Drying Mango (*Mangifera indica* L.) with Solar Energy as a Pretreatment for Bioethanol Production

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The drying kinetics of mango were examined as a first step of pretreatment for biofuels production. This method exploits the potential of the carbohydrate present in the raw material, where the concentration for fermentation was adjusted to 20 g/L of reducing sugars. Dehydration was carried out by natural convection using a solar dryer. The solar dryer employed was made of transparent acrylic, and it had an internal volume of 0.125 m^3. The dehydration was performed through natural convection. The dehydration achieved 95.6% moisture removal in 28 h and reached maximum temperatures of 52 °C and 56 °C, corresponding to first and second phases, respectively. The minimum temperature reached was 21 °C. The rate of drying was evaluated during the first stage, between 0 to 4 hours, with radiation maxima of 991 and 1014 W/m^2 for that day. At the peak of radiation the drying rate was 0.060 g H_2O/ g dry mass/ min.

Keywords: Mango; Solar dehydration; Dry basis; Wet basis; Natural convection

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INTRODUCTION

Mango (*Mangifera indica* L.) is one of the most popular and abundant tropical fruits in Southeast Asia, specifically in the region of Indo-Birmanica.

It has been reported (Reddy and Reddy 2005) that mango has been cultivated in India for more than four centuries and is currently grown in 85 countries. The total world production in 2010 was 26,147,900 MT. Asia and Eastern countries produce about 80% of the total world production. The main mango producing countries are India, China, Mexico, and Pakistan. The surface area planted with mango in Mexico in 2012 was 186,964 hectares, with a production of 1.6 million tons per year and an average yield of 9 tons per hectare (SIAP 2013). According to a report published by Reddy, mango contains a high concentration of sugar (16 to 18% w/v). Sucrose, glucose, and fructose are the main sugars in ripe mangos, with small amounts of cellulose, hemicellulose, and pectin.

Drying can be defined as the process of removing moisture from a product with respect to time, and it can be performed in two stages. In the first stage, moisture inside the product is brought to the surface, and the water vapor is removed by a constant flow of dry air.

The second stage involves a slow drying rate, and the drying process is related to the properties of the material to be dried (El-Sebaii and Shalaby 2012). Drying, a basic process in the preservation of crops and some foods, can be performed using solar radiation as the main source of energy. The amount of energy required for dryers depends on the materials to be dried as well as the technology employed for treatment (Pirasteh *et al.* 2014).

There are two methods to remove moisture: evaporation and vaporization. Evaporation will be defined here as when the vapor pressure of moisture in the solid surface is equal to the atmospheric pressure. This is done by increasing the temperature of the moisture to the boiling point in an unsaturated gas phase, according to a report published by Bowen and Saylor (2009), who carried out experiments on evaporation from heated water placed in a container. They heated water to a particular temperature and then it was allowed to cool; cooling causes an unstable temperature gradient and thus convection. In natural systems such as lakes and oceans, evaporation of water can occur due to absorption of sun's radiation. The IR component of the radiation is absorbed within a thin layer at the top. In these situations there may not be any convection in the water.

In vaporization, drying is carried out by convection, *i.e.*, by passing hot air over the product. In this case, the saturation vapor pressure of moisture on the solid is less than atmospheric pressure.

Factors that affect the drying rate include air temperature, air velocity, type of product, product thickness, moisture content of the product, drying method, temperature, moisture diffusivity, and structure of the drying system. The drying air temperature and flow rate is important in drying applications (Karim and Hawlader 2004; Seyfi 2013).

After harvesting agricultural products, such as mangos, the product generally has to be pretreated for market. During pretreatment, one can use various chemical treatments to retain the ripeness and avoid spoilage during the exportation process. Given the considerable amount of harvest, is not possible to maintain optimal product conditions for export (such as spending quality standards). The increased temperature and humidity, as well as the water in these products, facilitates decomposition.

Dehydrated products can be stored for a while and taken advantage of for processing after harvest. Thus, solar drying has been considered as the most effective preservation process for most tropical crops (Ekechukwu and Norton 1997).

Removing the moisture necessary to maintain fruit is a process that can be used to provide carbohydrates to be used for other purposes. One example is the conversion of sugars, by the biochemical pathway of alcoholic fermentation, to ethanol (Yussof 2006). Biomass is a well-known renewable energy source that is of interest for biofuel production. The use of biomass as an energy source is not only very competitive in price and quality compared to fossil fuels, but using biofuels can drastically reduce CO_2 emissions. The mango is a potential raw material for bioethanol production because of its high yield production.

The objective of this research was to pretreat a raw material in order to conserve the sugars present in it, and later to store the raw material for further processing without loss of carbohydrates, because they are the main source of carbon of microorganisms for their metabolism to the production of bioethanol in the alcoholic fermentation step.

EXPERIMENTAL

Materials

Raw material

Ataulfo mango (*Mangifera indica* L.), which was selected as the raw material, was obtained from market waste in Temixco Morelos, Mexico. To prepare the samples to be dehydrated, slices were cut using a Kitchen Aid (USA) brand slicer to obtain a thickness of 3/16 inch (0.47 cm). These materials were dried by solar energy with a dehydrator and then milled with an industrial blender.

Sugar analysis

The DNS (3,5-dinitrosalicylic acid) technique was used to quantify the reducing sugars that will be consumed in the fermentation process, using fructose as a standard at a concentration of 1 g/L (Miller 1959). The Spectronic 20 Genesys (USA) spectrophotometer was used at a wavelength of 540 ηm.

Methods

Solar drying

For the dehydration of mango, laboratory solar dryers were used; they were designed and built at the Instituto of Energías Renovables of U.N.A.M., located in the town of Temixco, Morelos, Mexico. The dryers were facing south and placed in series with an inclination of north latitude 18 ° 50.36' to leverage more radiation. Each solar dryer had an area of 0.48 m^2. The material of these devices was clear acrylic having a thickness of 0.3 millimeters. The dehydration was carried out by a natural convection process (solar radiation values were obtained through the data base of the Instituto de Energías Renovables from Universidad Nacional Autónoma de México). The Institute gets weather information and continuous and reliable solarimetric data for the geographic location: latitude 18 ° 50.36' north, longitude 99 ° west 14.07'.

The particular characteristics of these devices include the clear acrylic building material with an inner volume of 0.125 m^3 and the exhaust system for moist air, with a capacity of 2 +/- 0.1 m^3/h. These dryers remained facing south, according to the latitude of the place, for better radiation. The equipment used and the product to be dehydrated are shown in Fig. 1.

Fig. 1. The solar drying of mango samples

The removal of moisture was done through the natural process of air convection. Consequently, the thickness of the mango wafer affected the acceleration or delay of the drying process. A smaller thickness decreased the drying time.

Natural convection process

A fluid moving from one point to another, in addition to transporting mass and momentum, also carries energy. Heat convection is strongly dependent on the flow mechanism characteristics, *i.e.*, the distribution of speeds and the flow regime (laminar or turbulent). Equation 1 corresponds to Fourier's law to calculate the heat flux (Cengel and Ghajar 2011),

$$q = -k_f \left(\frac{\partial T}{\partial y}\right) y = 0 \tag{1}$$

where k_f is thermal conductivity of the fluid.

The convective heat transfer depends on the density, viscosity, fluid velocity, thermal conductivity, and specific heat of fluid (Cengel and Ghajar 2011).

Drying kinetics

Drying kinetics are based on the change in the average amount of moisture over time. The drying kinetics show the amount of evaporated moisture, time, and energy consumption. However, the change of moisture depends on the transfer of heat and mass between the surface of the body, the environment, and the interior of the material to be dried (Molnar 2006). Solar drying is a process usually described by three diagrams: the drying curve, the drying rate curve, and the temperature curve.

Moisture content

The moisture content of a food is usually expressed as moisture percentage. Mathematically, this is the ratio of the mass of water contained in the food sample (adsorbent) and the total mass of food sample containing moisture (adsorbate), expressed as a percentage (Ferreira *et al.* 2014). However, the moisture content is used as the variable plotted on the vertical axis of vapor adsorption isotherms and is often expressed as the ratio of the mass of water (adsorbate) divided by the mass of dry matter (adsorbent). These two different methods of determining moisture content in a food sample are known as "wet basis" (w.b.) and "dry basis" (d.b.), respectively (Figura and Texeira 2007).

Dry basis

Equation 2 was used to determine the moisture concentration on a dry basis. The ratio of the mass of water to dry matter was used to calculate the percentage of moisture present.

One can also use Eq. 3 to calculate moisture content on a dry basis. This equation includes the ratio of the mass of water divided between the total mass of the product minus the mass of water. Equation 4 is used for the same purpose but takes as a starting point the moisture content on a wet basis.

$$X_{\text{w, d.}b.}=\frac{m_{\text{water}}}{m_{\text{dry matter}}} \tag{2}$$

$$X_{\text{w, d. b.}}=\frac{m_{\text{water}}}{m_{\text{total mass}}-m_{\text{water}}} \tag{3}$$

$$X_{\text{w, d. b.}}=\frac{1}{\frac{1}{X_{\text{w, w. b.}}}-1} \tag{4}$$

The quantity $XW_{,d.b.}$ is the moisture content on a dry basis, and the corresponding units are represented as g H_2O/g dry matter.

Wet basis

Equation 5 determines the moisture content of the product on a wet basis, which maintains a relationship between the mass of water and between the total mass of product. In Eqs. 6 and 7, the same results are obtained, taking into account initial conditions, the mass of water and the total mass of the product. Thus one can obtain the moisture content on a dry basis, respectively, as shown in the equations.

$$X_{\text{w, w. b.}}=\frac{m_{\text{water}}}{m_{\text{total mass}}} \tag{5}$$

$$X_{\text{w,d.b.}}=\frac{m_{\text{water}}}{m_{\text{dyr mass}}+m_{\text{water}}} \tag{6}$$

$$X_{\text{w, w. b.}}=\frac{1}{\frac{1}{X_{\text{w, d. b.}}}+1} \tag{7}$$

In these equations $X_{w,\ w.\ b.}$ is the moisture content on a wet basis, and the corresponding units are represented as g H_2O/g wet matter.

Calculation of water content percentage and initial moisture

A thermo balance (MB4S moisture measurement, OHAUS, Spain) was used to obtain the moisture content of the mango samples under the conditions established by the NMX-F-083-1986 (temperature/time: 105 °C/A30). An evaporation study was performed by means of the difference in weight of a known sample using an analytical balance, model OHAUS ScoutPro Brand.

Drying rate

The drying rate is the amount of water that is removed per unit time, and it governs how fast the product is dried. This process is described by Eqs. 8 and 9.

$$\int dt = -\frac{m_s}{A} \int \frac{dx}{w_D} \qquad (8)$$

$$W_D = -\frac{mdx}{Adt} \qquad (9)$$

In these equations X_0 and X_1 are the moisture content from time zero to time t, respectively.

Temperature curve

The product-temperature curve is obtained by plotting the data of drying temperature of the product against moisture content over time.

Drying time

Drying time depends on the material; it defines the features of the drying curve. The drying time should be determined separately for the first and second drying periods.

Equation 9, which defines the drying rate, can be rearranged to obtain the drying time. The amount of water removed from the product can be calculated using Eq. 10 as follows (Ashare 1974; Al-Juamily *et al*. 2007):

$$W_r = \left(\frac{X_i - X_f}{1 - X_i} \right) \qquad (10)$$

Here X_i and X_f are the initial and final moisture content of product over wet basis.

The useful energy required to dry a certain amount (on dry weight basis) of a product can be obtained using Eq. 11.

$$UE_{dry} = \left(\frac{1 - X_f}{1 - X_i} \right) s \left(T_d - T_a \right) + \left(\frac{X_i - X_f}{1 - X_i} \right) h_{fg} \qquad (11)$$

In Eq. 11 the first term on the right side represents the useful energy required for sensible heating of the crop from ambient temperature (T_a) to the drying temperature (T_d). The second term represents the useful energy required for the evaporation of moisture in the crop, with h_fg representing the enthalpy of evaporation of water at the drying temperature. The specific heat s of the wet crop can be estimated using the Siebel's formula obtained from the ASHARE handbook and product dictionary application (Ashare 1974).

RESULTS AND DISCUSSION

The average drying temperature was 45 °C. During the drying process, maximum temperatures of 52 °C and 56 °C, corresponding to the first and second stage respectively, were obtained. Furthermore, radiation peaks for these temperatures reached 991 and 1014 W/m^2 for each stage. This study showed that drying velocity depended on the concentration of radiation collected by the collector or drying area. The results obtained during the monitoring of mango drying are shown in Table 1. For this investigation, four samples were analyzed to discern the kinetics of drying. The amount of initial moisture was 79.9% on a wet basis, from which data were obtained on a dry basis. The average weight of the initial samples was 17.4 g. The average dry matter content of these samples was calculated to be 3.5 g d.m. (grams dry matter). The dry matter content was measured in order to be able to calculate the maximum amount of moisture removed during the mango drying process. The values of drying temperature, radiation, and moisture removed as a function of time and drying rates are shown.

Table 1. Mango Drying Data

Time (hours)	**Temperature (°C)**	***G* solar radiation (W/m^2)**	**Average weight of the samples (g)**	**Average g H_2O of the samples**	**Moisture d.b. (g H_2O/ g d. m.)**	***dX/dT* (g H_2O/g d.m. min)**
10:45	35	874	16.1	12.866	3.978	0.010
11:00	37	895	15.6	12.366	3.823	0.010
11:15	39	931	15.1	11.866	3.668	0.019
11:30	42	941	14.2	10.966	3.390	0.008
11:45	44	960	13.8	10.566	3.267	0.010
12:45	50	991	11.8	8.566	2.648	0.060
13:45	52	1014	8.9	5.666	1.752	0.005
14:45	52	729	7	3.766	1.164	0.010
15:45	55	590.1	5	1.766	0.546	0.003
16:45	54	353.7	4.4	1.166	0.360	0.001
17:45	48	151.7	4.3	1.066	0.329	0.001
08:40	21	383.3	4.2	0.966	0.299	0.001
09:40	31	605.1	4.1	0.866	0.268	0.001
10:40	42.5	610.4	4	0.766	0.237	0.000
11:40	50	984	3.9	0.666	0.206	0.001
12:40	56	991	3.8	0.566	0.175	0
13:40	56	920	3.8	0.566	0.175	0

g d.m.: grams of dry matter, d.b.: dry basis

A higher content of moisture was removed in the first stage of mango drying. The available radiation is graphed in Fig. 2 *vs*. the drying days.

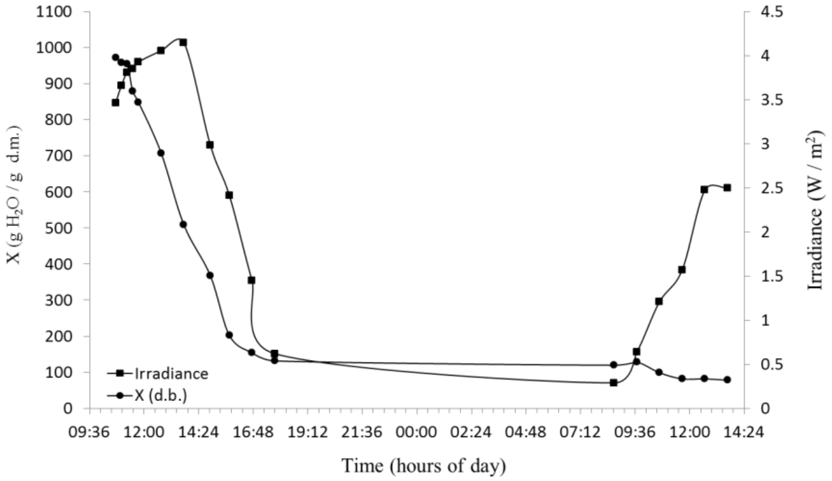

Fig. 2. Drying curve of mango by solar radiation, (—●—) kinetic drying of mango and (—■—) solar irradiance of day (G)

For the first hours of the day, a constant drying rate was maintained due to less radiation. In this context, the solar radiation increases the temperature inside the drying chamber; therefore, moisture loss is proportional to the solar radiation, so if radiation and temperature are kept constant, the drying rate of the product is greatly increased. The first 7 hours of drying correspond to the first stage of drying, which removed 86.4% of the moisture. The second drying step, corresponding to 5 hours of varying radiation as shown in Fig. 2, removed 95.6% of the moisture, on average. Figure 2 displays the mango drying curve with the results expressed on a dry basis. Where each value in points in the curves correspond to samples taken on the day of the experiment.

Parameters of drying, such as moisture loss and the time required for dehydration, are essential for analysis and determine the kinetics of drying. The drying rate is one of the most important parameters of the process, because it determines the product drying time and moisture loss as a function of process time. In this way, the drying rate as a function of grams of water removed per gram dry matter per minutes against grams of water removed on dry matter could be found; this data can be calculated for each time in the kinetic determination of drying. Thus the drying curve for mango, or the maximum drying speed, was 0.06 g H_20/g d.m. min. This maximum value is obtained during the first drying step. In Fig. 3, the drying rate curve is shown; this is the ratio of the drying rate against the moisture content of the sample.

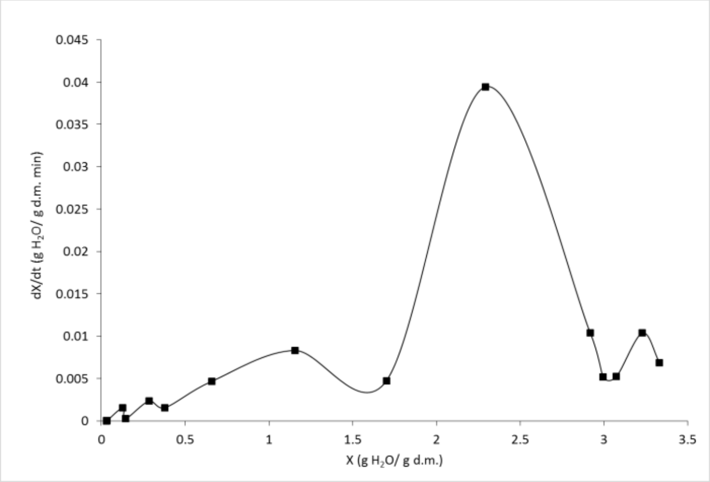

Fig. 3. Drying rate curve of mango

Analysis of the temperature during the drying process is one of the main factors in solar drying. The temperature depends directly on the radiation at the site. Therefore, a constant temperature reduces drying time. The solar drying temperature is not stable, because it depends directly on the radiation available at the drying site.

The solar drying temperature is not stable, because it depends directly on the radiation available at the drying site, *i.e.*, which it is considered a transient process Figure 4 presents the drying temperatures observed for mango. Figure 4 presents the drying temperatures observed for mango. The maximum temperature for the drying day was 56 °C and the minimum was 21 °C, which occurred when the solar radiation was zero.

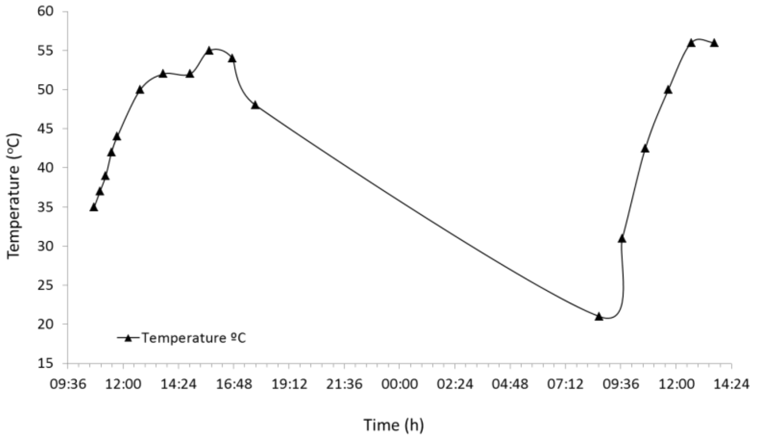

Fig. 4. Temperature inside the solar dryer

One of the main goals of this research was to preserve and maintain the highest possible concentration of carbohydrates in the mango. Thus, the methodology for the conservation of the carbohydrates of this raw material was established. Colorimetric analysis was carried out *via* the 3,5-dinitrosalicylic acid (DNS) method to quantify the total reducing sugars. Carbohydrates are metabolized by microorganisms during alcoholic fermentation for the production of bioethanol for use as biofuel.

Through the DNS method, the calibration curve used for the analysis of available carbohydrates is shown in Fig. 5. A high coefficient of determination of 0.99 was obtained.

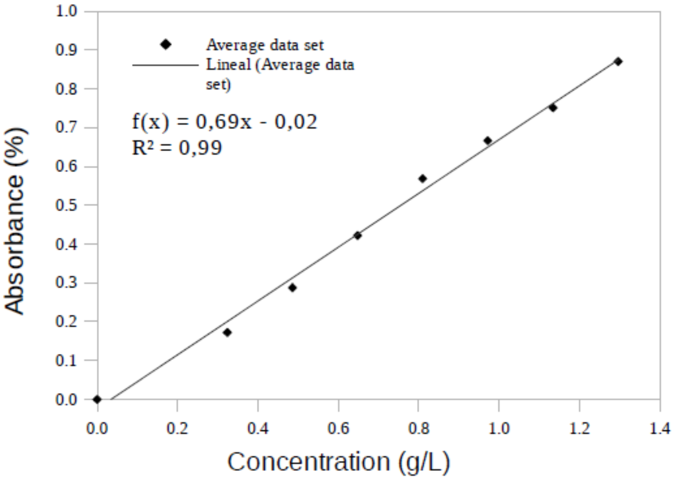

Fig. 5. Fructose calibration curve

The analysis of the results shows the total concentration of reducing sugars in g/L, quantified by coloration. Here, the absorbance data of the samples are shown in order to find the concentration of reducing sugars and, therefore, determine the exploitable potential of this raw material. The calculation was done using the equation obtained from the calibration curve of fructose. An average 20.1 g/L of reducing sugars was obtained by the DNS method.

CONCLUSIONS

1. Using solar dryers, 95.6% of moisture was removed from mango. The final drying time was, on average, 28 h with an average radiation of 758.6 W/m^2.
2. The concentration of total reducing sugars was 20 g/L, which used only 10 g of dry matter of mango with 100 mL of distilled water.
3. Solar energy can remove the moisture needed to keep the carbohydrates present in mangos for subsequent conversion to biofuels through the metabolic pathway of microorganisms.

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