International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Development and Assessment of a Mix-Mode Rack-Type Passive Vegetable/Fruit Solar Dryer

Orkuma J. G[1]., Samuel, D. A[2], Eziefula B. I[3] and Okoro, O.M[4]

[1] Department of Agricultural and Biosystems Engineering, Joseph Sarwuan Tarka University, Makurdi-Nigeria.
[2]University of Suffolk, UK.
[3] Chevron Nigeria.
[4] Schlumberger Turkey.

DOI : https://doi.org/10.55248/gengpi.5.1224.0216

ABSTRACT

A mix-mode solar dryer which incorporates a flat plate collector into a framed-rack dehydrator glazed with polythene was developed to address the difficulty encountered in drying tomatoes during bumper harvest times in Zaria, Nigeria. The evaluation results of the rack dryer using 10 kg of fresh tomatoes revealed a dry rate of 0.71 kg/hr and drying efficiency of 65.90 % when dehydrating tomatoes from an initial moisture content of 94 (% wb) to a final moisture content of 4.25 (% db). The efficiency of the dryer indicates its suitability for crop drying especially fruits and vegetables, with high moisture contents. This dryer will find great application in households and among operators of restaurants who can dry and store tomatoes hygienically within two days in batches for use during scarce periods.

Keywords: Development, evaluation, mix-mode, passive, vegetable/fruit, rack solar dryer

1. Introduction

Agricultural production in Nigeria is location specific, with 80% of the total production output coming from rural peasants dwelling in village with inadequate processing facilities and poor infrastructure across the country (Kolade & Harpham, 2014). Most of the farmers are illiterate with small holdings and poor finance and thus, their energy requirement for basic crop preservation is open sun drying (OSD). Common crops such as cereals, root and tubers, fruits and vegetables are usually harvested at high moisture content, these crops usually experience some internal physiological activities due to enzymatic reaction and are easily infested by microbes. Caking, moulding, sprouting and insects' infestation constitute problems at high moisture contents as most microbes, responsible for crops spoilage, require moisture to thrive and carry out their activities, this necessitates the need for dehydration among other considerations to preserve the crops. The OSD method is simple and somewhat rudimentary but considerably effective, as basically, crops are spreads on trays, mats, the bare ground, road shoulders of motor ways, surfaces of disused motor ways or raised platforms, often without pretreatment, for the sun and stream of ambient air current to dry them so that they can be stored for later use. Little capital is required on equipment expenditure but the process is labour intensive and inefficient. Diverse products are dried using these simple techniques. Moreso, there is no major social problems with the acceptance of OSD crops or their use by the local population for consumption. However, there are many technical and health problems associated with this basic drying process, including but not limited to long dry-times, cloudiness and rainfall, insects' infestation and high level of dust and atmospheric contamination as well as intrusion from rodents and humans. Fruits and vegetable are characterised by high moisture contents which impose greater difficulty in drying them (Arah *et al*., 2014), particularly tomatoes (*Solanum lycopersicum*) with 94 % moisture content (Eke, 2014). Tomatoes is cultivated across all the vegetational belts of Nigeria, with ripples of huge annually harvest which ranks the country second, after Egypt, as the largest producer of the fruits in Sub Saharan Africa (Ogunsola& Ogunsina, 2021). Annual estimated yields indicates that about 1.8 billion kg is produced per annum, however, over half of the yield is loss, postharvest, due to lack of know-how, low investment in processing and lack of institutional support (Bada et al., 2021). Consequently, farmers and end users are only able to dehydrate 50 kg of the tomato fruits, using OSD method, in a process that spans 5-10 consecutive days, based on climatic conditions, during harvest periods (Eke, 2014). The demand for these open sundried tomatoes, which is characterised by dark unsightly colour with impaired taste and flavour, is usually high during off-season periods among operators of hotels, restaurants and households. This necessitates the need to develop a cheap, simple mix-mode passive solar dryer to address the problems associated with OSD. The broad objective of this study is to develop, and evaluate the performance of a mix-mode rack-type passive vegetable/fruit solar dryer.

2. Materials and Methods

2.1 Determination of collector plate area

Ten kilograms of tomatoes were used for determining the area of the collector plate. The dry matter of 10 kg of tomatoes was calculated using equation;

$$D_m = W_t - \frac{W_t M_i}{100} \qquad (1)$$

Where; D_m - dry matter of tomato (kg), W_t - weight of fresh tomatoes (10 kg), M_i - initial moisture content of fresh tomatoes, (94 %) wet basis (wb).

$D_m = 10 - 10 \times 94/100 \ = 0.6$ kg

The quantity of water to be removed in drying 10kg of tomatoes from initial moisture content of 94% to 6% moisture content wet basis was determined with equation 2;

$$W_r = \frac{(MC_{id} - MC_{fd})D_m}{100} \qquad (2)$$

Where; W_r – quantity of water to be removed, kg, MC_{id} - initial moisture content of product (%) dry-basis, MC_{fd} - final moisture content of product (%) dry-basis (db)

The moisture content (MC_{db}) dry-basis was evaluated with equation 3 (Itodo *et al.*, 2002);

$$MC_{db} = \frac{100 MC_{wb}}{100 - MC_{wb}} \qquad (3)$$

Where; MC_{db} - moisture content (% db), MC_{wb} - moisture wet-basis (% wb).

$$MC_{id} = \frac{100 \times 94}{100 - 94} = 1566.67\ \%$$

$$MC_{fd} = \frac{100 \times 6}{100 - 6} = 6.38\ \%$$

Therefore,

$$W_r = \frac{(1566.6 - 6.38) \times 0.6}{100} = 9.36\ kg$$

The useful energy required to evaporate 9.36 kg of water was estimated using the sensible heating equation (Fekadu & Subudhi, 2018);

$$E_{eg} = W_{tom} Cp_{tom}(T_2 - T_1) + L_r W_r \qquad (4)$$

Where; E_{eg} - Collector useful energy gain (KJ), W_{tom} - Weight of tomatoes to be dried (10kg), CP_{tom} - specific heat of tomatoes, 3.98 KJ/Kg °C (Yin et al., 2022), T_1 - ambient air temperature, 30 °C (mean annual temp. Ahmadu Bello University, Zaria Metrological Station), T_2 - dryer air temperature, 55 °C degree (Purusothaman *et al.*, 2019), L_r – latent heat of vaporisation of water at temperature T_2, 2260 KJ/Kg (Datt, 2011), W_r - weight of water to be removed, 9.36 kg.

$$E_{eg} = 10 \times 3.96\ (55 - 30) + 2260 \times 9.36 = 22148.60\ KJ$$

The area of the collector was estimated using the useful energy gain equation 5 (Bhatia, 2014);

$$A_c = \frac{Q_u}{F_R \alpha_e I_i} \qquad (5)$$

$$Q_u = \frac{E_{eg}}{t} \qquad (6)$$

Where; A_c – area of flat plate collector (m^2), Q_u - collector useful energy (kJ), R_f - heat removal factor, approximately 0.7 for air cooled collector (Jeffery and Brownson, 2014), α_e= effective transmittance -absorbance product, 0.7 for single layer of transparent glazing and black painted surface (Eke, 2013), I_i incident solar radiation, W/m^2, approximately 420 W/m^2 for Zaria in the month of November (Eke & Arinze, 2011), t – time required to dry tomatoes to equilibrium moisture content, days.

A drying period of four days was assumed and the amount of heat energy needed during the drying process was computed as;

$$Q_u = \frac{22148.60}{4} = 5537.15\ kJ/day$$

Considering 8 hour of sunshine per-days, the amount of heat energy need become;

$$Q_u = \frac{5537.15}{8} = 692.14\ kJ/hr$$

The energy requirement per-seconds becomes,

$$Q_u = \frac{692.14}{60 \times 60} = 0.192\ kJ/s$$

The energy requirement in wattage becomes

$$Q_u = 1000 \times 0.192 = 192.26\ w$$

$$A_c = \frac{192.26}{0.7 \times 0.7 \times 420} = 0.93 \sim 1.00\ m^2$$

Since the dryer would be operated on the mixed -mode principle, it was assumed that the collector - plate should provide 70 % or 15504.02 kJ of the total (22148.60 kJ) energy requirement for drying the 10 kg of tomatoes from an initial moisture content 94 % to a final moisture content 6 %, wet-basis respectively, while the framed-rack dehydrator were the drying crops would be heated directly by solar radiation passing through the glazed rack would provide 30% or 6644.58 kJ of the remaining energy requirement. Hence the area of the collector-plate was designed based as 0.7 m^2 of the required total area of 1 m^2.

2.2 Description of the mix-mode passive solar dryer

The 20 kg solar drying system consist basically of two components coupled together, viz: the flat-plate collector and the framed-rack dehydrator for placement of the drying crops based on the thin layer drying approach. The system was constructed in the workshop of the Agricultural Engineering Technology Programme of the Samaru College of Agriculture, Ahmadu Bello University. Zaria, Nigeria.

The dryer was designed to operate on the mixed -mode principles by using direct and indirect solar radiation for heating and drying fruits and vegetables. In the direct heating mode, the vegetables that are placed on trays, inside a framed-rack dehydrator, receive direct beamed solar energy through the glazing covering the four sides of rack to heat the moisture inside the fruits which is evaporated and dissipated through the air vents on the back of the dehydrator. The indirect heating is realized through the incorporation of a flat plate collected attached to the base of the framed-rack dehydrator where air is heated and directed through the drying beds of the dehydrator. The flat plate solar collected is famous for its capability to trap both the beamed and diffuse components of the solar radiation even on cloudy days which made it suitable for this design (Itodo *et al.*, 2019).

The flat-plate collector

The flat-plate solar energy collector was made from 5 cm^2 afara wooden planks and framed into a rectangular structure using 5 cm nails. The length of the structure was 65.4 cm wide by 11cm high. The width was 74.9 cm long and 6 cm high. The difference between the height of the length and that of the width 5cm. The level end of the structure was fastened with 1 cm thick 50.7 cm by 71 cm plywood sheet to form the base. Wood shavings to a thickness of 6 cm were filled into the base to the height of the width forming planks to provide insulation and a 0.8 cm thick black corrugated metal roofing sheet was fastened over the wood shavings. A clear 0.2 cm polythene material was suspended and fastened on top of the length forming planks of the rectangular structure and held in place firmly using nails and wooden battens. The plenum -space between the collector plate and the polythene glazing- was 5 cm based on the recommendation Krishna and Rajev (2016) for optimal collector plate performance. One end of the flat plate collector was fixed with wooden legs 11cm high and the other end was connected to the space provided on the front side of the framed-rack dehydrator.

The framed-rack dehydrator

The framed-rack was also constructed from the same 5 m^2 afara wood for strength and durability into a

trapezoid as recommended by Purusothaman and Valarmathi (2019) using nails. The rear side of the trapezoid measuring 80 cm wide by 91 cm high has two openings measuring 3 cm high x 66 cm long, 29 cm apart on the rear covering plywood. The first opening is 39 cm from the base of the plywood immediately above first two layers of crop racks to facilitate the dissipation of moisture laden air from the dryer to the surrounding. The front side of the trapezoid was 80 cm wide by 72 cm high and shorter than the rear side by 19 cm. An opening, that is the rack plenum, was made 10.9 cm high x 74.8 cm wide on the base of the front side, 24 cm from the ground level for coupling the collector-plate. A door 73 cm wide by 44 cm high was fixed above the rack plenum by means of hinges and screws. The front and rear sides were joined together by five pieces of 45 cm long planks beginning from 24 cm above the ground level, placed 15 cm above each succeeding wood, on both flanks.

Four rack rails measuring 71.8 cm long by 79.8 cm wide were framed to hold the wooden trays for placing the tomato fruits. The first layer of the crossed woods forming the base of the trapezoid was covered with 1.5 cm thick sheet of plywood 24 cm above the legs from the ground level. The tops of the front and rear sides of the cuboid were joined by two pieces of 57 cm long planks slanting at an angle 19° to the horizontal and the whole wooden components forming the interior of the cuboid were painted with a selective black paint to enhance the adsorption of solar radiation. The front side, top and the flanks of the dehydrator were covered with 0.2 cm thick sheet of clear polythene glazing to maximize the collection of the beamed and diffused radiation and allow for the direct heating and drying of in-situ fruit/vegetable crops.

The study area is Zaria on latitude 11:11" N and so the collector-plate and the top side of the framed rack were inclined at 19° to the horizontal for maximum collection of solar radiation. Iordanou and Apostolidou (2013) recommended that collector-plates should be inclined at the angle of the latitude of their location plus or minus (± 15°) fifteen degrees for maximum reception of solar radiation respectively. So, 8° or about half of the plus 15° for was added to the latitude of Zaria to arrive at 19° to provide a premium for all season drying.

2.3 Experimental Setup and Data Collection

Instrumentation

An N filled Mercury in-glass thermometer of ranges – 5 to 300 °C were used for temperature measurement. The temperatures recorded during the testing were ambient air temperature, collector-plate outlet temperature and the core temperature of tomato slice samples of each rack and control as well as dehydrating rack vent outlets temperatures. The wet wick dry and wet bulb mercury-in-glass thermometer was used for humidity measurement. A digital hand-held wind vane anemometer held on top of the dryer was use for measuring wind speed and a digital HAENI solarimeter (Delta 118 model) was used to measure total solar irradiance on the surface of the flat-plate collector. Moisture content determination was based on the gravimetric method (ISO14242/2, 2000) using a Thermo 3510 laboratory gravity oven and a WT-X WANT (500 - 0.01 g) electronic balance and glass desiccators

Experimental Procedure

The solar drying unit was set-up as shown in Figure 1 and Plate 1 facing southward and the tests was conducted on 11^{th} -13^{th} October, 2023. During the test, freshly harvested red tomatoes were procured from a farm close to the experimental site and thoroughly washed with clean water and sliced into 15 mm thickness rings. Two and half kg of the tomatoes were placed on each of the four racks in the frame dehydrator and 1 kg was place outside as control. Thirteen laboratory thermometers were instrumented to monitor temperatures. The first was to monitor the collector plate outflow temperature, two each, were fixed in the core of the sliced tomatoes sample on each of the four racks in the dehydrator and the control and another two were place on each vent of the dehydrator. A wet and dry bulb temperature was placed in a shade to monitor atmospheric humidity. The solarimeter was placed slanting on the glazing of the flat plate collector to measure irradiance and the anemometer was held out above the dryer in the wind direction to measure the wind speed during the periods of taking readings. The climatic and dryer factors were recorded hourly from 8:00 am to 6:00 pm daily and the crop moisture content during two hours interval by removing two tomato samples from each rack and from the control for moisture content determination.

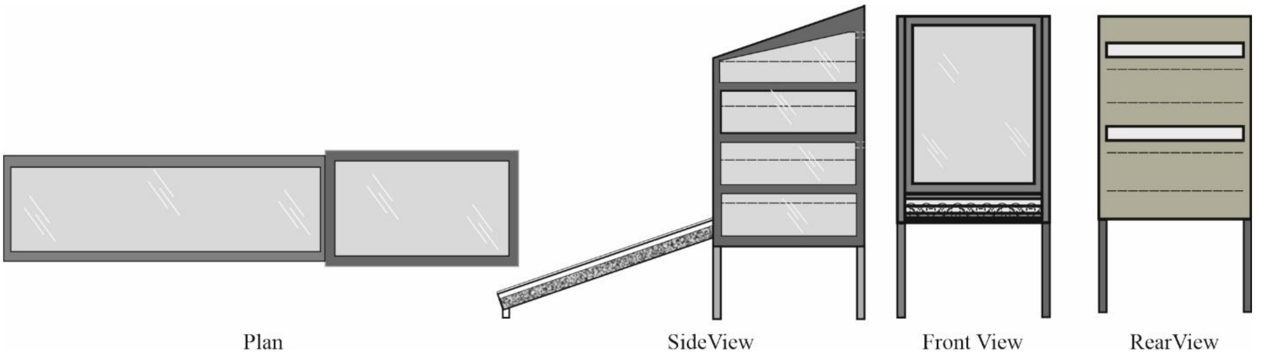

Figure1: Orthographic View of Solar Fruit/Vegetable Dryer

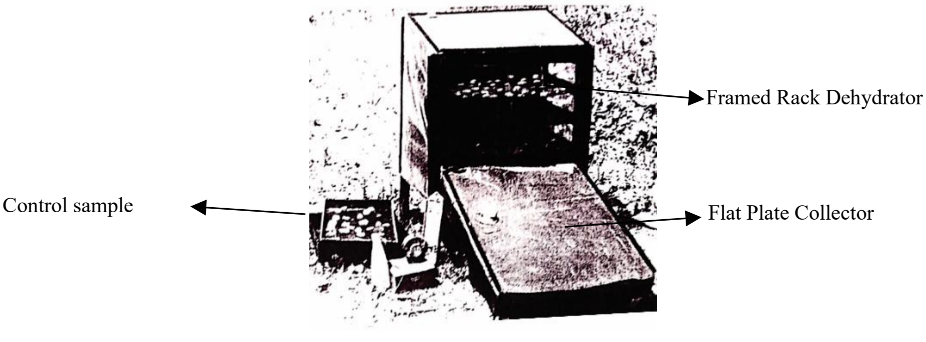

Plate 1: Rack Type Passive Solar Vegetable Dryer

2.4 Performance Evaluation and Data Analysis

The performance of the solar dry was evaluated by estimating the dryer efficiency using equation 7;

$$S_f = \frac{L_r W_r}{I_d A_{ce} t} \times 100 \qquad (7)$$

Where; S_f - system drying efficiency (%), L_r – latent heat of vaporisation of at 35 °C, 231580 KJ/Kg (Kaltiya *et al*, 2014), W_r - weight of water to be removed (9.36 kg), I_d - average daily solar irradiance on collector plate (480.81 Wm^2), A_{ce} – effective collector area (1 m^2), t – drying time, 19 hr (8 daily drying hour for 2 days plus 3 hr on the third day), $19 \times 60 \times 60 = 68{,}800$ sec. Therefore, $S_f = 65.91$ %.

3.0 Results and Discussion

Table 1 is the summary of parameters recorded during the experimental evaluation of the mix-mode passive solar rack dryer. The recorded mean dryer temperature was 35.56 °C and 8.56 °C (31.70 %) above the average ambient temperature of 27.00 °C (Figure 2). Eke (2014) reported a similar temperature value of 30.13% above ambient temperature for a metal solar dry for the same location. The dry temperature peaked at 12 noon and matained a plateaux of 44 - 46 °C uptill 3 pm (2 pm GMT) on the first experimenetal day. This was indicative that the passive rack dry showcased a higher drying performance over the control, due to the combined effects of the direct and indirect heating and conversion of the solar infrared radiation into heat energy, by the glazing on the dehydrator and collector plate. The tomatoes dried within the solar dryer were observed to dry faster than the control sample despite the continuous effect of wind and relative humidity over the control throughout the nights of drying.

The mean dryer and ambient relative humidities were 8.30 % and 21.67 % respectively. The low relative humidity of the dry can be attributed to the fact that, as the dryer air temperature was elevated, its relative humidity decreases and its moisture adsorbent profile increased (Figure 3). This enables the rapid heating and evaporation of the crop internal moisture and its subsequent adsorption and drying of the crops at a faster rate than OSD. Similar low humidity profiles for solar dryers have been reported (Eke, 2014; Aliyu *et al*., 2013; Itodo *et al*., 2002). Figure 4 is the drying curves of the tomato fruits and its shows a gradual decrease in the moisture content of the tomato samples in the solar dryer from 9 am until, then a rapid decrease from 2 -3 pm, indicating that dry was faster when the sun was overhead. The dry was able to dry 10 kg of tomato from an initial moisture content of 94 (% wb) to a final moisture content of 4.25 (% db) in 14 hours, spanning a time period of two drying days (8 am – 6 pm). Whereas, the moisture content of the control samples was at 9 (% db) at the end of second drying day. The dying rate of the dehydrator was 0.71 kg/hr and the drying efficiency was 65.90 %. The control tray had wind losses of 34 % with black spots and dust, observed on the surface of the tomato samples. On the other hand, the tomato samples in the rack dryer were dust free and maintained a bright red-orange colour and appealed to the eyes sight.

Table 1: Summary Statistics of Evaluated Parameters

			Humidity (%)		Temperature (°C)		
Statistics	**S_f (%)**	**Wind Speed (m/s)**	**Dryer**	**Ambient**	**Dryer**	**Ambient**	**Irradiance (Wm^2)**
Max.	82.01	5.00	12.71	31.00	47.00	32.00	830.00
Min.		0.10	5.20	16.00	21.00	19.00	72.00
Mean		2.39	8.30	21.67	35.56	27.00	480.81
Std. Dev.		1.45	0.48	1.05	2.07	1.07	271.12
Std. Error		0.39	2.05	4.47	8.79	4.52	63.90

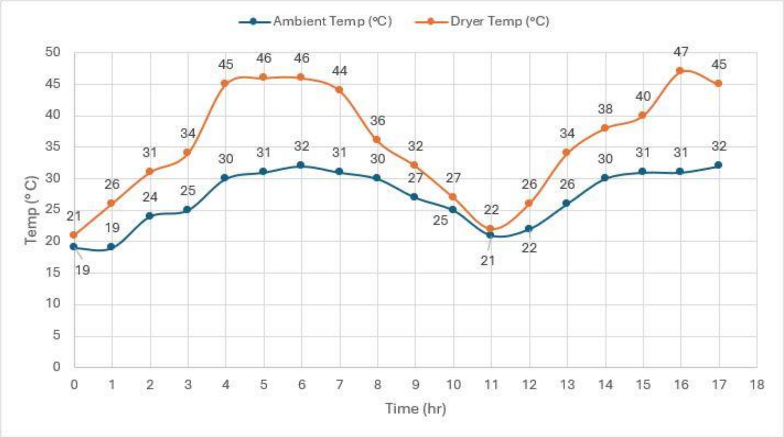

Figure 2: Diurnal Temperature Profile of Solar Dryer and Ambient Condition

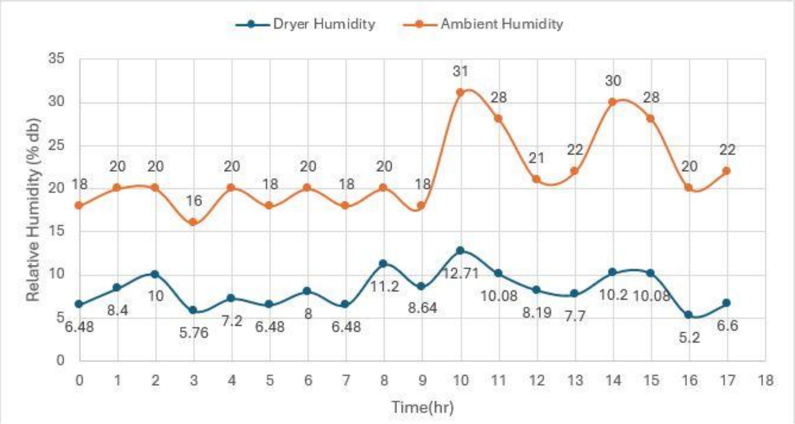

Figure 3: Diurnal Relative Humidity Profile of Solar Dryer and Ambient Condition

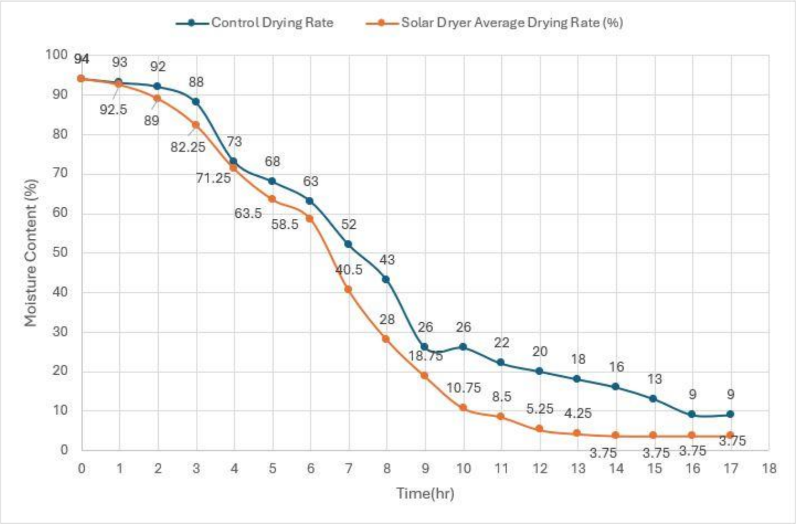

Figure 3: Drying Curves for Tomatoes

4.0 Conclusion

A mix-mode, rack-type passive vegetable/fruit solar dryer was developed in the Agricultural Engineering Technology Programme of the Samaru College of Agriculture, Ahmadu Bello University. Zaria, Nigeria, and its performance was evaluated by drying 10 kg of tomatoes and comparing the results with open-sun-drying. The results reveal that the rack dryer showcased a faster drying performance than the control. The dryer had a drying efficiency of 65.90 % at a dying rate of 0.71 kg/hr when dehydrating 10 kg of tomato from an initial moisture content of 94 (% wb) to a final moisture content of 4.25 (% db). The efficiency of the dryer indicates its suitability for crop drying especially fruits and vegetables with high moisture contents. This dryer will find great application in households and among operators of restaurants who can dry and store tomatoes hygienically within two days in batches for use during scarce periods.

References

Aliyu, B., Kabri, H. U., & Pembi, P. D. (2013). Performance evaluation of a village-level solar dryer for tomato under Savanna Climate: Yola, Northeastern Nigeria. *Agricultural Engineering International: CIGR Journal*, *15*(1), 181-186.

Arah, I. K., Kumah, E. K., Anku, E. K., & Amaglo, H. (2015). An overview of post-harvest losses in tomato production in Africa: causes and possible prevention strategies. *Journal of Biology, Agriculture and Healthcare*, *5*(16), 78-88.

Bada, M. M., Suleiman, A., Mustapha, A., Sambo, A. S., & Abdulaziz, K. (2021). Effects of Post-Harvest Losses on Profitability of Fresh Tomato (Solanum lycopersicum) Production and Marketing in Kano State, Nigeria. *American Journal of Marketing Research*, *7*(3), 35-43.

Bhatia, A. (2014). Heat loss calculations and principles. *M04-003 Continuing Education and Development, NY.*

Datt, P. (2011). Latent heat of vaporization/condensation. *Encyclopaedia of snow, ice and glaciers*, *5*, 248-253.

Eke, A. B. (2014). Investigation of low-cost solar collector for drying vegetables in rural areas. *Agricultural Engineering International: CIGR Journal*, *16*(1), 118-125.

Eke, A. B., & Arinze, E. A. (2011). Natural convection mud type solar dryers for rural farmers. *Nigerian Journal of Technological Development*, *8*(2), 92-108.

Eke, B. A. (2013). Development of small-scale direct mode natural convection solar dryer for tomato, okra and carrot. *International Journal of Engineering and Technology*, *3*(2), 199-204.

Fekadu, G., & Subudhi, S. (2018). Renewable energy for liquid desiccants air conditioning system: A review. *Renewable and Sustainable Energy Reviews*, *93*, 364-379.

Iordanou, G., & Apostolidou, E. (2013). Development of a Mathematical Lumped Parameters Model for the Heat Transfer Performance of a Solar Collector. *Journal of Engineering Science and Technology Review*, *6*(3), 5-9.

Itodo, I. N., Ijabo, J. O., Charles, J. A., Ezeanaka, N. N., & Akpa, S. O. (2019). Performance of desiccant solar crop dryers in makurdi, Nigeria. *Applied Engineering in Agriculture*, *35*(2), 259-270.

Itodo, I.N.; Obetta, S.E.; and Satimehin, A.A. 2002. Evaluation of a solar crop dryer for rural applications in Nigeria. *Botswana Journal of Technology*, 11(2): 58-62

Kaltiya, M. S., Abubakar, M. S., & Itodo, I. N. (2014). Prediction of global solar radiation using Angstrom-Page equation model for Makurdi Benue State, Nigeria. *American Journal of Engineering Research*, *3*(8), 145-150.

Kolade, O., & Harpham, T. (2014). Farmers' mobilisation of social capital for beneficial uptake of technological innovations in southwest Nigeria. *International Journal of Technological Learning, Innovation and Development*, *7*(2), 147-166.

Ogunsola, O.A & Ogunsina, G.A. (2021). Tomato Production and associated Stress: A Case of African Climate. *Single Cell Biology*, 10(4), 5

Purusothaman, M., & Valarmathi, T. N. (2019). Computational fluid dynamics analysis of greenhouse solar dryer. *International Journal of Ambient Energy*, *40*(8), 894-900.

Yin, J., Guo, M., Liu, G., Ma, Y., Chen, S., Jia, L., & Liu, M. (2022). Research progress in simultaneous heat and mass transfer of fruits and vegetables during precooling. *Food Engineering Reviews*, *14*(2), 307-327.