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DESIGN, DEVELOPMENT AND PERFORMANCE TESTING OF A NOVEL INDIRECT SOLAR DRYER

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ABSTRACT – A simple and innovative indirect solar dryer composed of integrated solar collector and drying chamber partitioned with a black cotton cloth which serve as heat absorber was constructed and tested. To study the performance of the dryer at no load (no drying product) and full load (with drying product) conditions, measurements of total solar radiation on a horizontal plane, temperature and relative humidity of the ambient and the dryer as well as the solids moisture loss-in-weight data were made for an hourly interval. At no load, average temperature ranged from 45-103OC during the no airflow-no sunscreen and with airflow-no sunscreen set-up conditions and, 45-62OC under the airflow-with sunscreen condition. At full load, drying of mango halves was done using no airflow-no sunscreen, with airflow-no sunscreen and with airflow-with sunscreen set-up conditions with temperature ranges from 41-91, 30-70, and 22-65OC respectively. Moisture content was reduced from 84.5% to an average of 11% (w.b.), and also beta-carotene loss varied from 15-30% as compared to 44% in sun drying. An equivalent CO2 emissions of 0.01 kg/hr per trial was produced from the used of electricity in running the exhaust fans.

Keywords: Black cloth, sunscreen, integrated dryer, mango halves, beta-carotene, carbon emissions

INTRODUCTION

The escalating awareness of the environmental impact of using fossil fuel has caught the attention of many. Several alternative sources of energy such as wind and biofuel were explored, harnessed their potential and developed a non-polluting device for them. Aside from these, the energy of the sun was the most studied alternative source of energy because it is abundant, inexhaustible, and non-polluting (Akinola, Akinyemi, and Bolaji, 2006). It is, in fact, much preferred to other alternative sources of energy because it is plentiful in most part of the world. In many developing countries, the use of solar

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energy as a source of renewable energy has gained wide acceptance. However, too much usage of fossil fuel in developing countries to meet energy demand, might cause dramatic energy crisis in the future (GES, 2015). According to Ecowatch (2013), global energy use will continue to rise rapidly, with total world consumption jumping from 524 quadrillion British thermal units (BTUs) in 2010 to an estimated 820 quadrillion in 2040. Therefore, we have to anticipate this scenario by the non-stop innovation of sustainable solar energy technologies to harness the sun's enormous power, such as the solar dryer.

Many years ago, various designs of solar dryers from several researchers have been tested and have shown positive results compared to open sun drying and artificial dryings such as the work of Das and Kumar (1989), Esper and Muhlbauer (1998), Bala and Mondal (2001) and many others. Because of its potential, the solar dryer has gained wide acceptance and continuous innovations were being done to improve performance and enhance its cost- effectiveness. Solar dryers are generally classified according to the mode of heating as direct, indirect and mixed-mode. Among of these three, the direct-mode did not acquire extensive application in drying high valued crops due to excessive discoloration and nutritional loss of dried products (Bechoff et al. 2009 and Ndawula, Kabasa, and Byaruhanga 2004). Indirect mode solar dryer has received so much attention because of the quality of dried product that it can produce and its innovation was focused on the solar collector.

The drawbacks of the indirect solar dryer from previous studies usually occupy large space and complexity of design as compared to direct solar dryers because; the solar collector is a separate item as reviewed by El-Sebaii and Shalaby (2012). Although, direct solar dryer designs are simple, it has more disadvantages than indirect solar dryer in terms of capacity, efficiency, and quality of drying product (Chaudhari and Salve, 2014); hence, indirect solar dryers were given wide attention in innovation. Recent studies were focused on solar collector design. A solar assisted drying system was evaluated consisting of drying chamber, V-groove collector of 13.8 m2 area, and two variable-speed centrifugal fans (Eltief, Ruslan, and Yatim, 2007). A flat plate solar air heater designed to accommodate various storage materials under the absorber plate to improve drying process is connected to a cabinet acting as drying chamber (El-Sebaii, Aboul-Enein, Ramadan, and El-Gohary, 2002). Sand was used as the storage material and drying experiments were conducted with and without storage materials for different spherical fruits, such as seedless grapes, figs and apples, as well as vegetables, such as green peas, tomatoes and onions. Results showed a decreased in drying time by 8 hours when storage materials were provided. Some studies used other heat storage media such as water and rock. This idea was applied in the work of Chauhan, Choudbury and Garg (1996) (as cited by El-Sebaii and Shalaby, 2012) for crop drying. On the basis of analytical results, it was observed that the drying time is significantly reduced on using the water and the rock as storage media.

From the above-mentioned studies, a new and simple innovative indirect solar dryer was conceived avoiding any complexity in design. The unique idea featured in this design is that the solar collector and the drying chamber are integrated similar to a direct dryer structure but, a black cotton cloth separates them which serve as heat absorber and heating the drying chamber indirectly by the solar radiation. The primary objective of this study was to construct and test a novel design of indirect solar dryer. Specifically, the thermal performance of the solar dryer has to be evaluated under no load (no drying product) based on the temperature profile generated and at full load (with drying product) based on the final moisture content, beta-carotene loss, system drying efficiency and system drying rate using ripe mango halves. Economic analysis of the novel solar dryer was also considered.

MATERIALS AND METHODS

Design process

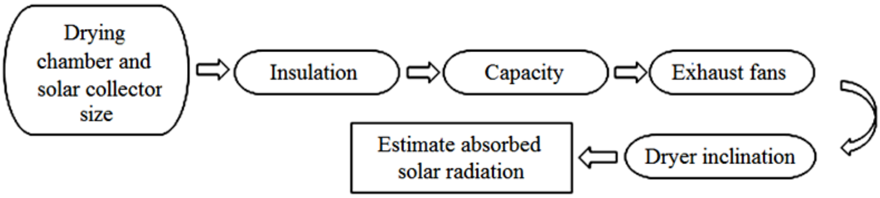


Fig. 1. Flowchart of the design process.

Figure 1 shows the sequence in the design of the solar dryer. The drying chamber was constructed to have a size such that a ¾-inch marine plywood was used. The length and width of the solar collector follow the geometry of the drying chamber. The solar collector was covered with transparent glass having 90% transmissivity. To have maximum absorbed solar energy by the black cloth, the solar collector together with the solar dryer was tilted equal to the latitude of the drying location. The drying chamber and the solar collector were insulated with two layers of aluminum foil separated by a ¼-inch air gap, to minimize heat loss. Aluminum foil has a high reflective property, and air gap has a very low thermal conductivity thus, making this combination a good insulation. The capacity of the solar dryer was based on the number of mango halves that could be arranged side by side in the drying tray. The number of days needed to dry this amount was computed by estimating the amount of solar radiation that can be absorbed by the solar collector according to Duffie and Beckman (1980) as follows,

$$S_H = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \frac{(1+\cos\beta)}{2} + \rho_g (I_b + I_d)(\tau\alpha)_g \frac{(1-\cos\beta)}{2} \text{ ----------- } (1)$$

where S_H is the hourly incident solar radiation that can be absorbed by the solar collector, I_b is the hourly beam radiation incident on a horizontal surface coming from the sun without having been scattered by the atmosphere (kJ/m^2), I_d is the hourly diffuse radiation incident on a horizontal surface coming from the sun after its direction has been changed by scattering by the atmosphere (kJ/m^2), R_b is the ratio of beam radiation on a tilted surface to that on a horizontal surface, $(\tau\alpha)_b$ is the transmittance-absorptance product for beam radiation, $(\tau\alpha)_d$ is the transmittance-absorptance product for diffuse sky radiation, $(\tau\alpha)_g$ is the transmittance-absorptance product for diffuse ground reflected radiation, ρ_g is the ground reflectance, $(1+\cos\beta)/2$ is the view factor from the collector to the sky, and $(1-\cos\beta)/2$ is the view factor from the collector to the ground. Summary of the estimated hourly-absorbed incident by the solar collector is given in table 1.

According to thermodynamics principles, the following equations will determine the number of days required to dry a predetermine amount of mango halves.

$$S_{day} = S_H \, x \, t_{hrs} \text{ ------------------------------------ } (2)$$

where S_{day} is the daily absorbed solar radiation, and t_{hrs} is the daily time duration.

Table 1. Estimated hourly-absorbed incident radiation by the solar collector.

HOUR	I_b MJ/m^2	I_d MJ/m^2	R_b MJ/m^2	θ deg	$(\tau\alpha)_b$	$(\tau\alpha)_d$	$(\tau\alpha)_g$	ABSORBED RADIATION			
								S_b MJ/m^2-h	S_d MJ/m^2-h	S_g MJ/m^2-h	S_H MJ/m^2-h
8-9	1.97	5.42	1.30	57	0.71	0.71	0.32	2.49	0.425	0.00308	2.900
9-10	2.06	5.73	1.23	44	0.67	0.71	0.32	2.59	0.449	0.00330	3.044
10-11	2.07	6.05	1.20	32	0.70	0.71	0.32	2.70	0.475	0.00345	3.180
11-12	2.13	6.37	1.18	24	0.71	0.71	0.32	2.79	0.500	0.00363	3.300
12-1	2.59	6.05	1.20	32	0.71	0.71	0.32	2.70	0.475	0.00345	3.180
1-2	2.10	5.73	1.23	44	0.70	0.71	0.32	2.59	0.449	0.00330	3.044
2-3	2.06	5.46	1.30	57	0.67	0.71	0.32	2.48	0.425	0.00308	2.916
3-4	1.97	5.42	1.54	70	0.45	0.71	0.32	1.94	0.425	0.00308	2.370
									Total S_{day}	23.934	MJ/m^2-day

$$Q_U = S_{day}\, A_C\, \eta \text{ ---------------------------------- } (3)$$

where Q_U is the useful thermal energy, A_C is the area of the solar collector (m^2), and η is the solar collector efficiency.

$$W_F = \frac{Q_U}{\left[C_{PF}\left(1-\frac{M_i}{100}\right)+C_{PW}\left(\frac{M_i}{100}\right)\right]\left(T_f-T_i\right)+h_V\left(\frac{M_i-M_f}{100}\right)} \text{ ---------------- } (4)$$

where W_F is the capacity of the dryer per day (kg/day), M_i and M_f are the fractional initial and final moisture content by weight (wet basis) respectively of the mango halves, C_{PF} and C_{PW} are the specific heat of drying product and water at 60^{O}F respectively.

$$t_{day} = \frac{W_{cap}}{W_F} \text{ ---------------------------------- } (5)$$

where t_{day} is the number of drying days.

The dryer was located in an open area where no tall trees or structure can hamper the solar radiation from 8 am to 4 pm. The space around the dryers was be free from any obstacles to allow good circulation of air. The dryer was tilted and oriented facing south when it is in the northern hemisphere to receive maximum solar radiaton according to Onigbogi, Sobowale, and Ezekoma (2012) (as cited by Ikrang, Onwe, and Onda, 2015). During night-time, any opening should be covered tightly to avoid reabsorption of moisture from the ambient air. When the dryer was tested at no load condition, only the temperature variations inside are measured as well as the ambient conditions and intensity of solar radiation. At full load test, mango halves taken from fully ripe mangoes are used and all drying parameters are measured at an hourly interval. Summary of the assumed and computed parameters to estimate the dryer capacity and drying time in terms of day are shown in table 2.

Table 2. Parameters used in the estimate of drying time and dryer capacity.

PARAMETER	MANGO	REMARK
	Value	
C_{PF}	3.8016 kJ/kg-^{O}C	Specific heat of drying product at 60^{O}C
C_{PW}	4.1843 kJ/kg-^{O}C	Specific heat of water at 60^{O}C
h_V	2358.5 kJ/kg	Latent heat of vaporization of water at 60^{O}C
T_i	29 ^{O}C	Estimated initial temperature of drying product
T_f	60 ^{O}C	Expected final temperature of drying product
M_i	81.4%	Initial moisture content of drying product
M_f	10-11%	Final moisture content of drying product
S_{day}	23.934 MJ/m^2-day	Daily absorbed solar radiation by the solar collector
η	30%	Conservative value of solar collector efficiency
A_C	1.3896 m^2	Actual solar collector area
Q_U	9984.4 kJ/day	Calculated useful thermal energy for drying per day
W_F	5.9 kg/day	Calculated weight of drying product per day
W_{cap}	16 kg	Estimated capacity of the solar dryer
t_{day}	3 days	Estimated total drying time

Philosophy of the innovation

The schematic diagram of the new solar dryer design showing the heating process and moisture removal is shown in figure 2. The new solar dryer design adopted the structural arrangement of a direct solar dryer, where the drying chamber and the solar collector are considered as single unit. The mode of heating the drying product is based on the concept of the indirect solar dryer where the drying materials are not heated directly by solar radiation. The solar collector of the new solar dryer design is made of transparent glass as covering and a black cotton cloth is provided 100 mm below it, which serves as a heat absorber. To employ indirect heating, the drying chamber which comprised the drying tray containing the drying materials, is constructed such that a black cotton cloth is above it with a gap of 100 mm. The transparent glass will allow the short wavelength (high energy) solar radiation but the black cotton cloth prevents the solar radiation reaching the drying materials. The black cotton cloth will continuously absorb heat from the solar radiation and reradiate it at long wavelength radiation (low energy) everywhere especially, to the drying materials. This long wavelength radiation cannot penetrate the transparent glass so it is trapped in the solar collector causing the solar collector to rise in temperature which is known as the “greenhouse effect”. To remove moisture during drying, four12-volts DC computer fans in series are provided at the converging nozzle at one end of the solar dryer. The series arrangement will produce a strong suction effect for an easy and fast rate of moisture removal.

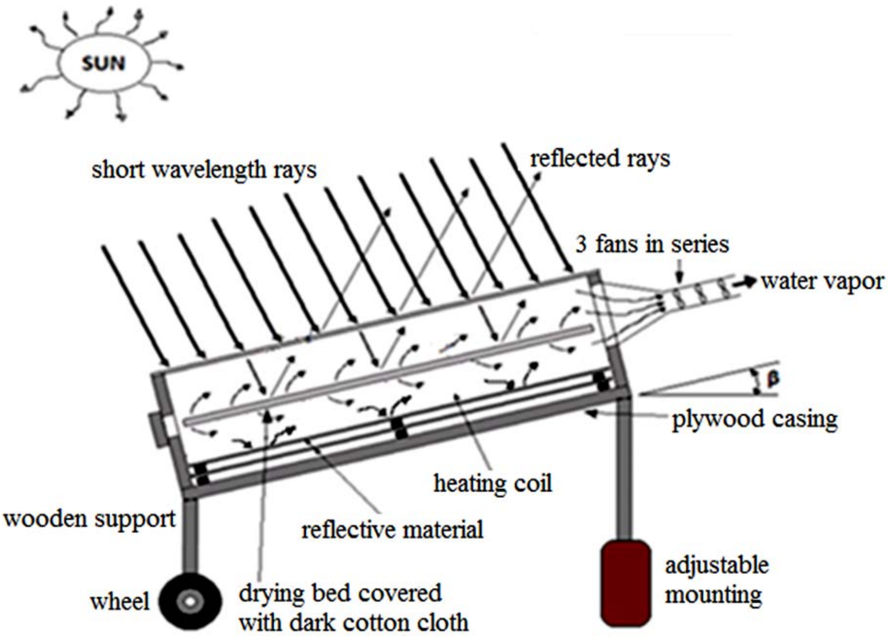


Fig. 2. Schematic diagram of the novel solar dryer showing the heating process of the drying product and its moisture removal.

Solar dryer

The summary of the materials required in the construction of the solar dryer and their specifications is shown in table 3. Marine plywood was chosen in constructing the solar dryer because it is easy to handle, strong and lightweight. The glazing material to cover the solar collector is an ordinary and low-cost transparent glass with 90% transmissivity. Heat absorber material is made of black cotton cloth. The drying tray is made of aluminum angle bar to form a rectangular shape and covered with aluminum mesh wire (coarse and fine). Locally available gypsum screws are used as fasteners. Two ordinary bicycle wheels are installed at the rear end of the dryer to make it mobile. Dimensions of the dryer are based on the concept that when the required material is cut into size, it will result to minimal waste.

Instruments and data collection

TENMARS mini pocket digital solar power meter model TM-750 with an accuracy of 10 W/m^2 installed on a flat surface adjacent to the solar dryer measures the hourly solar radiation flux incident on a horizontal surface. Lutron pocket type digital humidity meter model HT-305 measures the ambient temperature and relative humidity also in an hourly interval. Distribution of temperatures inside the dryer chamber was determined by measuring the temperature at extreme ends and at the center of the drying tray using glass thermometer with a scale range of -10 to $100^{O}C$ for an hourly interval. Simultaneously, Lutron digital anemometer meter model AM-4206 measured the exit velocity of gas coming out from the converging nozzle.

Table 3. Materials and specifications of the solar dryer.

PART	MATERIAL	QTY	DIMENSION
Drying chamber	¾-inch marine plywood	1	1930 mm long x 820 mm wide x 10 inches deep
Solar collector	¾-inch marine plywood	1	1930 mm long x 820 mm wide x 4 inches deep
Converging nozzle	¼-inch marine plywood	1	820 mm x 141 mm (inlet opening) and 141 mm 141 mm (exit opening) and 830 mm long
Drying tray	Aluminum angle bar and aluminum mesh wire	1	1900 mm long x 650 mm wide x 75 mm deep
Insulation	Aluminum foil		
Glazing	Transparent glass	1	¼ inch thick x 1930 mm long x 820 mm wide
Black cloth	Cotton	1	1930 mm long x 820 mm wide
Fastener	Gypsum screws		1 inch long
Roller Support	Wood and bicycle wheel	2	4 inches x 4 inches wooden support 510 mm bicycle wheel

Drying experiment

Lists of drying experiments are shown in table 4. It consists of No Load and With Load drying test. No load tests (without drying products) were conducted during selected days of February, June and July 2014 to determine the temperature profile of the dryer. The temperature profile was associated with the hourly solar radiation intensity, ambient condition and the effect of airflow and sunscreen. In the drying experiments, ripe mango halves were used as test samples. It was conducted during the month of February 2015, a period when mangoes are abundant. Weather condition during the tests varied from fair to intermittent cloudy sky and sometimes rain showers occurred in the late afternoon. Mangoes placed in a basket with a weight of 21 kgs were bought green from the source. Ripening was reduced to 3 days by placing a small amount of potassium carbide at the bottom of the basket beneath the mangoes to produce uniform ripeness. Ripe mangoes were washed with tap water, allowed to air dry, peeled with a sharp knife and sliced into halves removing the seeds. Mango halves with varying thickness ranging from 12 to 20 mm were then spread out side by side in the drying tray. The average weight of the mango halves per test is 9 kilograms. Sun drying was also conducted to compare the performance of the solar dryer. Moisture reduction was determined by weighing the representative sample every hour. The drying test stop when the weight of the representative samples became constant. Final moisture content and beta-carotene were analyzed by DOST laboratory using the oven method and HPLC respectively, an AOAC standard.

Table 4. Lists of drying experiments.

DRYING TEST	DATE	OBJECTIVE
No load (without drying product)	Selected days February, June and July 2014	Temperature profile of the solar dryer
With load (drying product is mango halves)	February 2014 and 2015	Compare the performance of the solar dryer with sun drying method base on the final moisture content, beta-carotene loss and system drying rate

Economic analysis

To study the performance of an investment, rate of return (ror) analysis was conducted. The value of rate (*i*) is determined by making the present worth (PW) of costs equal the present worth of benefits. It can be written as follows,

$$PW\ of\ costs = PW\ of\ benefits \quad \text{.......(6)}$$

The *PW of costs* and *PW of benefits* are given by the following equation,

$$PW\ of\ costs = C_{capital} + A_{costs}\frac{(1+i)^n-1}{i(1+i)^n} \quad \text{.......(7)}$$

$$PW\ of\ benefits = A_{benefits}\frac{(1+i)^n-1}{i(1+i)^n} \quad \text{.......(8)}$$

where A_{costs} is the annual costs and $A_{benefits}$ is the annual revenue.

Statistical analysis of data

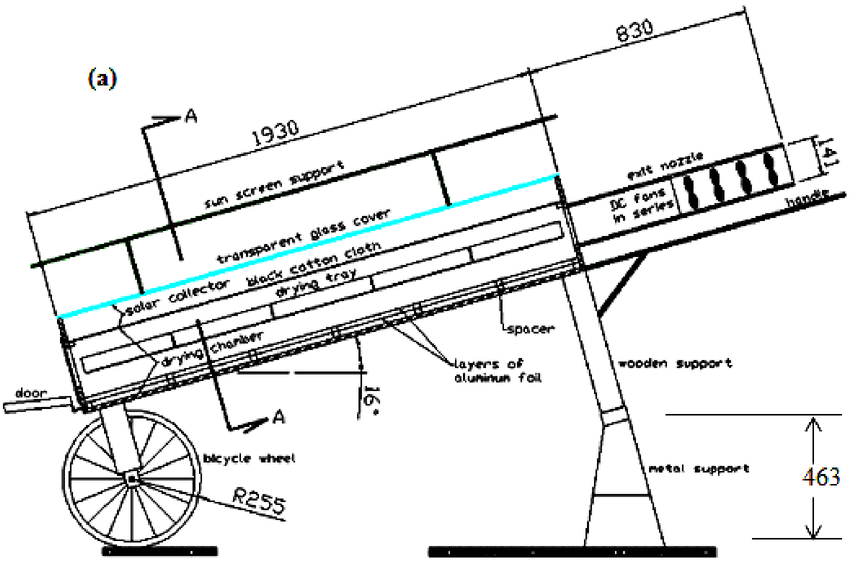
The relationships between the solar intensity, relative humidity, ambient temperature and the solar dryer temperature at no load and with drying product conditions were examined using Regression and Correlation analyzes. One-way ANOVA was used to determine if differences of temperatures (dependent variable) amongst the MP locations (independent variable) existed and Least Significant Difference was employed to isolate the differences. One-way ANOVA was also used to determine the differences of the drying methods (dependent variables) based on the performance parameters (independent variables). Analyzes of the statistical tools are at 95% ($p<0.05$) and 99% ($p<0.01$) confidence level using SPSS software.

RESULTS AND DISCUSSION

Construction of Solar dryer

A new indirect solar dryer was constructed and installed at the researcher's residence in Mapandan, Pangasinan (latitude of 15.9167^{O}N and longitude of 120.333^{O}E and at sea level). The solar collector and the drying chamber were integrated into one structural arrangement as shown in the sectional details of figure 3(a). The dryer was divided into three major sections; the upper, middle, and lower portions. The upper portion (UP) represents the solar collector, and the middle portion (MP) and lower portions (LP) represent the regions above and below the drying tray respectively, as shown in figure 3(b). The gross dimensions of the solar dryer were 2760 mm long, 820 mm wide, and a depth of 360 mm as shown in figure 3(a) and figure 3(b). The solar dryer structural frame, which includes the solar dryer box, the converging nozzle, and supports, were formed from ¾ and ½ inch marine plywood, and ordinary wood respectively. Rivets, wood glue, and metal screw were used as fastening materials. The solar dryer box comprising the solar collector and the dryer chamber has gross dimensions of 1930 mm long, 820 mm wide and 360 mm depth. Double layers of aluminum foil with 12 mm air gap in-between layer covers the inner surfaces of the solar box which serve as radiation shield and heat insulation. The solar collector has a depth of 4 inches and covered with a ¼ inch thick transparent clear glass. The drying chamber has a depth of 254 mm and housed an aluminum drying tray whose length is 1900 mm, 650 mm wide and a depth of 75 mm. The drying tray was made of 1” x 1” aluminum angular bar to form a rectangular shape as shown in figure 3(c). A 1½ inch aluminum flat bar was added on top of the angular bar all around the tray to form a total depth of 75 mm. The bottom part was provided with a fine aluminum screen as the top layer and a coarse one as support. The tray was subdivided into 10 compartments of equal sizes with the numbering of 1, 2, 5, 6, 9 and 10. A black cotton cloth was provided in-between the solar collector and the drying chamber to protect drying product from direct rays of the sun coming from the solar collector as shown in figure 3(a).

Two 510 mm diameter bicycle wheel were mounted at the rear ends to make it mobile and two 4” x 4” x 30” long wooden support at the front ends standing on a removable steel supports with a height of 463 mm making the solar dryer in an inclined position as shown in the figure 3(a). A converging nozzle made of ¼ inch plywood was provided which serves as an exit for vaporized moisture. Four 12 volt DC axial fans in series were provided inside the converging nozzle to facilitate the evacuation of vaporized moisture simultaneously, creating negative static pressure to accelerate vaporization process. A sunscreen support made of ¼” diameter steel bar was provided as support for the black polyester cloth when the solar collector is covered with it during high-intensity solar radiation especially between 9 AM to 3 PM to prevent the drying temperature goes beyond the recommended value. To monitor the temperatures at the different locations inside the solar dryer specifically in the middle portion, the solar box was provided with resealable holes for glass thermometer and humidity probe as shown in figure 3(d). Figure 3(d) also shows the solar dryer in a set-up position provided with sunscreen.



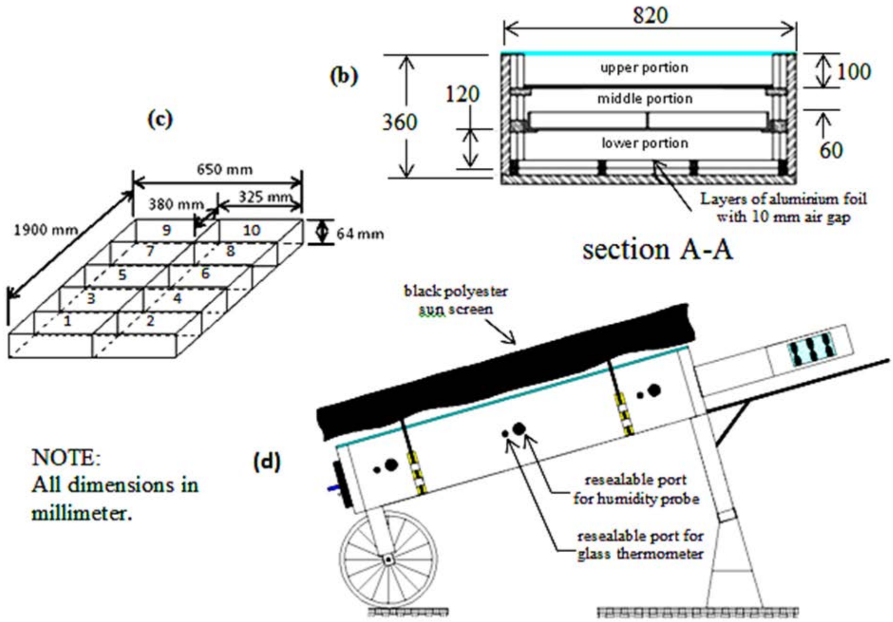


Fig. 3. (a) Side view details of the new solar dryer. (b) Details of solar collector at section A-A in set-up position. (c) Drying tray. (d) Side view of the solar dryer

During the no load test, the daily variation of the ambient condition and solar radiation for the selected days in February, June and July were plotted in figure 4. According to figure 4, the measured solar intensity recorded ranges from 137-1115, 27-1169 and 88-1195 W/m^2 during the test periods of February, June, and July respectively. The lower values were taken during the late afternoon when clouds cover the sky from moderate to heavy, whereas the higher values represent data between 11 am to 1 pm when the sky was clear and the sun's position was directly overhead the solar dryer. Maximum and minimum ambient temperatures were 36.4 and 25.5^{O}C respectively with corresponding relative humidity of 81.8% and 39.9%. Regression analysis showed that the intensity of solar radiation variation positively influence significantly the ambient temperature (F value = 14.6) but not the relative humidity (F value = 6.2). However, the ambient temperature has very strong influence on the relative humidity (F value = 106.8) with a negative correlation.

Temperature profile at no load

The variations of dryer temperature at no load condition can be observed in figure 5. Temperatures were measured at the middle portion (MP) of the drying chamber where the drying trays is located, specifically at the extreme ends of the drying tray MP 1&2 and MP 9&10 and at the midpoint, MP 5&6. At no airflow and no sunscreen set-up condition, maximum observed temperatures at locations MP 9&10, 5&6 and 1&2 were 103, 98, and 92^{O}C respectively with minimum values of 75, 69, and 62^{O}C correspondingly. With airflow but no sunscreen, maximum observed temperatures at same above-mentioned locations were 105, 101, and 98^{O}C respectively with minimum values of 41, 41, and 37^{O}C correspondingly while, with airflow and sunscreen, the maximum temperatures are 89, 84 and 85^{O}C with minimum values of 45, 45, and 45^{O}C in the same order. Although there are differences in the values of dryer temperatures from the different MP locations, results of statistical analyzes using ANOVA and LSD did not show any significant differences at alpha = 0.05 for every set-ups (no airflow-no sunscreen, with airflow-no sunscreen, and with airflow-with sunscreen). However, significant differences existed in the temperature variations amongst the different set-ups. The solar intensity influenced the dryer temperature significantly (F value = 8.8) with positive weak correlation at a significance level of 0.01.

From those figures mentioned above, it can be presumed that the dryer temperatures generated by the solar collector at different set-ups were sufficient for the purpose of mango halves drying.

Temperature profile at full load

The 1st trial in solar drying ripe mango halves was carried out on February 19, 2014 for four days. The 2nd and 3rd trials were conducted in the following year of the same month. No airflow and no sunscreen drying set-up was used during the 1st trial and with airflow and no sunscreen on the 2nd trial. Sunscreen was used in the 3rd trial only during high intensity sunshine hours. For qualitative analysis, sun drying was also conducted as the control. The mango halves have to be dried up to the final moisture content of 10-11% wet basis for safe storage (Akoy, Horseten, and Luecke, 2008). Weather conditions during the trials varied from fair to an intermittent cloudy sky with occasional rains.

Solar radiation intensity, ambient conditions (temperature and relative humidity), dryer temperatures and humidity at different locations (MP 1&2, 5&6, and 9&10) were recorded every hour. Variations of solar intensity and ambient conditions were plotted in figure 6. Ranges of ambient temperatures and relative humidity recorded during the consecutive 3 trials were 29-41^{O}C, 28-39^{O}C, 24-37^{O}C and 22.9-59.3%, 36.7-71%, 39.3-82.3% respectively. Graph of dryer temperature and relative humidity variations during the tests are shown in figure 7. Average recorded temperatures and relative humidity from the solar dryer in the order of trials 1, 2, and 3 ranges with values of 41-91^{O}C, 30-70^{O}C, and 22-65^{O}C and 12-67%, 45-93%, 45-83% respectively. The ranges of temperature during the 3rd trials were lower than in the 1st and 2nd due to the provision of airflow and sunscreen during high-intensity sunshine hours. The variations of the dryer temperatures during the tests were significantly influenced by the variations of solar intensity (F value = 89) with strong positive correlation (Pearson’s correlation = 0.66). Dryer relative humidity was significantly influenced by the dryer temperature (F value = 32.16) with negative correlation (Pearson’s correlation = -0.469). But no significant differences existed between temperatures at the different MP locations. This can be observed apparently from figure 7 where the behavior of MP curves almost overlap one another, especially in the 2nd trial when airflow was provided and in the 3rd trial when sunscreen was used during strong sunshine hours.

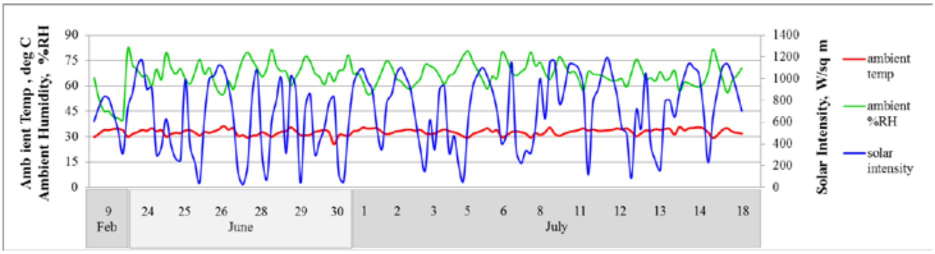


Fig. 4. Hourly variations of solar intensity and ambient condition during the No Load tests in February 8, June 24, 25, 26, 28, 29 and 30 and July 1, 2, 3, 5, 6, 8, 11, 12, 13, and 18.

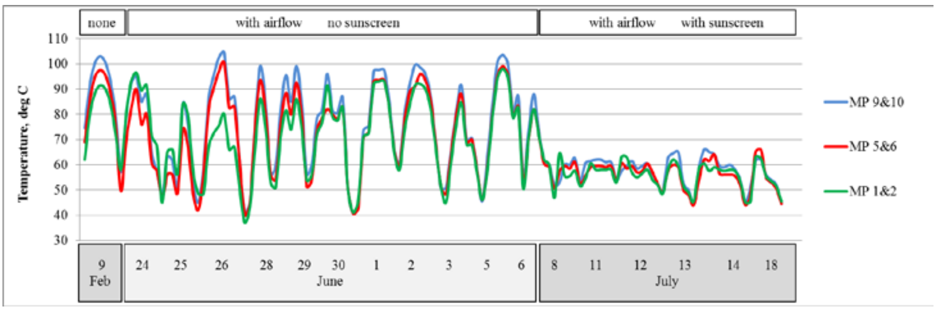


Fig. 5. Hourly variation of average dryer temperature at different MP locations in February 9 (no sunscreen-no airflow), June 24, 25, 26, 28, 29 and 30 and July 1, 2, 5, and 6 (no sunscreen-with airflow) and July 8, 11, 12, 13, 14, and 18 (with sunscreen-with airflow).

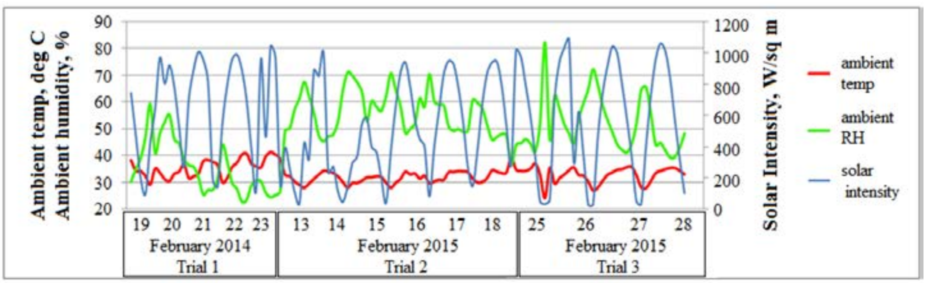


Fig. 6. Hourly variation of solar intensity and ambient condition during the drying of mango halves in February 2014 and 2015.

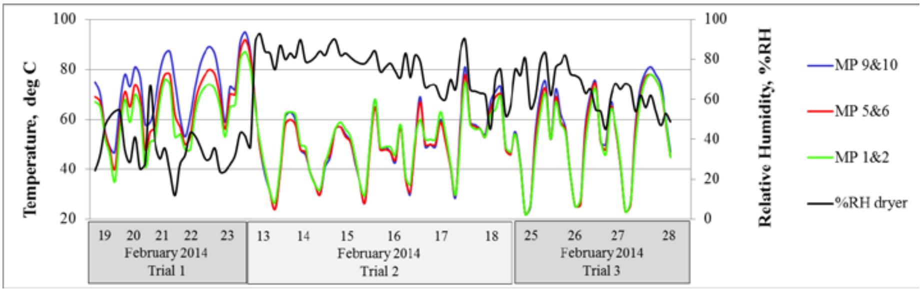


Fig. 7. Hourly variation of dryer temperatures at MP 1&2, 5&6 and 9&10 including the %RH inside the dryer during the drying of mango halves in February 2014 and 2015.

Moisture content and drying rate

The variation of moisture content with time is shown in figure 8 for the solar dryer and sun drying. Sun dying curves show almost linear behavior throughout the drying period with negative and steeper slope than the nonlinear curve of solar drying. The difference in their behavior can be accounted to the rate of drying that is faster in sun drying which is apparent in figure 9. ANOVA analysis confirmed this that significant difference existed in the drying rate between the drying methods at a significance level of 0.05. Desired final moisture content between 10-11% was attained in the solar dryer but not in the sun drying whose values ranged between 13-14%.

Quality of mango halves

Although, the solar dryer has slower drying rate, the fast drying rate of sun drying had caused surface hardening according to Barel (1998) (as cited by Zahouli et al., 2010) which resulted to inefficient moisture removal. This phenomenon can be related to the thickness of the samples before and after drying as shown in figure 10. Thicknesses of fresh mango halves ranged between 15-20 mm. Final thicknesses of dried samples ranged between 2-4 mm from the solar dryer which are on the average thinner than in sun drying. Browning and darkening in color was apparent in sun drying method than in solar drying, evidently shown in figure 11 due to direct exposure to ultraviolet rays coming from the sun. Color change of mango is significant when drying is too long as observed by Elamin (2014). Dried mango halves from sun drying are wrinkled but smooth surface was observed from solar drying. Average beta-carotene loss was lower in solar drying than in sun drying with values of 22% and 44% respectively. No significant difference was observed in the beta-carotene loss among the 3 trials using the solar dryer.

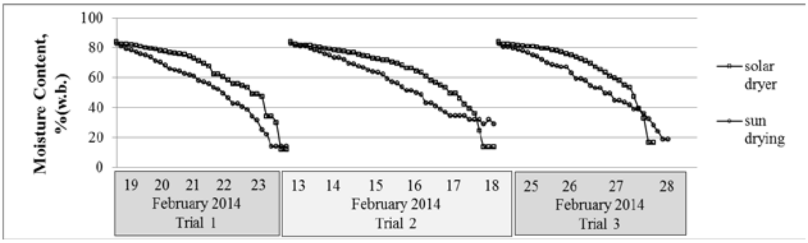


Fig. 8. Daily variations of moisture content during the 3 trials.

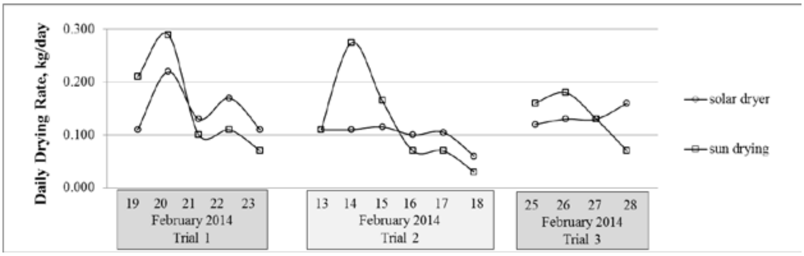


Fig. 9. Daily variations of drying rate during the 3 trials.

Improvements and drawback of the novel solar dryer

The novel solar dryer showed the following improvements: a) lesser beta-carotene loss compared to the visqueen-covered solar dryer made by Ndawula, Kabasa, and Byaruhanga (2004), b) thicker mango slices can be dried from 84.2% to 13.9% in 4 days compared to the solar tunnel studied by Bala and Janjai (2009) which dried thinner mango slices from 78.87% to 13.47% in 3 days, c) average daily drying efficiency of 25% can be achieved which is higher than the indirect solar dryer designed by Gatea (2011), and d) the average power consumption per drying test is 0.3 kWh which is equivalent to 0.1627 kg of carbon emissions and much lower than the drying system studied by Khalifa, Al-Dabagh, and Al-Mehemdi (2012). The only drawback of the novel solar dryer compared to other indirect solar dryer is the capacity which has only one tray. To increase the capacity, a multi-layer solar dryer in drying kokam fruits was tested by Sengar, Mohod, and Khandetod (2012) which could be applied to the novel solar dryer as an innovation.

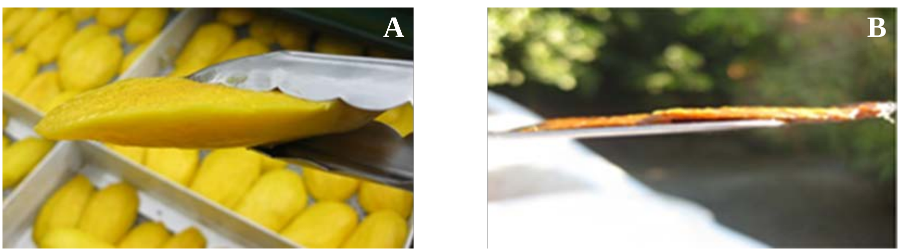


Fig. 10. Thickness of mango halve (a) before and (b) after solar drying.

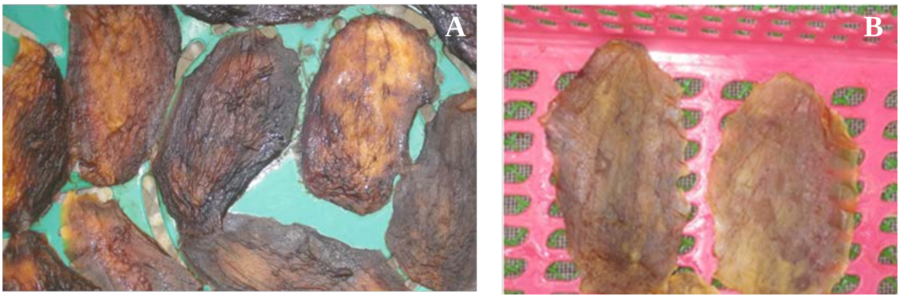


Fig. 11. Texture and color of dried mango halves after drying from (a) sun drying and (b) solar drying methods.

Rate of return

The solar dryer assumed to have a profitable life of 5 five years considering nowadays with continuous research, new technology may emerge in a short span of time. The yearly revenue was also assumed to be constant during the profitable life. The initial investment (capital cost) is the cost of constructing the dryer and the cost of drying are the costs of fresh product, electricity and wearable parts of the dryer. The labor cost was computed for an ordinary person who owns the solar dryer for business in the rural area for a drying period of 6 months starting November to May; the peak season of mango. The labor cost includes the ripening of mango, preparation of mango halves and drying process. The cost of electricity was based on the average electricity charge of 10 pesos pesos per kWh in the rural area. The solar dryer can consumed approximately an average of 0.7 kWh for one time drying at full capacity. The kWh consumption per year will be the number of drying times multiplied by 0.7 kWh. The maintenance cost was based on the yearly replacement of the four DC fans in series worth 250 pesos per piece. The number of drying times per year was assumed at 24 times making a total of 216 kilos of fresh mangoes equivalent to 118 kilos of dried mango halves per year for a solar dryer capacity of 9 kilos. Cost of dried mango at the source was assumed at conservative price of 300 pesos per kilogram, around sixty percent of the retail price of 500 pesos per kilogram in the market. Breakdown of capital costs and costs of drying are shown in table 5 and 6 respectively. Cash flow diagram is shown in figure 12. Equations 7 and 8 were used for the PW of costs and PW of benefits respectively. Both equations contained the same unknown, the variable rate i. To determine i, equation 6 was applied where the PW of costs and PW of benefits are equated. The result showed, i has an approximate positive value of 25.86%. This could be increased by selling the product directly to consumer.

Table 5. Material and construction costs of the novel solar dryer.

PART	COST (Php)
Dryer enclosure	4777
Drying tray	1824.5
Solar collector	1160
Fan	555
Bicycle wheels	975
Construction and installation	7600
CAPITAL COST	16892

Table 6. Yearly cost of drying and revenue.

ITEM	COST (Php)	YEARLY COST (Php)
Fresh mango	40/kg @ 216 kg/year	8640
Salary of worker	100/day x 8 days x 24 times/year	19200
Electricity	10/kWh x 0.7 kW/drying @ 24 times of drying	168
Maintenance	250/DC fan x 4	1000
	TOTAL YEARLY COST	29008
		REVENUE (Php)
Dried mango	300/kg x 118 kg/year	35400

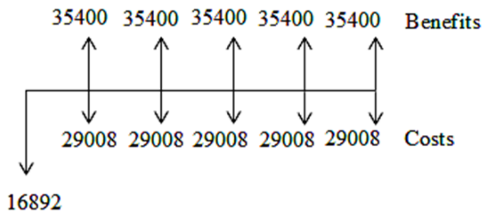


Fig. 12. Cash inflow and outflow diagram.

SUMMARY AND CONCLUSIONS

A new solar design was constructed and evaluated under no load condition to determine the temperature profile at 3 different set-ups: first, no airflow and no sunscreen, second, with airflow and no sunscreen, and third, with airflow and with sunscreen. The first and second set-up achieved a similar average maximum temperature of 104^{O}C and 89^{O}C for the third set-up; suitable for drying any agricultural product. The whole set-up of the solar dyer was also tested using mango halves as drying sample. The first, second, and third set-ups were applied to the 1st, 2nd, and 3rd trials respectively. The provision of airflow and sunscreen can maintain low dryer temperature even at strong sunshine hours and can achieve better quality of drying. In comparison with sun drying, the solar dryer was better in achieving the desired final moisture content with lower beta-carotene loss and better surface color. Due to this valuable information the following opinions are recommended for attention in using this novel solar dyer.

a) To produce lesser browning, the drying time must not exceed 2 days because browning starts to accelerate beyond this. To achieve shorter drying time, thin slices of fresh mangoes in the range of 3-5 mm are desirable.
b) Beta carotene loss can be greatly minimized by providing sunscreen between 10 AM to 3 PM to maintain the temperature range between 40 to 50^{O}C.

STATEMENT OF AUTHORSHIP

The first author conducted the literature research, prepared the conceptual framework, performed the experiments and undertook the preparation of the manuscript. The second and third authors made important recommendations in the conduction of the research, identified important issues and reviewed the paper

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