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Concentrated solar drying of tomatoes

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ABSTRACT

Fruits and vegetables are an integral part of the human diet. Many developing countries such as Tanzania experience post-harvest losses of 40%, and there is little ability to preserve and store foods for off-season consumption due to expensive or unreliable energy and a lack of access to refrigeration. Alternatively, fruits and vegetables can be dehydrated using solar crop dryers. Because many developing countries are in tropical regions, properly dehydrating fruits and vegetables to moisture levels appropriate for storage and off-season consumption can be difficult. In an attempt to overcome the challenges of the high humidity, intermittent clouds, and haze often present in tropical climates, this paper investigates the effectiveness of adding a concave solar concentrator built from low-cost, locally available materials to a typical Tanzanian solar crop dryer. Two identical solar crop dryers were constructed, with one serving as the control and the other for testing the solar concentrator. Drying trials using Roma tomatoes with initial moisture content of approximately 90% were conducted in Davis, California (38° 32′ 42″ N/121° 44′ 21″ W) in various climatic conditions throughout the summer and fall. Tomatoes were considered dried at 10% moisture content. Temperature, relative humidity, and solar radiation were measured outside as well as within each of the dryers to determine how the addition of a solar concentrator can affect the drying rate of tomatoes in solar crop dryers. The concentrator proved to be effective, reducing drying time by 21% in addition to increasing internal dryer temperature and reducing relative humidity. An additional study on the quality of the fresh and dried tomatoes found that the pH, titratable acidity, color, Brix, lycopene, and vitamin C determined there was no significant difference in quality between tomatoes dried with and without the concentrator.

Introduction

Traditional solar fruit drying is often a slow process impeded by the high humidity, haze, and intermittent clouds experienced in tropical regions. In sunny, arid places, solar crop drying is a relatively simple process, and can often be accomplished without the need for a solar dryer. The warm, dry air's high capacity to take on moisture quickly removes moisture from fruits. Although simply exposing fruits to direct sunlight will often be sufficient for drying, crop dryers are often utilized to protect fruits from dirt, insects, and contamination. In humid, tropical climates, however, drying can be impeded (Forson et al., 2007). With the humid air's reduced capacity to absorb moisture from the drying fruits, using a solar crop dryer coupled with a solar concentrator helps to improve the drying rate by increasing internal dryer temperature and radiation.

Today, large-scale mechanized dryers are often used to dry fruits in industrialized countries. These machines force air heated by boilers across the fruits to quickly dry them. This improved process, however, is often not viable in many developing countries. The large amount of capital needed for machinery is often prohibitively expensive for small-scale farmers in rural areas. The fuel or electricity to power the machine may not be available or affordable, in addition to leading to environmental problems associated with greenhouse gas emissions (Blair et al., 2007). For these reasons, this project only considers non-mechanized solar crop dryers, and in particular, a dryer design commonly found in Tanzania.

So that the solar concentrators can be used in a developing country context by rural farmers with no technical knowledge or skills, each solar concentrator tested in this project was subject to certain restraints. The total cost of the concentrator was to not exceed $30, and materials must be readily obtainable in developing countries. It must have a lifetime of at least three years, with no repairs during the first year. The concentrator must be able to be transported by one or two people, and must be modular so that it can be adapted for dryers of various sizes. A farmer without technical construction skills must be able to build the concentrator, and lastly, it must be fixed with no sun tracking or moving parts.

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After drying trials were completed, tomato quality was studied in both dried and fresh samples. When choosing which tomatoes to buy, consumers use color and appearance as indicators of quality. The same holds true for dried tomatoes. Consumers often associate a dark red color with sweet, ripe tomatoes. This color is due in part to a high concentration of lycopene (Barrett and Anthon, 2008). Lycopene may also protect against various epithelial cancers (Shi et al., 1999). For this reason, color and lycopene, along with °Brix (soluble sugar content), pH, titratable acidity, and vitamin C were measured.

This project aims to increase the drying rate of tomatoes in solar crop dryers with the addition of solar concentrators. It focuses on developing countries, and provides a possible solution to reducing the 40% post-harvest losses often experienced in these regions (Gustavsson et al., 2011). In addition to the general goal of being able to decrease the high post-harvest losses seen in many developing countries and provide poor, rural farmers with a way to increase their income, the specific research objectives of this project were to:

1. Design and construct a solar concentrator for testing as an addition to a typical Tanzanian solar crop dryer, in an attempt to reduce tomato drying times.
2. Evaluate the effectiveness of solar concentrators by measuring:
   - Technical performance (internal dryer temperature, relative humidity, and radiation)
   - Product quality (pH, titratable acidity (TA), color, Brix, lycopene, and vitamin C)

Materials and methods

Raw materials

Processing tomatoes were obtained from grower collaborators participating in a University of California, Davis tomato variety evaluation project. Tomatoes were grown from transplants and watered with subsurface drip irrigation and standard commercial practices. Healthy, red ripe mature tomatoes were selected by hand, then washed and cut into 5 mm thick slices. The sliced fresh tomatoes were weighed on a scale before being placed onto the top and bottom drying racks within two solar dryers, and were weighed again on two hour intervals during drying trials.

Construction materials including wood, screws, corrugated aluminum sheets, polished aluminum sheets, spray paint, clear plastic wrapping, and metal downspout piping for the solar dryers and solar concentrator were purchased at local hardware stores in northern California.

Design of the solar crop dryers

The solar crop dryers used in these experiments were built from a design commonly found in Tanzania (Fig. 1—obtained from Bertha Mjawa, Ministry of Agriculture Food Security and Cooperatives, Republic of Tanzania government). The dryer consists of a lightweight wooden frame that is 1.5 m tall, 1.8 m wide, and 1 m deep wrapped in a 4 mm thick clear plastic sheet supported on four 0.3 m legs. There is a corrugated piece of aluminum painted black on the floor of the dryer which is called the absorber plate (for absorbing solar radiation). There are four removable drying racks (of 0.8 m × 0.8 m), two of which are near the top of the dryer and two near the absorber plate on the bottom. Each rack has a square frame filled with mesh onto which sliced tomatoes are placed. Cooler, dry air enters the dryer near the absorber plate through a screened window and rises across the drying racks and tomatoes. Warm, moist air is removed at the top of the dryer through another screened window.

Design of the solar concave concentrator

The concave concentrator (seen in Figs. 2 and 3) was built from a wooden L-shaped frame. A polished aluminum sheet with reflectance of 0.8 was attached at the bottom and top of the frame to form the concave reflective surface. The reflective surface is 1.71 m^2 (1.88 m × 0.91 m).

Solar drying trials

Drying trials using 5 mm thick sliced tomatoes (with initial moisture contents between 92.2 and 94.4%) were conducted in Davis, California

Fig. 1. Two solar crop dryers commonly found in Tanzania.

Fig. 2. Front view of concave solar concentrator.

in various climatic conditions throughout summer and fall. Tomatoes were placed on a top and bottom drying rack within each dryer, and were considered dried when they reached 10% of their initial moisture content. If, for example, the initial weight of a tomato with 94% moisture content is 100 g, there are 94 g of water and 6 g of dry mass. This 6 g of dry mass will remain constant as water is lost during the drying process. At 10% moisture content, the tomato would possess 9.4 g of water weight plus the original 6 g of dry mass for a total of 15.4 g, and for the purposes of this project, this is when the tomato is considered sufficiently dried.

Temperature and relative humidity were measured at the top and bottom rack within each dryer and solar radiation was measured at the top rack. The same three parameters were also measured in ambient conditions.

During the drying trials, dryer 1 was located west of dryer 2, and both were oriented towards the south. One dryer served as the control, with no concentrator, while the other utilized the concentrator (see Fig. 4). To limit any possible errors caused by performance variation between dryers, the concentrator was alternated between each of them. Table 1 summarizes the details of the drying trials.

Fig. 3. Testing the focus of the concave concentrator using a laser.

Data collection and analysis methods

Solar concentrator technical performance and equipment

To evaluate the technical performance of the concentrator, temperature, relative humidity, and solar radiation readings were recorded every 15 s on a H22-001 HOBO Energy Logger. Temperature and relative humidity on the top and bottom drying racks of each dryer, and in the ambient air was measured using model S-THB-M002 HOBO 12 Bit Temperature/Relative Humidity Sensors. Model S-LIB-M003 HOBO Silicon Pyranometers were placed on the top drying rack of both dryers for measuring solar radiation. A measuring scale was used to weight the sliced tomatoes on each rack of the dryers on a two hour interval to determine drying rate.

Determining % total solids (TS) and dry weight content

Total solids for tomatoes used in the 7/16, 9/26, and 9/28 drying trials were determined using the following equation:

$$\%\ \text{Total solids (TS)} = 100 * (\text{dry wt.–tare})/(\text{wet wt.–tare})$$

The wet weight was simply a small quantity of tomato juice (8–10 g). The dry weight was determined by drying the small quantity of tomato juice for 3 h in a RVT400 vacuum oven between 55 and 60 °C. Since this process was not done for the tomatoes used during the 10/24 trial, the dry weight content was later determined using a regression analysis of Brix (soluble solids) vs. total solids for 16 tomato samples during the 2011 UC Davis processing tomato growing season.

Tomato quality evaluation methods and equipment

After each drying trial was completed, the dried tomatoes from the top and bottom drying racks of both dryers, and the fresh tomatoes used that day were frozen at −80 °C for subsequent analysis. When trials were completed, water was added to each frozen sample to reconstitute it to its original fresh weight, and then the samples were allowed to thaw overnight. They were then blended and prepared for the following quality testing procedures.

Titratable acidity, pH, °Brix, Bostwick and color measurements. Samples were evaluated for titratable acidity using titration with NaOH (AOAC International, 2000). The remaining juice was deaerated and the

Fig. 4. Dryer 2 (left) is exposed to the concave solar concentrator. Dryer 1 (right) is the control.

temperature adjusted to 25 + 0.2 °C, then used for determination of pH and °Brix (soluble sugars). Independent duplicate Bostwick consistency readings were obtained on each sample (Barrett and Anthon, 2001). Readings reported are the distance (cm) that a volume of juice of fixed dimension flowed in a trough in 30 s. A smaller reading corresponds to less flow, or product of higher consistency.

Color (HunterLab, Reston, VA) values were also measured on microwaved, deaerated juice. Instrumental color measurements were made on juice samples placed in glass sample cups. L value (white to black or light to dark), a (green to red) and b (yellow to blue) measurements were taken with a Hunter colorimeter. The colorimeter was calibrated with a white tile and a standard tile of a color similar to that of the sample. L, a, and b values were determined by averaging the results of three independent readings per sample. From the L, a, and b values, USDA tomato scores were calculated. In addition, overall color was measured on microwaved deaerated juice using a Light Emitting Diode (LED), a standard colorimeter used by the California tomato industry (Valero et al., 2003).

Lycopene measurements. A modification (Barrett, 2001) of the method published by the AOAC International (2000) was used for lycopene analysis. First 100 μl of microwaved tomato juice was pipetted into a screw cap tube using a 100 μl Drummond micropipette. Then 7.0 ml of 4:3 (v/v) ethanol:hexane was added, the tube was capped, vortexed, then incubated out of bright light, with occasional vortexing. After 1 h 1.0 ml water was added to each sample and then shaken briefly. Samples were allowed to stand 10 min to afford phase separation and dissipation of air bubbles. A sample of the hexane layer was read at Abs 503 versus hexane in the spectrophotometer (Shimadzu, Japan). Lycopene levels in the hexane extracts were then calculated according to:

$$\mu\text{g lycopene/g fresh wt.} = (A_{503} \times 537 \times 2.7)/(0.1 \times 172) = A_{503} \times 84.3$$

Table 1
Weather conditions and experimental design of tomato drying trials.

Trial #	Date	Weather	Dryer 1	Dryer 2
1	7/16/2011	Sunny	Control	Concave concentrator
2	9/26/2011	Mainly Sunny	Concave concentrator	Control
3	9/23/2011	Sunny	Control	Concave concentrator
4	10/24/2011	Haze	Concave concentrator	Control

where 537 g/mol is the molecular weight of lycopene, 2.7 ml is the volume of the hexane layer, 0.1 g is the weight of sample added, and 172 $(\text{m-M})^{-1}$ is the extinction coefficient for lycopene in hexane. Duplicate samples were analyzed.

Ascorbic (reduced) and dehydroascorbic (oxidized) acid measurements. Raw and microwaved tomato juice samples were analyzed for ascorbic acid, dehydroascorbic acid and total phenolics. Ascorbic acid was determined using a spectrophotometric method (Latapi and Barrett, 2006). One gram of the sample was homogenized with distilled water using a Polytron (Brinkmann Instruments Inc., Model PCU11, Westbury, NY) until a thick paste was obtained. The paste was centrifuged and the supernatant removed for analysis. In a 3 ml cuvette, 2.5 ml of 0.1 M sodium phosphate, pH 6.5, 0.1 ml of sample, 0.4 ml of water, and 0.5 ml of 1.0 mg/ml horseradish peroxidase (Sigma Type II) were mixed. The sample was read at Abs 265 in a spectrophotometer (Shimadzu, Japan) to determine total ascorbic acid, 50 mM hydrogen peroxide was added and the sample was read again after it reached a stable absorbance value at 265 nm to determine oxidized or dehydroascorbic acid. Ascorbic acid content was expressed as mg/g dry weight. Measurements were performed in triplicate.

Results and discussion

Concentrator performance results

Results of drying trials on four different days with varying weather conditions are presented in Table 2. The use of a concentrator leads to the greatest percentage reduction in drying time on September 28th. On this fully sunny day with an average ambient solar radiation of 551 w/m^2, the tomatoes in the dryer with the concentrator reached the 10% moisture content level at 1.54 h, or 22.3% faster than those in the control dryer. Other drying trials conducted on July 16th, September 26th, and October 24th yielded reductions in drying time of 1.71 h (21.3%), 1.74 h (20.8%), and 1.31 h (18.8%), respectively. Ambient solar radiation on these days averaged 781, 581, and 478 w/m^2. Although July 16th had the highest solar radiation from the drying trials, it actually had the lowest average ambient temperature and second highest ambient relative humidity. From this trend, it can be seen that sunny conditions and higher ambient solar radiation leads to increased concentrator effectiveness on reduction of drying time, and concentrators can still be effective when ambient temperature and relative humidity are not favorable.

Table 2
Weather conditions and reduction in drying time in the dryers using concave concentrators as compared to those without concentrators.

	July 16th		Sept. 26th		Sept. 28th		Oct. 24th		Averages	
	Hou rs	Percentage	Hours	Percentage	Hours	Percentage	Hours	Percentage	Hours	Percentage
Reduction in drying time										
Top rack	1.11	15.3%	1.32	17.0%	0.72	12.3%	1.75	24.9%	1.22	17.4%
Bottom rach	2.31	27.3%	2.15	24.7%	2.37	32.3%	0.87	12.6%	1.92	24.2%
Average	1.71	21.3%	174	20.8%	1.54	22.3%	1.31	18.8%	1.57	20.8%
Concentrator performance										
Temp top, °C	−0.5		1.3		1.3		1.3		0.8	
RH top, %	−2.8%		−0.6%		−0.4%		−1.2%		−1.3%	
Temp bottom, °C	0.5		2.7		1.8		1.1		1.5	
RH bottom, %	−2.4%		−1.7%		−0.4%		−0.8%		−1.3%	
Solar radiation, W/m^2	−16		error		30.8		93.9		36.3	
Ambient conditions										
Weather description	Full sun, slightly cool		Early haze, then sun		Full sun		Haze entire day		N/A	
Temp, °C	24.1		27.7		33.3		24.6		27.3	
RH, %	47.6%		44.2%		31.5%		48.6%		43.0%	
Solar radiation, W/m^2	781		581		551		478		597.5	

As expected, the dryer coupled with the concentrator exhibited lowered relative humidity than the control dryer. This was true during all of the four drying trials, with the largest reduction of 2.8% at the top drying rack and 2.4% at the bottom drying rack seen on July 16th. The September 26th trial showed reductions of 0.6% and 1.7%, September 28th showed 0.4% and 0.4%, and October 24th showed 1.2% and 0.8%.

The use of the concentrator resulted in a higher average temperature in the dryer in all cases except for July 16th on the top rack. Each of the three other drying trials exhibited larger temperature increases than July 16th when comparing the dryer coupled with the concentrator to the control dryer, yet had smaller reductions in drying time. This suggests that reducing relative humidity within the dryer plays a larger part in reducing drying time than increasing temperature.

Unfortunately, increases in solar radiation within the dryer due to use of the concentrator were not able to be accurately measured. With direct solar radiation arriving from above and radiation reflected from the concentrator arriving from below, coupled with scattering within the dryer, multiple pyranometers within each dryer would be necessary. Attempts to measure solar radiation, using one pyranometer per dryer in this study, led to highly variable results. Despite this, it is obvious that the addition of a concentrator, if positioned properly, will increase the exposure of the tomatoes to solar radiation.

The drying rates of each drying trial are displayed in Figs. 5–8. The dotted line labeled "10% moisture content" is the point in the trial where the tomatoes are considered sufficiently dried. In all cases, the tomatoes on the top and bottom drying racks of the solar dryer using the concentrator reached the 10% moisture content level before those in the control solar dryer without the concentrator.

Dry weight content of samples

Tomatoes used in drying trials on 7/16, 9/26, and 9/28 were determined using the vacuum oven to have dry weight contents of 5.62%, 5.61%, and 6.10%, respectively. The tomatoes from the 10/24 trial were determined by regression analysis to have a dry weight content of 7.82%.

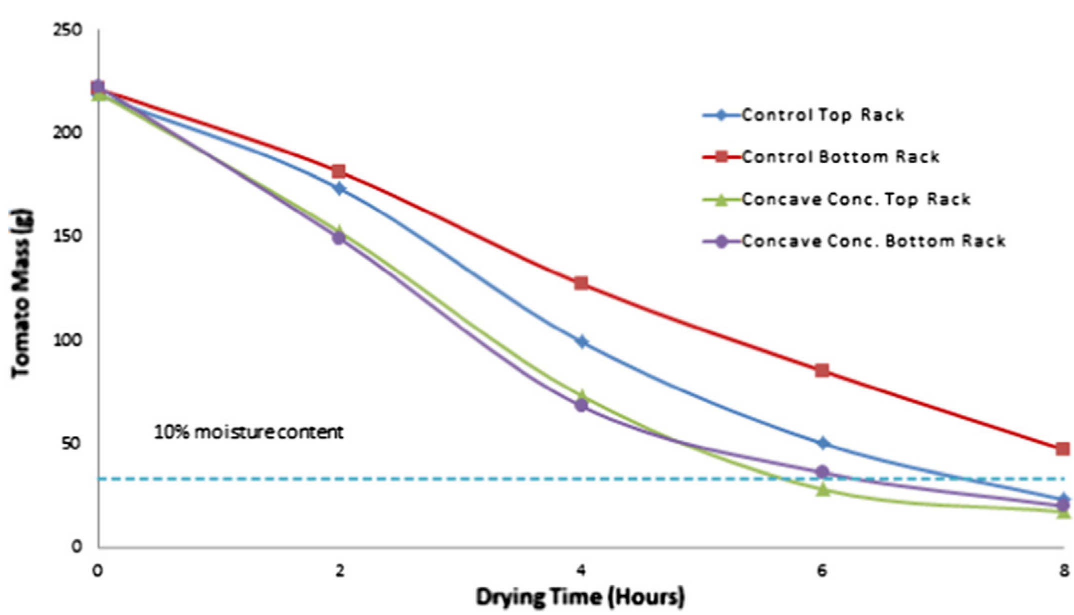

Fig. 5. July 16th reduction in tomato mass over time on the top and bottom racks of solar dryers with and without concave concentrators.

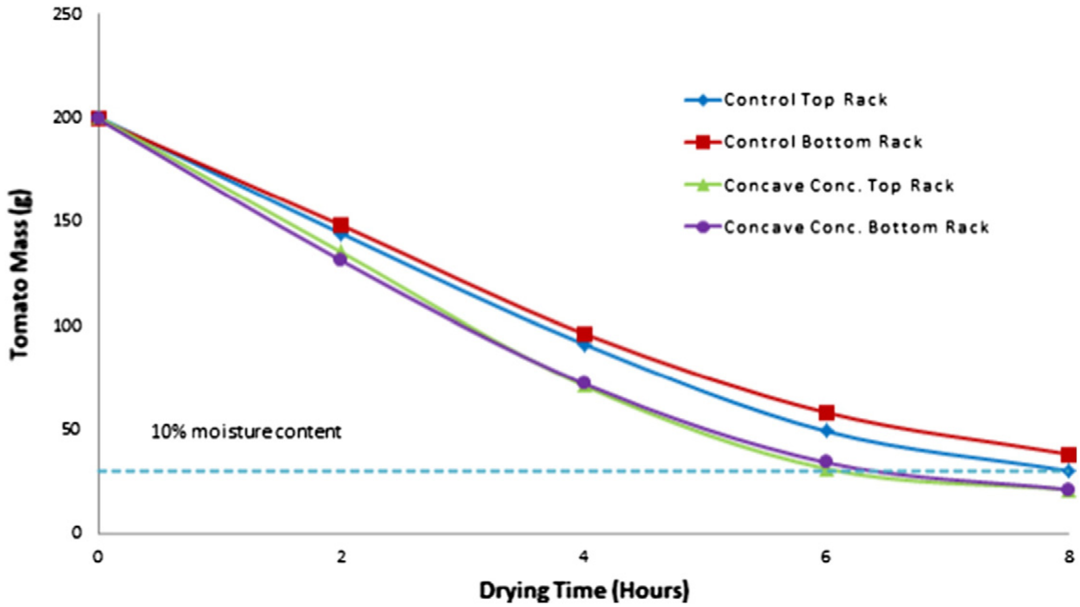

Fig. 6. September 26th reduction in tomato mass over time on the top and bottom racks of solar dryers with and without concave concentrators.

Tomato quality results

In three of the four days of drying trials (9/26, 9/28, and 10/24), pH, TA, color, Brix, lycopene, and vitamin C content in the dried tomatoes and fresh tomatoes were measured (Tables 3–7). For each day, there are five samples of tomatoes: bottom drying rack of the dryer with the concentrator, top drying rack of the dryer with the concentrator, bottom drying rack of the control dryer, top drying rack of the control dryer, and fresh. Samples were rehydrated to their original weight prior to analysis, therefore the quality components are compared on an equivalent weight basis to their fresh counterparts.

Table 3 illustrates that in every case, pH increased in the dried tomatoes compared to the fresh tomatoes for that day. The titratable acidity (TA) correspondingly decreased compared to fresh fruit in all but one sample. On September 26th, the fresh tomatoes had a pH of 4.17 and TA of 38%, and the four dried samples had pH and TA ranges of 4.23–4.40 and 31%–42%, respectively. On September 28th, the fresh tomatoes had a pH of 4.21 and TA of 42%, and the four dried samples had pH and TA ranges of 4.35–4.46 and 28%–31%, respectively. Similarly, on October 24th, the fresh tomatoes had a pH of 4.27 and TA of 41%, and the four dried samples had pH and TA ranges of 4.31–4.49 and 27%–31%. There was no difference between using, and not using, the concentrator as far as pH and TA are concerned.

Color changes are summarized in Table 4. Drying tomatoes in a solar dryer with or without the concentrator does not have an effect on the color of the tomatoes compared to the fresh ones.

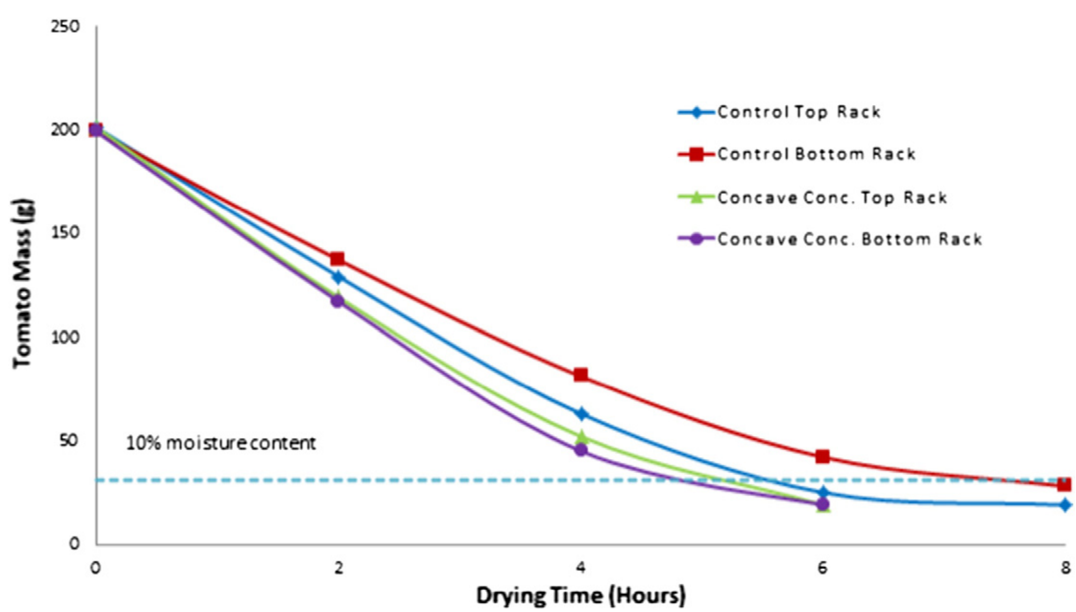

Fig. 7. September 28th reduction in tomato mass over time on the top and bottom racks of solar dryers with and without concave concentrators.

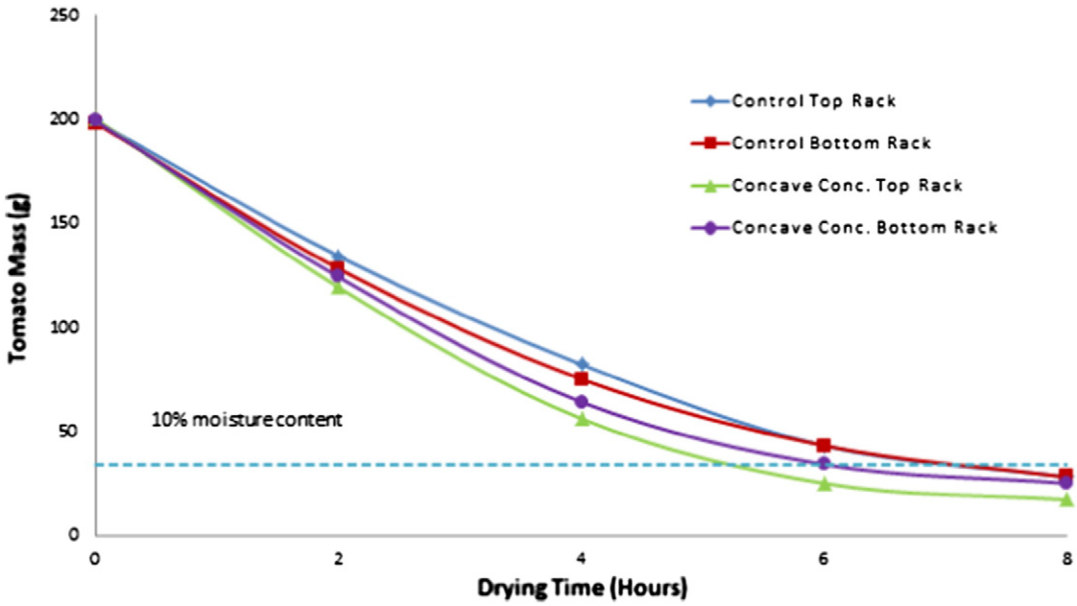

Fig. 8. October 24th reduction in tomato mass over time on the top and bottom racks of solar dryers with and without concave concentrators.

Brix, or the sugar content of the dried tomatoes, is reduced in every case as compared to the fresh (Table 5). On September 26th, fresh Brix was 6.7% and the range of the dried samples was 5.7%–5.9%. On September 28th, fresh Brix was 7.9% and the range of the dried samples was 6.4%–7.1%. On October 24th, fresh Brix was 7.3% and the range of the dried samples was 5.1%–6.9%. There was no difference in Brix between using, and not using, the concentrator.

Lycopene content (mg/kg fresh wt.) in dried samples decreased in every case compared to the fresh tomatoes (Table 6). It ranged between 61% and 93% of the lycopene content of fresh tomatoes. On September 26th, fresh lycopene content was 131 mg/kg and the range of the dried samples was 107–117 mg/kg. On September 28th, fresh lycopene content was 138 mg/kg and the range of the dried samples was from 114 to 129 mg/kg. On October 24th, fresh lycopene content was 159 mg/kg and the range of the dried samples was from 96 to 135 mg/kg. There was no difference in lycopene content between using, and not using, the concentrator.

Vitamin C content (μg/ml) also decreased in every dried sample compared to the fresh. It was reduced to between 49% and 93% of fresh tomato vitamin C content (Table 7). On September 26th, fresh vitamin C content was 320 μg/kg and the range of the dried samples was 209–297 μg/kg. On September 28th, fresh vitamin C content was 303 μg/kg and the range of the dried samples was from 186 to 230 μg/kg. On October 24th, fresh vitamin C content was 259 μg/kg and the range of the dried samples was from 128 to 207 μg/kg. There was no difference in vitamin C content between using, and not using, the concentrator.

Discussion

In a previous study where flat-plate solar concentrators were utilized for drying tomatoes, drying times were decreased by approximately 27% on perfectly sunny days, but only 3.1% and 7.4% while using various methods to simulate hazy conditions. The concentrators were repositioned by hand every hour to more accurately focus on the tomatoes (Stiling et al., 2012). In the current study, it was expected that by using curved reflective surfaces, drying times could be reduced by approximately the same amount of time, without the need to reposition the concentrator. This was indeed what we found, in fact given that the conditions tested in the current study were on average not perfectly sunny, the average drying time reduction of 21% with the curved concentrators was an improvement over the flat-plate concentrators.

In another study conducted by Scanlin et al. (1999), internal dryer temperatures were increased by 2.4–4.8 °C by the use of a flat-plate reflector positioned vertically above the solar absorber, rather than to the side of it. This increase was determined to be unnecessary since

Table 3
pH and titratable acidity in fresh and dried tomatoes on the top and bottom racks of solar dryers with and without concave concentrators.

Date	Sample #	Rack	Tomatoes	pH	%Titratable acidity	% of fresh pH	% of fresh TA
26-Sep	1	Bottom	Concentrator	4.23	0 42	101%	112%
	2	Top	Concentrator	4.33	0.37	104%	97%
	3	Bottom	Control	4.40	0.31	106%	82%
	4	Top	Control	4.32	0.37	104%	99%
	5	–	Fresh	4.17	0.38	100%	100%
28-Sep	6	Bottom	Concentrator	4.37	0.30	104%	71%
	7	Top	Concentrator	4.46	0.28	106%	66%
	8	Bottom	Control	4.35	0.31	103%	72%
	9	Top	Control	4.42	0.29	105%	69%
	10	–	Fresh	4.21	0.42	100%	100%
24-Oct	11	Bottom	Concentrator	4.31	0.29	101%	70%
	12	Top	Concentrator	4.49	0.27	105%	66%
	13	Bottom	Control	4.42	0.28	104%	69%
	14	Top	Control	4.44	0.31	104%	75%
	15	–	Fresh	4.27	0.41	100%	100%

Table 4
Color of fresh and dried tomatoes on the top and bottom racks of solar dryers with and without concave concentrators.

Date	Sample#	Rack	Tomatoes	L	a	b	a/b
26-Sep	1	Bottom	Concentrator	69.61	12.56	6.83	1.84
	2	Top	Concentrator	72.71	14.78	8.33	1.78
	3	Bottom	Control	71.56	14.23	7.53	1.89
	4	Top	Control	73.58	15.65	8.23	1.90
	5	–	Fresh	72.08	16.32	8.71	1.87
28-Sep	6	Bottom	Concentrator	69.66	11.14	6.24	1.78
	7	Top	Concentrator	70.49	11.86	6.27	1.89
	8	Bottom	Control	71.94	12.26	6.53	1.88
	9	Top	Control	70.15	11.55	6.14	1.88
	10	–	Fresh	69.33	13.20	5.97	2.21
24-Oct	11	Bottom	Concentrator	70.05	11.11	5.93	1.87
	12	Top	Concentrator	69.40	11.20	5.69	1.97
	13	Bottom	Control	68.43	10.76	4.85	2.22
	14	Top	Control	70.45	12.00	5.95	2 02
	15	–	Fresh	67.38	11.04	4.58	2 41

Table 6
Lycopene content of fresh and dried tomatoes on the top and bottom racks of solar dryers with and without concave concentrators.

Date	Sample-S	Rack	Tomatoes	Lycopene (mg/kg fresh wt.)	% of fresh
26-Sep	1	Bottom	Concentrator	117	89%
	2	Top	Concentrator	107	82%
	3	Bottom	Control	110	84%
	4	Top	Control	110	84%
	5	–	Fresh	131	100%
28-Sep	6	Bottom	Concentrator	114	82%
	7	Top	Concentrator	123	89%
	8	Bottom	Control	119	87%
	9	Top	Control	129	93%
	10	–	Fresh	138	100%
24-Oct	11	Bottom	Concentrator	96	61%
	12	Top	Concentrator	112	70%
	13	Bottom	Control	135	85%
	14	Top	Control	116	73%
	15	–	Fresh	159	100%

the dryer was already achieving temperatures suitable for fruit drying and pasteurization. These authors achieved further increases in temperature by applying angled reflectors on both sides of the absorber. It can be seen that in many cases, solar fruit dryers may already achieve temperatures suitable for properly drying fruit without the use of concentrators, although inefficient dryers such as those used in the current study can benefit from their use. Additionally, the increased temperature due to concentrator use in the current study did not negatively affect the tomato quality, likely because the Tanzanian style dryers couldn't reach optimal temperature requirements for drying tomatoes without their use.

There were several potential sources of error in these experiments. Most are associated with the inability to measure solar radiation accurately inside each dryer. There is no single location that can represent how much radiation is present on each tomato slice. There is also scattering within the dryer. Since the pyranometers were positioned to measure radiation from the sun above them, it is possible that a small amount of reflected solar energy from the concentrator originated from below the pyranometer. Further, the tomatoes on the top rack can shade some of the tomatoes on the bottom racks, so all the tomatoes are receiving slightly different amounts of radiation and are in turn drying at different rates. Lastly, due to a relatively short wire length of the measuring equipment, the two dryers could not be separated sufficiently to avoid shading from one dryer on the other at early and late parts of the day. For this reason, the east-most dryer dried slightly quicker during the morning hours, and the west-most dried quicker in the afternoon.

Table 5
Brix (soluble sugar content) of fresh and dried tomatoes on the top and bottom racks of solar dryers with and without concave concentrators.

Date	Sample#	Rack	Tomatoes	% Brix	% of fresh
26-Sep	1	Bottom	Concentrator	5.9%	88%
	2	Top	Concentrator	5.7%	85%
	3	Bottom	Control	5.3%	87%
	4	Top	Control	5.9%	88%
	5	–	Fresh	6.7%	100%
28-Sep	6	Bottom	Concentrator	6.8%	86%
	7	Top	Concentrator	6.4%	81%
	8	Bottom	Control	6.6%	84%
	9	Top	Control	7.1%	90%
	10	-	Fresh	7.9%	100%
24-Oct	11	Bottom	Concentrator	6.1%	84%
	12	Top	Concentrator	5.1%	70%
	13	Bottom	Control	6.5%	89%
	14	Top	Control	6.9%	95%
	15	–	Fresh	7.3%	100%

With the large size of the Tanzanian style dryer, it is very difficult to know where the best location to concentrate is, within the dryer. Much of the concentrated energy is likely passing through the dryer without interacting with the fruits or absorber plate. All of this energy is wasted. Depending on the size of the dryer, it may be unpractical to build a concentrator large enough to effectively increase radiation across the entire dryer and fruits. For this reason, it is recommended to use the concave concentrator with a wider, shorter solar crop dryer instead of the current solar crop dryer being used widely in Tanzania. Additional dryer improvements should also be made before using a concentrator. The north wall (when drying in the northern hemisphere) does not receive much direct solar radiation and in the case of the solar crop dryer used in these experiments, loses much heat through its near-zero insulated wall. To improve the dryer's function, this north wall could be insulated and covered with an additional absorber plate. This vertical plate could much easier receive the concentrated solar energy from the concave concentrator, which would further help reduce the drying rates in the tomatoes.

For highest quality, many studies, including Andritsos et al. (2003), recommend drying tomatoes at mild temperatures between 45 and 55 °C. Temperatures lower than this lead to longer drying times, increasing the risk of microbial activity. Higher temperatures can result in shell hardening, and can cause color and aroma quality losses (Andritsos et al., 2003).

Another study on pre-drying treatments of sun dried tomatoes showed that certain treatments, such as salt dipping and sodium metabisulfite dipping of tomatoes improved quality. Salt dipping as a pre-drying treatment led to reduced yeast counts in the dried product because salt is an effective antimicrobial. Sodium metabisulfite dipping improved color and also reduced yeast counts and off-odors (Latapi and Barrett, 2006). For these potential improvements in dried tomato quality, future work on this project could include pre-treatments of tomatoes. There are a number of concentrators and configurations that could also be tested on both direct and indirect solar dryers to see how they affect internal dryer temperature, relative humidity, radiation, and thus drying time and tomato quality. It would also be interesting to test a concentrator on various solar dryers to see which dryer design is most suitable for the addition of a concentrator.

Conclusions

The addition of the concave concentrator to one dryer reduced drying times by 21% on average as compared to the control dryer. This was accomplished by an increase in the internal dryer temperature and a lowering of the relative humidity, allowing for more favorable drying conditions. Although solar radiation incident on the tomatoes was also

Table 7
Vitamin C content in fresh and dried tomatoes on the top and bottom racks of solar dryers with and without concave concentrators.

Date	Sample #	Rack	Tomatoes	Reduced ascorbic acid conc. (μg/ml)	Dehydroascorbic acid conc. (μg/ml)	Vitamin C (μg/ml)	% of fresh
26-Sep	1	Bottom	Concentrator	11	197	209	65%
	2	Top	Concentrator	25	201	226	70%
	3	Bottom	Contro1	87	210	297	93%
	4	Top	Contro1	18	227	245	77%
	5	–	Fresh	132	189	320	100%
23-Sep	6	Bottom	Concentrator	0	204	204	67%
	7	Top	Concentrator	0	186	186	62%
	8	Bottom	Control	11	219	230	76%
	9	Top	Control	0	224	224	74%
	10	–	Fresh	63	240	303	100%
24-Oct	11	Bottom	Concentrator	17	190	207	80%
	12	Top	Concentrator	0	128	128	49%
	13	Bottom	Contro1	0	178	178	69%
	14	Top	Contro1	0	183	183	71%
	15	–	Fresh	53	206	259	100%

increased, it was unable to be accurately measured. The concentrating panels can be constructed by farmers with no technical construction skills, therefore can help increase dried fruit yield by increasing drying rate and decreasing spoilage. It was also shown that the use of a concentrator did not negatively affect tomato quality. Titratable acidity, pH, color, Brix, lycopene, and vitamin C were measured in dried samples with and without using a concentrator with minimal differences. The ability of rural farmers in developing countries to sell dried fruits, therefore, should not be affected by the use of concentrators.

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