there were significant differences in the times taken to achieve the desired final moisture content of 10% on a wet basis or 0.11 grams of water per gram of dry solids on a dry basis. For forced-air drying at 50EC and an air velocity of 0.5 m/s, this process took approximately 11 hours. In comparison, 16 hours of exposure to adequate drying conditions were required for solar drying, which would take three days based on six hours of drying time per day. Open-air drying was even slower, requiring over 24 hours of drying time. With six hours of suitable drying conditions per day, this could take up to four days. Recognizing that mangoes are often harvested just before the rainy season in many areas, six hours of drying per day is not an unrealistic estimate.

Mathematical models of the kinetics were developed for the three drying processes based on experimentally obtained results. These equations can be used as a means of predicting the relative amount of time required for drying mangoes in open-air, solar, and forced-air drying systems.

From experimental observations and predictions based on the mathematical drying models, it is recommended that mango drying be performed in forced-air dryers whenever possible. This will enhance the degree of control and uniformity of the drying process while reducing the risk of microbial growth, and insect or rodent infestation which were problems during prolonged solar and open-air drying.

Based on the lengths of time taken to dry mango slices with 85% wet basis moisture, it is recommended that due caution be taken in drying materials with higher moisture contents (for example, tomatoes at 95% moisture, or 19 grams of water per gram of dry solids). This is particularly true for regions experiencing high relative humidities and poor sunlight conditions during the harvesting period for these crops.

ACKNOWLEDGMENTS

The financial support of the Canadian International Development Agency (CIDA) and the University of Guelph is gratefully acknowledged.

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