Optimization of roselle drying time and drying quality

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*[1]Dept. Irrigation Universidad Autonoma Chapingo. Km 38.5 Carr. Mexico Texcoco, Chapingo, Mexico; and [2]Colegio de Posgraduados, Montecillos, Estado de México. *Email: fhahn@correo.chapingo.mx*

Hahn, F., G. Hernández, J. Hernández, C. Pérez and J.M. Vargas. 2011. **Optimization of roselle drying time and drying quality**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 53: 3.1–3.8. In solar drying, end-product quality is often adversely affected by open-air exposure to pollution leading to lower economic profits for producers. A polyethylene plastic covered tunnel was constructed for drying roselle calyxes. Three different drying techniques were evaluated and compared to search for optimum drying conditions. Calyx color images, water loss and calyx crispness of dried products were evaluated along the tunnel. Roselle drying using fan control took 27 hours, optimizing energy consumption and increasing air temperature within the tunnel. An air recirculating system using silica gel for removing air moisture decreased the drying time to 8 hours and obtained crisper calyxes. Moisture retained by the silica gel desiccant material was automatically removed by heat regeneration. Calyxes were dried in 4.5 hours at 70°C with a hybrid solar-biogas system. One kg of biogas was burned per kg of dried product. **Keywords:** Biogas, silica gel desiccant wheel, roselle calyx, solar tunnel, crispness ratio.

La qualité du produit final est souvent perturbée par une exposition au air à la pollution conduisant à une baisse des bénéfices économiques pour les producteurs. Pour le séchage des calices de roselle un tunnel recouvert de plastique en polyéthylène a été construit. Trois différentes techniques de séchage ont été évalués et comparés les temps de séchage optimal. Des images de la couleur du calice, la perte d'eau et la fraîcheur du calice de produits séchés ont été évaluées au long du tunnel. Le séchage de roselle à l'aide de un ventilateur a pris 27 heures en l'optimisation de la consommation d'énergie et l'augmentation de température dans le tunnel. Un système de recirculation de l'air a été utilisé avec de gel de silice pour éliminer l'humidité de l'air. Le gel a diminué le temps de séchage à 8 heures et obtenu calices bac à légumes. L'humidité retenue par le gel de silice déshydratant matériel a été automatiquement supprimée par récupération de la chaleur. Les calices ont été séchés en 4,5 heures à 70°C avec un système hybride solaire-biogaz. Un kg de biogaz a été brûlé par kg de produit séché. **Mots-clés:** Biogaz, Gel de silice déshydratant roue, Roselle calice, Tunnel solaire, Ratio de fraîcheur.

INTRODUCTION

Roselle (*Hibiscus sabdariffa*) is a tropical shrub with an approximate height of three meters and is found around the world. It is commercially produced in several states of Mexico (Barrios 2000). The dark red calyx (referred to as roselle) consists of a group of sepals which surround and protect the flower petals being used in the production of teas and juices. Roselle can be used in the treatment of kidney or stomach diseases and for reducing cholesterol levels and fatty acids found in the blood (Prasongwatana et al. 2008).

Dehydration is a preservation method that involves the removal of biologically active water in order to reduce microorganism growth (Esper and Mühlbauer 1998). With a longer product shelf life, dried products can be sold all year-round. The drying process eliminates the water or humidity content of the calyxes but must maintain the nutritional properties, specifically the ascorbic acid content (Meza et al. 2008). Traditionally, calyxes are spread over open area floors and dried naturally by the incidence of solar radiation. Roselle is stored when it is completely dry, after three or four days depending on ambient temperature and relative humidity conditions. End-product quality is affected by open-air exposure to pollution leading to lower economic profits for producers.

Sharma et al. (1995) showed that solar drying is an energy efficient and cost effective system for drying tomatoes and mushrooms. Karathanos and Belessiotis (1997) successfully conducted solar drying experiments with currants, figs, plums and apricots while Bala et al. (2003), dried pineapple slices inside a tunnel drier covered with a flat plate solar collector. A direct type natural convection solar dryer was tested with bananas and mango relating drying kinetics and heat balance (Gbaha et al. 2007). Thepent (2009) tested a combined solar tunnel dryer with biogas for continuous drying of banana and mango. The dryer operated under solar depletion and on rainy days employed the biogas as an auxiliary heat source, operating in both daytime and nighttime.

Desiccants are chemicals that can be classified as either adsorbent, which absorb moisture without accompanying physical and chemical changes, or absorbents, which absorb moisture accompanied by physical or chemical changes (Davanagere et al. 1999). Most absorbents are liquids and most adsorbents are solids. Silica gel has a high capacity to absorb moisture and then release it at a higher temperature. A stationary desiccant bed was employed in a solar dryer during daytime and used for extending the drying process during nighttime (Thoruwa et al. 1996). A fixed silica gel bed was integrated to an apricot solar dryer, shortening the drying period from 55 to 44 h, (Riyad and Jacques 2001). Low temperatures (up to 40°C) were used with silica gel for drying mushrooms, effectively decreasing the Maillard browning reaction rate (Gürtas and Evranuz 2000).

This paper analyzes three different systems for roselle calyx drying using the same polyethylene plastic tunnel. Drying time, product quality and ambient parameters were monitored and compared for each system. The first one used controlled fans for heating the air inside the tunnel to its maximum capacity; the second one recirculated air and passed it through a silica gel desiccant filter for drying the air, while the last method used a hybrid solar-biogas combination for drying the calyxes with hot air.

MATERIALS and METHODS

A 3.00 m long, 0.90 m wide and 1.10 m high polyethylene plastic covered tunnel was developed at the Universidad Autonoma Chapingo (Fig. 1). The semi-elliptic drying chamber presented major and minor radius of 0.45 and 0.25 m, respectively. Transparent polyethylene reflected radiation from 0.1 to 0.14, and transmitted from 0.70 to 0.85 (Flores et al. 2003). At a height of 0.65 m a black polyethylene film was fixed to heat the air encountered between this film and the plastic cover (1.17 m^3). The product tray (3 m long x 0.9 m wide) fixed to a rigid framework at a height of 0.8 m, presented a galvanized sieve with square grids of 0.01 x 0.01 m.

The calyxes were dried at the INIFAP research centre located at Iguala, Guerrero, Mexico, (18° 23′ 17′′ N, 99° 28′ 26′′ N) where the roselle plants were grown. Iguala's average relative humidity during the harvest month is about 70%, so the amount of water that can be absorbed by the air is small and the traditional dehydration process is slow. Roselle var. "Tecoanapa" was harvested the previous day at 19:00 hr and gathered in bags during the night to avoid calyx dehydration before drying. The maximum solar radiation collected by the tunnels was obtained at an inclination angle of 18° with respect to the floor. The air was extracted from the tunnel using four extractor fans at a speed of 0.12 m/s (model 4715FS-12T-B50, 115 V@ 0.19 A) once air flow had passed through the calyxes.

Three drying systems were built for drying roselle calyxes:

- Fan controlled solar drying;
- Recirculating air drying by silica gel moisture removal;
- Biogas heating of the drying air

The monitored product variables were: initial weight (weight of ten calyxes of fresh product), final weight of the same calyxes, relative humidity, radiation and tunnel drying temperature. Roselle quality parameters used were color measurements and final relative humidity correlated to crispness measurement.

Fan controlled solar drying

Drying time depends on air temperature, which at high ambient RH is slow. Air inside the tunnel was heated and its relative humidity increased with the water removed from the calyxes. RH data was acquired every five minutes using a relative humidity sensor (mod TRH-303, RIXEN, Taipei, Taiwan) with an accuracy of ±2%. The RH temperature-compensated sensor was fixed 10 cm under the polyethylene cover at the middle of the tunnel. A timer (mod 80.91, FINDER, Torino, Italy) automatically turned on the fans for a period of 5 minutes every half an hour from 8:00 to 12:00 and hourly from 12:00 to 18:00 (Hahn 2008). The incoming solar radiation was measured with a silicon pyranometer (mod CS300, Campbell Scientific, Loughborough, UK). A group of ten calyxes were weighed every half hour with a balance (mod Scout Pro SP202, OHAUS, NJ, USA), thus determining water loss.

Recirculating air drying by silica gel moisture removal

Air was recirculated to the desiccant filter containing silica gel to remove water vapor (Fig. 2). Two metallic ducts (Fig. 2–6) conducted the wet air through valve 7 towards the desiccant wheel (Fig. 2–1). This wheel (457 mm of diameter and 38 mm wide) presents twelve symmetrical sections containing silica gel to uniformly distribute the incoming air. A 120W extractor (Fig. 2–2) pulled the humid air which got expanded as it passed through the silica gel; dry air returned to the tunnel through valve 4. During heat regeneration for automatic gel drying, valves 3 and 8 were opened while valves 4 and 7 were closed and air circulated through the heater (Fig. 2–9). After drying the silica gel valves 4 and 7 were closed and dry air moved to the tunnel (Fig. 2–10) injecting uniform air using two drilled tubes (Fig. 2–5). The extractor always worked as this cycle repeated continuously during the drying period.

The automatic heating system used a 2 kW resistance rolled inside a stainless steel tube controlling regenerative

Fig. 1. Chamber used for roselle drying.

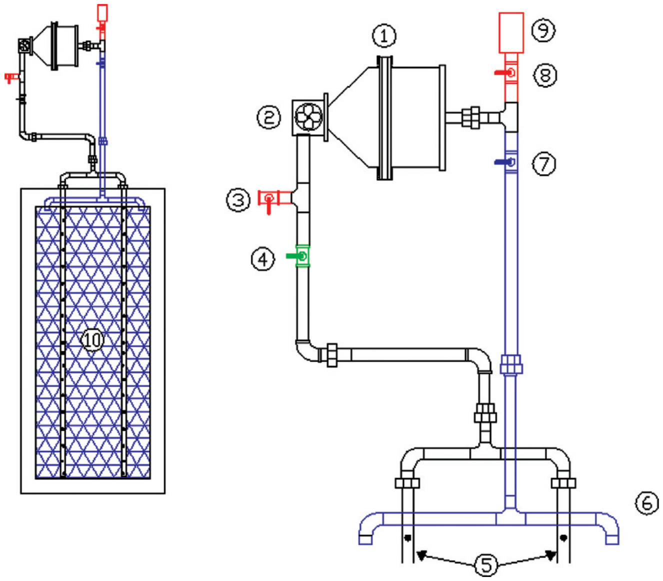

Fig. 2. Recirculating air drier composed of (1) dessicant filter, (2) extractor, (3) wet air expulsion valve, (4) tunnel return valve, (5) air conducting tube, (6) suction tube, (7) tunnel output valve, (8) hot air valve, and (9) heater.

temperature by ±1°C. Seventeen (1/4’’) holes were drilled in another serial tube to reduce air temperature to 100°C. An embedded circuit based on the microcontroller AT 89C51 controlled the timing of the four electro-valves using four relays. The filter removed humid air moisture for one hour by opening valves 4 and 7. Regenerative heating was then applied for fifteen minutes, closing valves 4 and 7 and opening valves 3 and 8. Twenty silica gel samples of 150 g were prepared having identical moisture content. Hot air at four different temperatures was applied to find the optimum regeneration temperature and drying exposure time.

Airflow rate was measured with a digital anemometer (Thermo-Anemometer, EXTECH) and regulated by adjusting the DC voltage of the blower. Air movement was maintained between 0.5 and 0.7 m/s. The dry bulb temperature was measured with a K-type thermocouple connected to a data logger, as well as the RH value. Water loss was obtained by weighing the same ten calyxes every half hour.

Biogas heating of the hot drying air

Biogas was produced by a University biodigestor using cattle dung, with carbon dioxide removed from the methane biogas by scrubbing. Biogas was then compressed and stored in cylinders. Air within the tunnel was heated with solar energy, but when the drying temperature was below the set point temperature biogas was burned. Set point temperatures were fixed at 60, 65 and 70°C to study drying time and biogas consumption. A burner heated the incoming air and pushed the hot air through two (Fig. 2–10 cm-diameter) metallic tubes. Two holes 6 cm apart were drilled every 20 cm. The heating effect of the hot air injected through the tube holes was studied to look at final produce homogeneity. Heat was initially applied towards the black polyethylene sheet and after rotating the tubes it was directed towards the sieve holding the calyxes.

Quality measurements

The tunnel was divided in three sections evaluating the final moisture of the calyxes per area; the sections being (air opening, AO) where air enters the tunnel, middle section (MS) and extractor section (ES) where humid air is removed. During air recirculation, air enters and leaves the tunnel on the same side; extractor fans are not used and ES samples, by their position, are those more distant from the re-circulating entrance. Crispness, which can be related to calyx relative humidity, was measured with a small motor of 1/30 HP which ran at 25 RPM. The motor shaft was connected to a pair of aluminum drums (7.5 cm diameter) spaced 0.4 cm, each turning in opposite directions. Roselle calyxes were pulled and passed through the small spacing between drums; a dry calyx broke in several pieces while a humid calyx passed entirely. After breaking, a sieve retained the large pieces of the calyx, letting small pieces pass. Dry calyxes from each tunnel section were weighed before introducing them to the crispness detector, and after passing between the drums; the pieces retained by the sieve provided the final weight. The crispness ratio or breaking index is the ratio between the initial and final weight (Hahn 2009).

RGB (red, green blue) images of the calyxes can provide quality information. As the camera view angle

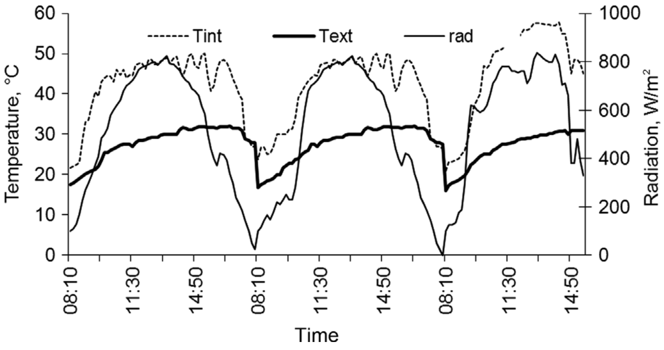

Fig. 3. Radiation and temperature measured inside and outside the drying tunnel.

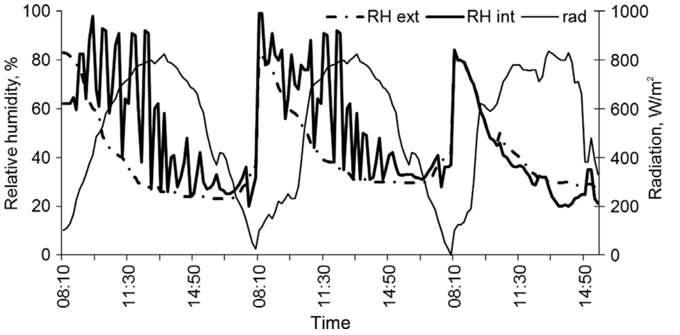

Fig. 4. Radiation and relative humidity measured inside and outside the drying tunnel.

(Mod. 46, Sony) did not allow taking an image of all the calyxes, yellow divisions were positioned under the drying calyxes. Calyxes were not always separated from the "cacalote", a hard tissue containing the seeds, but a vision algorithm eliminated them. A vision algorithm scanned bit by bit the entire drying surface image acquiring the red, green and blue values; then eliminated those considered as "cacalote" or galvanized sieve. Cacalote average R-G-B values were of 169-145-135 so pixels having an R/G value below 1.28 were discarded. Pixels containing galvanized sieve presented an average R-G-B value of 185-220-248, and were eradicated when $R/G < 1$. The average intensity and standard deviation of red, green and blue values per section were obtained for each drying system.

RESULTS and DISCUSSION

The results obtained from the three different drying systems using the plastic tunnel inclined by 18 degrees under solar days without clouds are presented. Calyxes are spread out in a volumetric film of 0.135 m^3 over the sieve. If this film constitutes one sixth of the entire tunnel volume, condensation appears when the hot air temperature reaches 55°C. Condensation is avoided when the tunnel volume is nine times greater than the calyx film volume at this temperature. The RH sensor used to measure the moisture in each system provided a current output of 4–20 mA avoiding voltage drop in the cable. Its response was slow, providing unreliable data when RH was acquired every 30 seconds, so measurements were taken every 5 minutes.

Fig. 5. Drying of recirculating air.

Fan controlled solar drying

Roselle calyxes were dried to a final relative humidity of 12% in 27 hours. External temperature increased from 18°C in the morning up to 30°C in the afternoon, having a peak radiation of 820 W/m^2 at 13:10 (Fig. 3). Inside the tunnel the temperature increased to a maximum value of 50°C during the first two days and up to 58.5°C on the third day. Fans turned on 13 times on the first day and condensation appeared during the first five RH peaks (Fig. 4). The extractors replaced the humid air with ambient air. Relative ambient humidities of 77% and 28% were found during the first day at 9:00 and 14:00, respectively. Air relative humidity remained high inside the tunnel on the second day at 12:30 as calyxes were still humid. On the third day high RH peaks vanished increasing tunnel temperature to 58.5°C.

Although a shorter drying time of 21 hr was obtained with continuous air extraction, controlled extractors reduced energy consumption. By reducing air speed movement, hotter air moves within the tunnel and drying

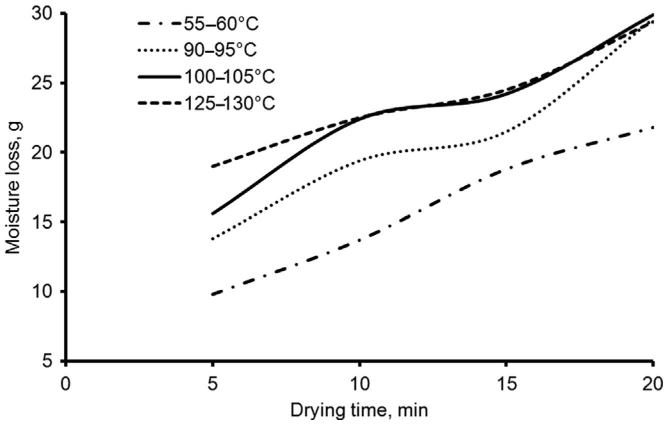

Fig. 6. Heat applied at different temperatures to reduce sílica gel moisture.

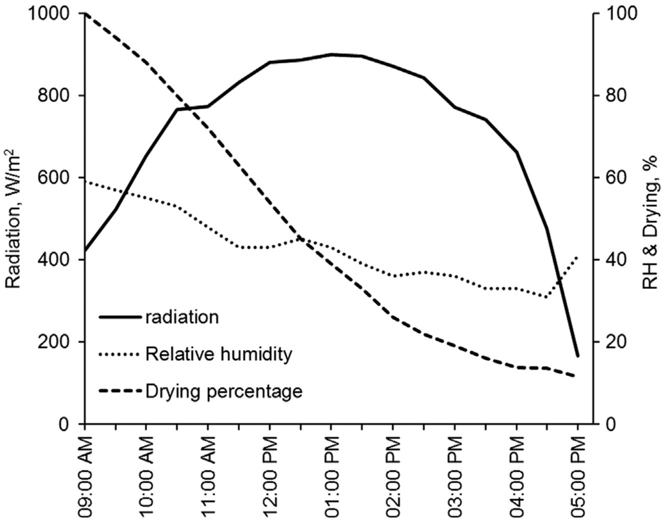

Fig. 7. Roselle weight loss achieved during drying.

time decreases. Air turbulence produced by recirculating fans inside the drier decreased drying time by one hour.

Roselle drying time decreased as air temperature increased as reported by Saeed et al. (2006). Roselle drying time decreased with a lower air relative humidity; drying was accelerated when the air humidity dropped off from 50% to 30% (Krokida et al. 2003; Timoumi et al. 2004). Calyx drying time at 30% RH decreased from 38.6 to 4.4 hours by increasing the temperature from 35°C to 65°C, (Saeed et al. 2008). Only 10% of water loss before 10:00, when the air exceeded 50% RH, was obtained during the three days.

Drying by moisture removal of the recirculating air

The recirculating air system requires more equipment than the conventional solar drier (Fig. 5). In the recirculating system, silica gel dries fast (Weintraub 1991). Dry gel surface area should be limited to prevent RH from dropping too quickly, as the speed at which dry gel adsorbs moisture is faster than the rate at which silica gel desorbs moisture. Silica gel moisture is removed efficiently with heat; maximum temperature applied should not exceed 200°C. At high temperatures air flow should be slow, while at high air flow rate, silica gel can be dried at 40°C (Pramuang and Exell 2007). Maximum silica gel moisture removal was achieved by heating the desiccant material at 100-105°C for 20 minutes (Fig. 6). Higher temperatures did not extract the moisture at a faster rate.

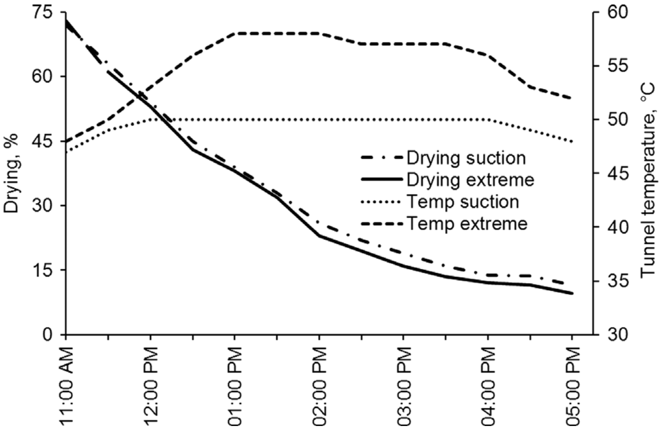

Fig. 8. Temperatures and drying times measured at both tunnel sides.

The system started operation at 9:00 and dried the calyxes to final moisture of 12% in 8 hours (Fig. 7). The initial temperature recorded inside the tunnel was 39°C at 9:00 and increased to 45°C at 10:30. Although the initial moisture inside the tunnel was 60% RH, the recirculating system maintained the air below 45% RH. By noon the calyxes had lost half their water content, and the air moisture was at 41% RH. Temperature inside the tunnel remained at 50°C from noon to 16:00 and decreased to 48°C at 17:00 (Fig. 8).

The blower caused a non-uniform air movement along the tunnel. Maximum temperature difference between the tunnel front and back wall was twelve degrees (Fig. 8). In the section where air was not vacuumed, the drying rate was slower. Dense desiccant material within the filter presents static pressure to the airflow increasing energy consumption.

Madhiyanon et al. (2007) reported a regeneration drying temperature of 100°C similar to the one used in this paper. Air moisture with the silica gel rotating wheel was half the one obtained in this experiment. Without rotation the desiccant filter saturates quicker as humid air is always applied at the same filter zone. If the desiccant wheel turns, air tunnel and silica gel could dry simultaneously. In the proposed recirculation system, one goal was to decrease the system complexity, so wheel rotation was avoided. The best air velocity for drying calyxes was of 0.7 m/s, similar to the one reported by Madhiyanon et al. (2007).

Biogas heating of the drying air

Hot air was introduced to the tunnel inside two metallic tubes that reached temperatures of 90°C; tube orifices injected the hot air at a speed of 0.6 m/s. Drying resulted from conductive-convection heat transfer. Calyxes were dried by forced convection from the hot air injected mixed with the air heated around the metallic tubes by thermal conduction. Although drying time remained similar, injection trajectory affected roselle calyx drying homogeneity, as shown in Table 1. With the tube holes pointing down, 87% of the calyxes were completely dried. When the holes pointed up, 75% of the calyxes were dried since a blind area between both tubes appeared where no heat was applied.

The final moisture of the calyxes was reached after 4½ hours at 70°C, while it required 5 hours at 60°C (Fig. 9). Tunnel air temperature can be controlled by varying the extractor speed and seven minutes were required to raise the air tunnel temperature from 29°C to 52°C at 9:00. Drying started at noon with radiation and moisture values of 875 W/m^2 and 35% RH, respectively (Fig. 10). Three and a half hours later, the radiation decreased to 700

Table 1. Final average relative humidity based on tube orifice position.

		Final RH distribution,%		
	Drying time, hr	<10	10.1 <RH <11.8	>11.9
Holes toward black polyethylene	4.5	–	87	13
Holes toward calyxes	4.5	12	63	25

W/m^2 while relative humidity decreased to its minimum value of 20%. The temperature inside the tunnel exceeded 70°C several times with solar energy and biogas; one kg of biogas was burned for three and a half hours. Calyxes dried at a temperature of 60°C, burned only 0.9 kg of biogas for 3½ hours. Drying time just over four hours was similar to the one reported by Meza et al. (2008) under air temperature varying between 48 to 68°C. Temperature below 60°C was only applied during the first four minutes increasing gradually to 68°C. Yang et al. (2006) proposed a hybrid solar-biogas drier suggesting a minimum of 50% of methane for proper drying. In this prototype biogas consumption was 40% due to the high solar radiation.

Product quality

Drying time and energy consumption were obtained and compared for the three drying systems (Table 2). Air moisture removal in the recirculating system reduced drying time with respect to the fan controlled system, although energy consumption increased. Calyx water loss and crispness per section were obtained in the tunnel for each drying method (Table 3). With fan control drying, low crispness calyxes were uniformly distributed throughout the tunnel. In the recirculation system the crispness increased with a maximum value of 89% at the side where air re-circulates to the desiccant filter. The hybrid system presented the shortest drying time and calyxes maximum water loss took place at the extractor side. Of the three systems, the crispest product was obtained by the hybrid system; product losses of 20% are expected as dry calyxes break-down easily during shipping.

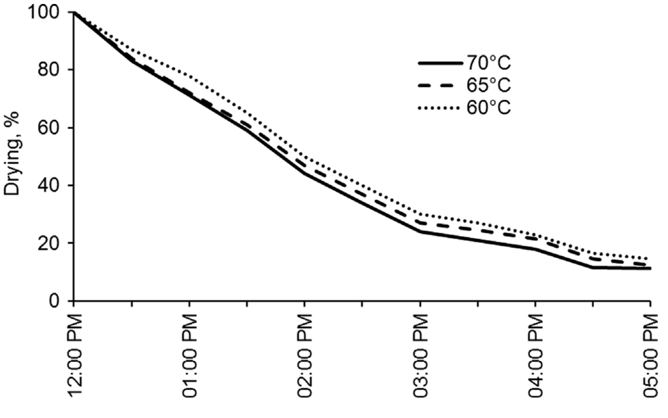

Fig. 9. Roselle drying rates when different temperatures were applied.

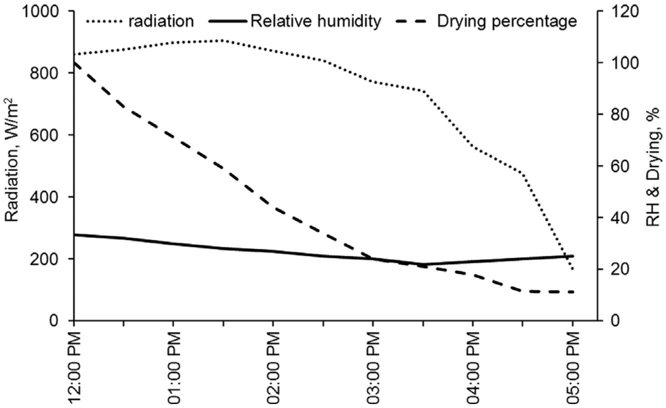

Fig. 10. Drying kinetics, relative humidity and radiation obtained during hot air drying at 70°C.

Dried calyxes color RGB values were averaged at the tunnel edges for each drying technique and the results are shown in Table 4. Three and thirteen percent from the image pixels corresponded to the sieve and "cacalotes", respectively; these pixels were removed and those remaining were averaged per section. For the same final roselle moisture, different calyx color resulted from each drying method. For example, the hybrid system presented the higher green intensity, but the lower red intensity. Calyx blue intensity values from the fan control drier were lower than those obtained from recirculation and hybrid systems. Fan control presents a high standard deviation on red intensity data as long drying time affects calyx color appearance; green and blue intensities were not as sensitive as the red one. Calyx color intensities on the hybrid system

Table 2. Energy consumption, drying time, average relative humidity and temperature obtained for each drying scheme.

	Energy, W	Avg temp, °C	Avg RH, %	Drying time, hr
Solar drying on floor	–	30	40	70
Fan control	Low	45	70	27
Recirculating system	High	50	43	8
Biogas heating	Low-med	69	26.7	4.5

Table 3. Crispness and water loss encountered at different sections of the tunnel for each drying technique.

	Crispness, %			Water loss, %		
	ES	MS	AO	ES	MS	AO
Fan control	98	98	97	11.5	11.7	11.7
Recirculation system after 8 hr	83	85	89	11.3	11.5	11.8
Hybrid system at 68°C for 4.5 hr	73	76	75	11.2	11.3	11.5

ES: Extractor section; MS: Middle section; AO: Air opening.

Table 4. RGB average color intensities and standard deviations obtained from the dried calyxes at the two sides of the tunnel for each drying method.

	Color average/std dev at extractor section			Color average/std dev at air opening section		
	R	G	B	R	G	B
Fan control	143/2.7	56/1.7	66/1.9	156/3.1	66/1.6	72/2.1
Recirculation system after 8 hr	140/1.8	65/1.2	88/1.1	138/1.1	56/1.15	90/0.98
Hybrid system at 68°C after 4.5 hr	130/0.9	91/0.98	98/0.96	135/0.98	88/0.96	93/0.97

were homogeneous, so standard deviation values were beneath one.

CONCLUSIONS

All the drying schemes reduced the drying times from the conventional solar drying consisting of spreading the calyxes over the floor. The tunnel dried calyxes increased product quality obtaining a cleaner and pathogen-free product, protecting it from rain, insects and dust. Three roselle calyxes drying systems with different parameters were implemented and can dry rapidly to avoid fungal appearance. It was found that the ratio between the volumetric film where calyxes are spread and the entire volume should be 1/9 to avoid condensation.

A crispness detector using a motor drive was developed and determined the dryness of the calyxes. Color measurements were taken and provide data concerning calyx drying, differentiating it from the sieve and “cacalote” by using red green ratios. Dried calyx RGB color intensities depend of drying time.

The fan controlled system was the easiest to implement, but calyx drying time was too slow. Drying time can be reduced by increasing temperature by ten degrees and reducing air flow. Low crispness and red brightness are indicators of biological active water presence in dried calyxes. The recirculation scheme presents a good drying time which can be reduced by rotating the desiccant wheel, but is the most complex and power consuming system. This dried product presents the best crispness as it is dry, and does not break easily.

The hybrid system dries the calyxes very quickly and therefore the product is very crispy and breakable. Its drying temperature should be reduced the last half an hour in order for the product to be less crispy. Biogas is an excellent alternative for drying under cloudy days and for nighttime drying. The metallic tubes separation affected roselle calyx drying homogeneity, producing a better drying when the injected hot air hit the black polyethylene sheet and was reflected back to the calyxes. One kg of calyxes was dried per kg of biogas burned at 70°C.

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