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Review Article

Review on Solar Drying in Nigeria

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ABSTRACT

Nigeria, as one of the countries in the African continent has its challenges regarding to agricultural crops cultivation and its preservation methods. Traditional methods of preserving crops are commonly adopted by the local populace over solar dryer appliances. The reason for these includes being cheaper method, does not require much technical know-how, is easily learnable, the area for drying the agricultural crop produce being unlimited etc as when compared to solar dryers that needs materials to be fabricated, required little or medium knowledge of technical know-how, financial requirement for its fabrication which could range from few dollars to thousands of dollars. Solar dryer working principles, components, various classifications, and its mode of air movement and mode of heat transfer were discussed on this article. The article also reviewed some of the experimental researches on solar drying in Nigeria carried out by various scholars. The review of the published works on solar drying of various crops under different drying techniques were carefully studied. The results showed that, significant works on solar drying in Nigeria have been carried out even though its potential is greatly under-utilized due to various factors militating against it.

REVIEW ARTICLE

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- Drying

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INTRODUCTION

Nigeria, which was once a British colony got her independence in 1960. It was mostly under military rule until 1998 allowing the transition from military rule to civilian ruling. According to Anonymous (2019), Nigeria shares border with Gulf of Guinea, found between Benin and Cameroon. It is the most populous black country in the

African continent with a population of around 198 million (Anonymous, 2018) with a projection to double by 2050.

As a big country with various ethnic groups, more than 500 indigenous languages and multifaceted religions, it is situated at a location that helped her to have excellent weather condition. These weather conditions added to her rich arable lands encourages agriculture. Some of the popular agricultural crops cultivated and produced in Nigeria are cocoas, palm oil, corn, rice, sorghum, millet, maize, cowpea, soya beans, onions, okra, pepper, cassava (manioc tapioca), yams, rubber, cattle, timbers, etc. (Anonymous, 2022)

Unfortunately, as the weather conditions encourages agricultural cultivation, it also lead to loss of agricultural produces, mostly vegetables and fruits due to inadequate preservation methods. Generally, the preservation of agricultural produce is an ancient practice (Mulet *et al.*, 1993). Agricultural produces were dried in the open under the sun to preserve it. The importance of this practice was reduced because of the climatic adversities which leads to high product losses and the requirements of a lot of manpower during the drying process. To manage these problems related to open air sun drying such as low efficiency, agricultural product loss and deterioration, solar dryers were introduced (Romano *et al.*, 2009).

Solar drying

A solar dryer as an appliance helps transmit the heat from heat source to a product and at the same time transfer moisture found in the agricultural crops from the surface to the surrounding air (Chauhan *et al.*, 2015). The basic function of any given solar dryer is to increase the vapor pressure of moisture found inside the crop produce and increase the moisture carrying capacity of the drying air by decreasing its relative humidity (Sangamithra, 2014). During the solar drying process, the warm air captures moisture from the dried agricultural products. According to Elhage *et al.* (2018), the total quantity of moisture removed depends on the temperature of the dried air found in the environment. Figure 1 explains in general, the principle of solar dryer.

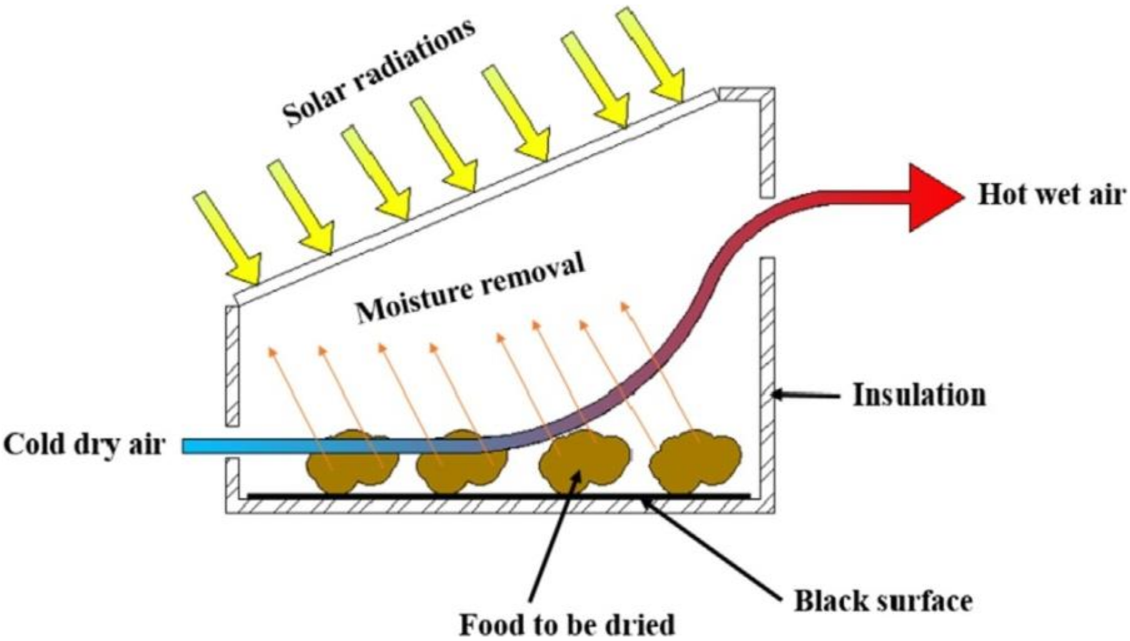


Figure 1. Schematic of principle of solar dryer (Elhage *et al.*, 2018).

Different components of Solar Dryers

As generally known, solar dryers are made up of three different components which include the drying chamber, air heater and air flow system. The location where the agricultural crops to be dried are placed is known as the drying chamber, which most times are covered leading to the protection of the agricultural products from dust and dirt. That chamber is mostly insulated, which helps in the increase the drying efficiency. The solar collector is a box with a transparent cover, while the remaining part is painted dark to prevent heat loss. The solar collector helps in raising the temperature of compartment air higher than the surrounding temperature of the dryer. On the other hand, the remaining component called air flow system happens to serve as exit point where moist air moves to the environment (Ekechukwu and Norton, 1999a; 1999b; 1999c).

CLASSIFICATION AND MODE OF AIR MOVEMENT

According to Figure 2, solar dryers are classified according to the air flow movement, the mode of transfer of heat in the chamber and type of drying chamber (Elhage *et al.*, 2018).

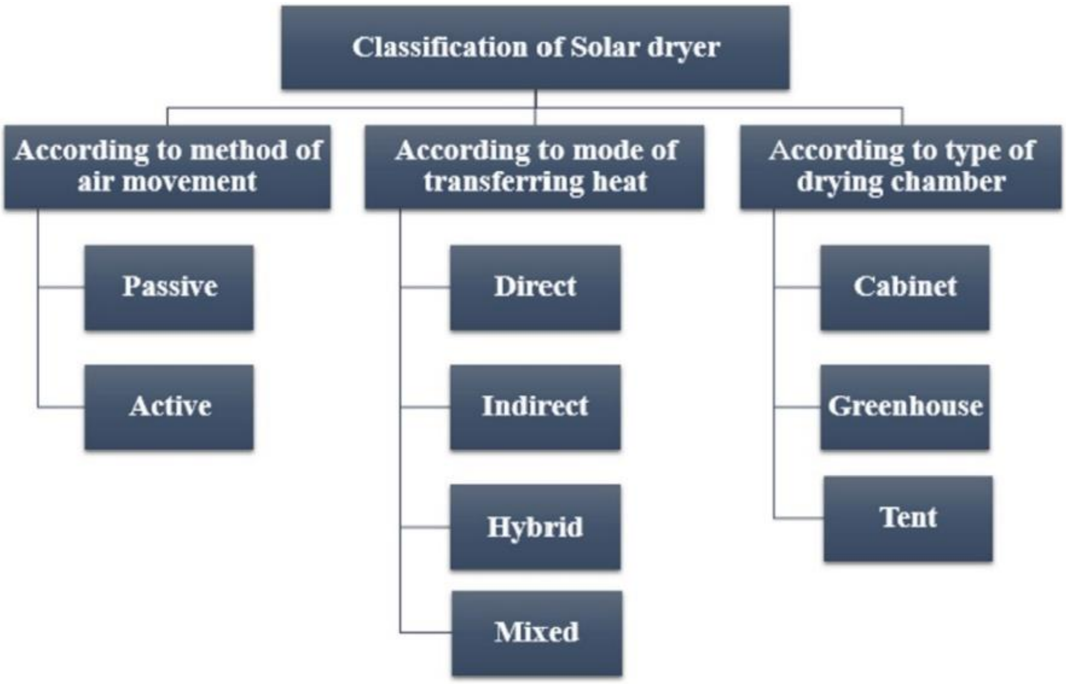


Figure 2. Classification of solar dryers (Elhage *et al.*, 2018).

Kumari *et al.* (2014) in a review paper showed several designs, detailed constructional features, and operational principles of a solar dryer system. Fudholi *et al.* (2010), on the other hand, presented a review of four types of solar dryers, which include direct dryer, indirect dryer, mixed dryer, and hybrid dryer. This was achieved by regarding the material to be dried, economic, and technical aspects. Over the years, the progress of solar drying systems of agricultural crop produce has been based on technical directions such the compact designs of the collector, and long-lasting drying system. Also, Elhage *et al.* (2018) research work showed the different types of solar dryers that are widely used. In addition to the active and passive type of solar dryers, it categorized dryers into indirect, direct and mixed dryers. Figure 3(a) and 3(b) shows the direct passive and direct active solar dryers while Figure 4(a) and 4(b) shows indirect passive and indirect active solar dryers.

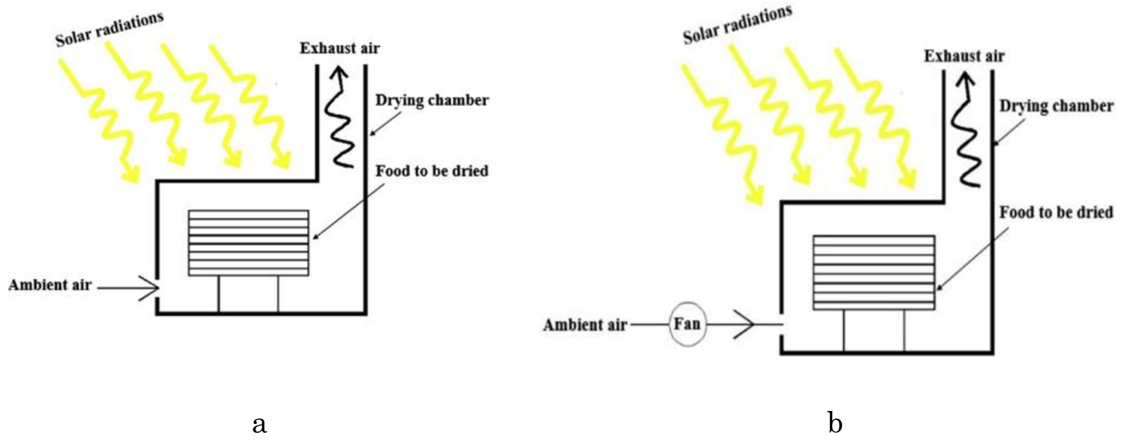


Figure 3. (a) Direct passive, (b) Direct active solar dryer (Elhage *et al.*, 2018).

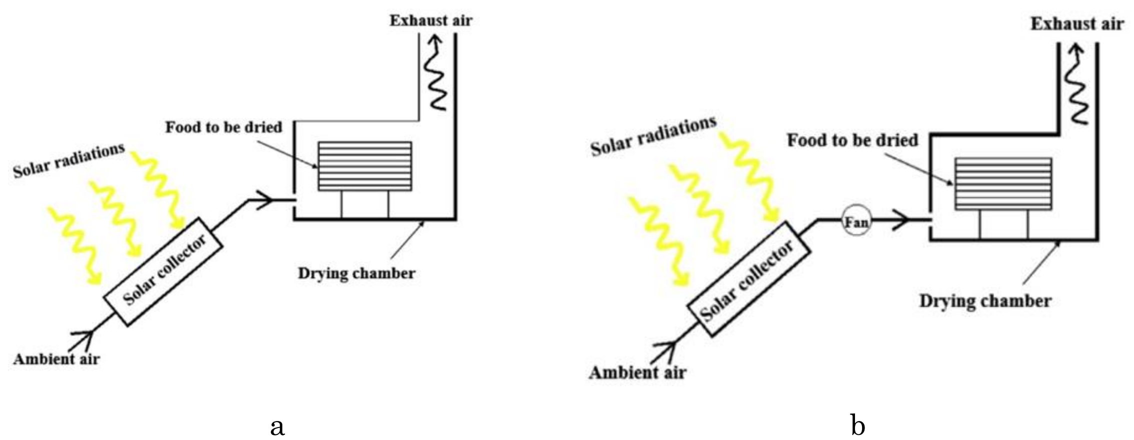


Figure 4. (a) Indirect passive, (b) Indirect active solar dryer (Elhage *et al.*, 2018).

The figures above, also show the mode of air movement in the dryers, which on the long run affects the drying rate of the agricultural crop produce found in the drying chamber of the solar dryers. The passive solar dryer which is based on the natural movement of air have slow drying rate. This is a result of the slow movement of air across the drying chamber. This particular type of dryers are commonly known as natural convection solar dryers. The active solar dryers on the other hand, will require fan to move air through the dryer components. It could be mounted on either inlet or at the exit. They have higher drying rate due to the fan, but with the disadvantage of electrical energy being needed to operate the fan (Elhage *et al.*, 2018).

Mode of heat transfer

According to Zarezade and Mostafaeipour (2016), direct solar dryer is made up of the drying chamber which is covered by transparent glazing of plastic or glass. In direct solar dryer, crop produce is placed in an enclosure. The radiation from the sun is absorbed by the material and the internal surfaces of the drying chamber thereby generating heat. The generated heat evaporates moisture from the crop produce found inside the solar dryers leading to its drying. Bala and Debnath (2012) opined that, indirect solar dryer consists of drying chamber which has opaque cover, fan, solar collector. This solar collector may be fixed plate type of collector or concentrated type collector. In indirect solar dryer, the drying chamber is not exposed directly to solar radiation from the sun. Indirect solar dryer has a high drying rate compared to direct solar dryer. Moreover, air velocity, drying temperature and solid loading can simply be controlled in indirect solar dryer when compared to direct solar dryer (Kapadiya and Desai, 2014). Finck-Pastrana (2014), designed and studied the drying process of an indirect solar dryer.

Mixed mode solar dryer is the combination of direct and indirect types (Bala and Debnath, 2012; Stiling *et al.*, 2012; Prakash *et al.*, 2016; Sekyere *et al.*, 2016). The mixed mode solar dryer has the highest drying rate when compared with both direct and indirect solar dryers. Hybrid solar dryers are dryers that have both natural energy source (solar energy) and another energy source such as fossil fuel or biomass (Lopez-Vidana *et al.*, 2013; Reyes *et al.*, 2014; Kouchakzadeh, 2016). When compared to other dryers, hybrid dryers reduce the drying time of the agricultural produce to the barest minimum. These solar dryers on the other hand are very expensive to manufacture and definitely will lead to dependency on fuel. Drying rate of given solar dryers is affected by several parameters which include the type of material used in the construction of the dryers, its loading and pre-treatment method used, temperature found inside the dryer, the drying air velocity and lastly but not the least, relative humidity (Elhage *et al.*, 2018). Leon *et al.* (2002), gave detailed review of parameters that are generally used in testing and evaluating different types of agricultural crop produce in solar dryers.

SOLAR DRYING RESEARCH IN NIGERIA

In this article, the authors's aim to review some of the solar drying research carried out in Nigeria over the past few decades.

DISCUSSIONS

Igbeka (1986) opined that, the drying capacity of a passive solar grain dryer adaptable to rural farmers are affected by parameters like solar radiation, type of grain which will affect the air flow resistance, absorption of solar radiation and moisture movement. Also, moisture content of the grain at harvest, wind velocity and height variation among the air inlet and outlet of the dryer is very significant when the study was carried out. From the experimental results, a flat plate collector cum-dryer (Figure 5) gives best drying results when compared with a solar with a drying chamber and a flat plate collector with an in-bin storage (Figure 6). The social-economic standard of the farmers was not found to inhibit the adoption of the solar dryer while the use of locally available materials for construction of solar dryers was emphasized.

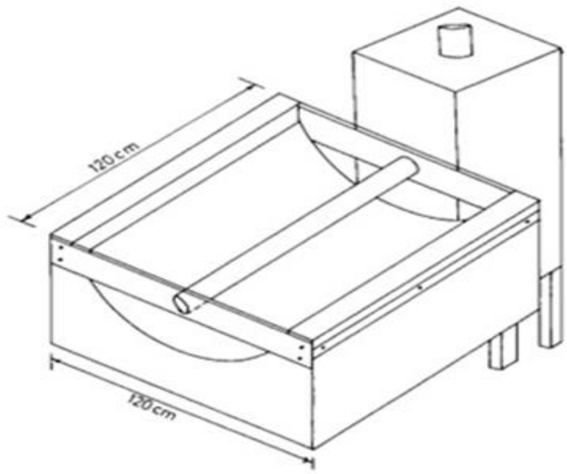


Figure 5. Flat plate collector (Igbeka, 1986).

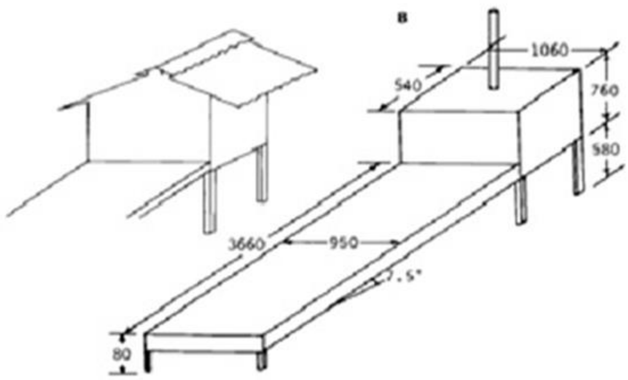


Figure 6. Flat plate collector with in-bin storage cum dryer (Igbeka, 1986).

Olufayo and Ogunkunle (1995) in their academic study of natural drying of cassava chips in the humid zone in Nigeria found out that, variations in the drying patterns of chips dried at about equal weight per unit area was very negligible. The parameters recorded and used to determine the results are the sunshine hours during the drying, daytime temperature when the experiment was carried out and relative humidity of the environment.

Ekechukwu and Norton (1998) research on effects of seasonal weather variations on the measured performance of a natural circulation solar energy tropical crop dryer, logical conclusion on performance of the dryer being dependent on variations in insolation, ambient temperature and relative humidity was significant. Also, the drying conditions during dry season was approximately constant. In wet season, drying conditions were significantly unpredictable which resulted in poorer drying. Isieka *et al.* (2012) research study on the effects of selected factors on drying process of tomato in forced convection solar dryer, found at 95% probability level, between the mean of three glazing materials used, there was no major significant difference. Mean slice thickness of tomato and Mean air flow rates shows high significant different when measured at 99% probability level. The result showed, an increase in air flow rate with corresponding decrease in material slice thickness leads to increase in the drying rate.

In the experimental research study on natural circulation solar air heating system (Figure 7) with phase change material energy storage by Enibe (2001), it was discovered that, there is a great potential for its applications in crop drying and poultry incubation. The system showed that, the peak temperature rise was around 15 K on the other hand, the maximum airflow rate and peak cumulative useful efficiency were about 0.058 kg s^{-1} and 22%, respectively. The single-glazed flat plate solar collector which happen to be integrated with a phase change material (PCM) heat storage system showed that, the system is suitable for agricultural drying. The experiment also showed that, when a suitable valve is available towards the control of the drying chamber temperature, it can also be used and operated as a poultry egg incubator.

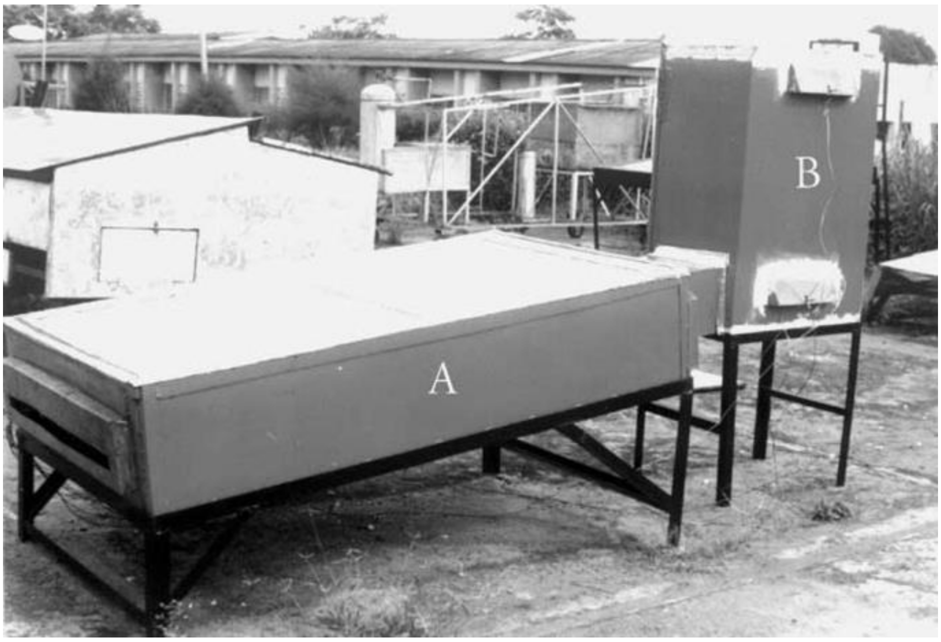


Figure 7. The air heating system (A-collector assembly with energy storage and air-heating subsystems; B-heated space) (Enibe, 2001).

In the evaluation of pebbled bed solar dryer, Okonkwo and Okoye (2005) found out that, moisture content of the cassava chips drops drastically from 73% to 10% (w.b.) when compared to open-air sun drying which reduced to 22.2% under the same period of experiment. They also observed that, the samples at different levels in the drying chamber trays were not drying at the same rate with the tray at the topmost having the highest drying rate. During the experiment, the absorber temperature was 72ºC, while the bed temperature for storing heat in the dryer was 58ºC. The chamber temperature of the dryer being 57ºC was noted when the maximum ambient temperature was 34ºC. It shows that, drying the cassava chips under solar dryer saves time and offer quality products as its advantages over open air sun drying.

Bolaji (2005), in his experimental study carried out regarding to the performance evaluation of a simple solar dryer found out that, inside the dryer with yam chips, the temperature from the heat source was higher than the ambient temperature in the drying process. In the experiment, the dryer was able to remove 72.8% of moisture (d.b.) in one day (10 h) experiment which shows a drying rate of 0.46 kg h^{-1}. After the experiment, he determined the system drying efficiency of the solar dryer as 59% despite using a locally available material for its construction (Figure 8).

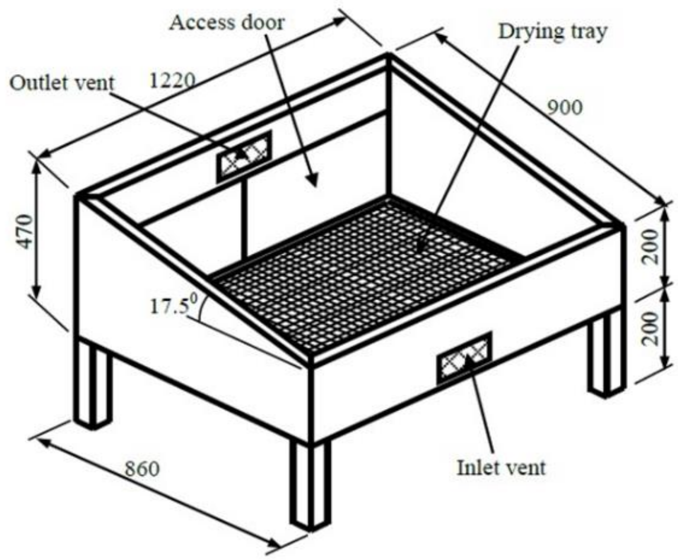


Figure 8. A simple solar dryer (Bolaji, 2005).

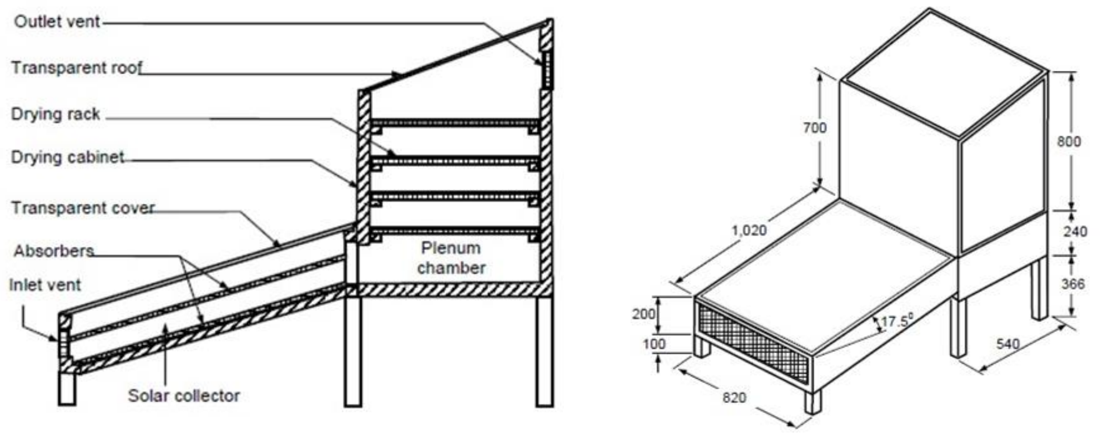
Akinola and Fapetu (2006) in their study on the evaluation of traditional and solar fish drying system in Nigeria noticed the predominant method adopted being the traditional methods in fish processing and drying methods. This result was obtained from the questionnaires administered to people in the sampled local governments and who have been in fish business for over 32 years.

Ezekoye and Enebe (2006) research on development and performance evaluation of modified integrated passive solar grain dryer, the drying crop produces (groundnuts and pepper) took maximum of 8 days and 5 days to dry when at average relative humidity of 43% and average temperature of 63°C. On one hand, the collector efficiency was 10% and dryer efficiency 22%. In the study on direct passive solar dryer for tropical crops carried out by Alonge and Hammed (2007), they got the maximum temperature of 59°C inside the dryer and 38°C outside under no load test condition. The cost of the dryer was cheap as a result of the use of local materials for its construction.

Akinola and Fapetu (2006) research on exergetic analysis of a mixed-mode solar dryer, was able to find average exegetic efficiency of 56% and thermal efficiency of 66.95%. It also showed, drying in a cabinet dryer made drying more attractive as well as conserve energy. Ozuomba *et al.* (2013) in the experimental research study on fabrication and characterization of direct absorption solar dryer, showed the technicalities involved in absorption solar dryer fabrication. The experiment also showed that the margin between the internal and external temperature was as high as 55°C with potential for its application in drying various agricultural products in addition to it being environment friendly.

Ajadi *et al.* (2007) carried out experimental study on effect of dust on the performance of a locally designed solar dryer, discovered dust as a limiting factor of solar thermal system. The result showed significant variation among the control and experiment dryers' temperatures. Ukegbu and Okereke (2013), in their research study on effect of solar and sun drying methods on nutrient composition and microbial load in selected vegetables; African spinach, fluted pumpkin and okra found out that, there were significant changes on the proximate analysis, vitamin, minerals and microbial load analysis on vegetable samples after drying. The study also showed that, solar drying of vegetables led to retaining of more nutrients and is relatively hygienic with reduced microbial. Okoroigwe *et al.* (2015) in research study on comparative evaluation of the performance of an improved solar-biomass hybrid dryer, it was found that, a redesigned biomass solar dryer with a back pass solar collector and heat exchanger showed a significant improvement in agricultural drying. The efficiency of the solar dryer based on solar, biomass and a combined solar biomass showed a significant increase in the drying of fresh okra, fresh groundnut and fresh cassava chips when a test was carried out. Irtwange and Adebayo (2009) research experiment on development and performance of a laboratory scale passive solar grain dryer in a tropical environment, the mean drying rate of the 10 kg of freshly harvested maize to be 0.7 kg day^{-1} was determined while in direct comparison with sun drying, the drying rate of 0.3125 kg day^{-1}. Its advantages over the traditional sun drying methods include faster drying rate, reduction of spoilage by microorganisms and handling convenience. Musa (2012) carried out experiment on the drying characteristics of cocoa beans using an artificial dryer, it was found that high drying rates were achieved easily when there is increase in drying air temperature and velocity in the given solar dryer.

In the experimental evaluation of the performance of a mixed-mode solar dryer (Figure 9) carried out by Bolaji and Olalusi (2008), the drying rate and system efficiency of the mixed mode dryer after the analysis of the data was 0.62 kg h^{-1} and 57.5% respectively.



a b

Figure 9. View of mixed-mode solar dryer (Bolaji and Olalusi, 2008).

Ajao and Adedeji (2008) in their research study regarding to the assessment of the drying rate of some crops in solar dryer, it showed average value of the tropical crop (Yam) drying rate was 9.0 g h^{-1} which had system drying efficiency of 18% while on other hand, the lowest drying rate was for pepper at 1.6 g h^{-1}. The experiment proved that the drying occurs under constant rate falling period and decreases when the material moisture content is less than maximum hygroscopic content. Ekechukwu and Norton (1999a) in their research review of solar energy drying systems study carried out a detailed review of various designs and performance evaluation of flat-plate solar energy collector for low temperature. The appropriateness of each design and the component materials selection guidelines was actualized and concluded to be a useful parameter to be considered. In their study, where higher temperature is desired, double or triple-glazed solar energy air heater can be used. This helps to reduce drastically the upward convective and re-radiative heat losses. Dairo *et al.* (2015), during experimental study of solar dryer kinetics of cassava slices in a mixed mode flow dryer discovered that, between the 10 commonly used thin layer drying models for drying curve modelling of the cassava slices, there was significant changes. The Midilli and Logarithmic Models showed better fit to the experimental drying data of cassava slices.

Aliyu and Jibril (2009), research on utilization of greenhouse effect for solar drying of cassava chips found, over 30% savings in drying time was achieved in the dryer. This is a great savings when compared to open-air sun drying. Also showed that, the organoleptic quality of the cassava chips is great as a result of retaining their white color (indicating no growth of mould). Fagunwa *et al.* (2009) in their experimental research study on the development of an intermittent solar dryer for cocoa beans discovered cocoa beans showed good qualities during its quality assessment. When free convective drying was used, pH of 6.35, acid value of 3.40 mg g^{-1} with mildly bitter taste were obtained while using convective solar dryer, increase in moisture re-absorption and acidic flavor were obtained. The cocoa seeds were successfully dried from initial moisture content of 53.4% (w.b.) to safe moisture level 3.6% (w.b). Lawrence *et al.* (2013) research on design, construction and performance evaluation of a mixed mode solar dryer, it was found that average dryer temperature to be 40.9 ºC. 100 kg holding capacity mixed mode solar dryer was incorporated with a black painted conical chimney. This serves as an additional absorber with the experimental test carried out at 10%, 25% and 50% load capacity for the cassava chips. Result showed the drying rates varies with coordinate position of trays. It decreases from the bottom up to a minimum, at the middle of the tray and starts increasing up to the top tray.

Yohanna and Umogbai (2010) while reviewing the solar energy potential in Nigeria, listed the various sectors it could be utilized such as crop drying, poultry production, manure drying, dairy production, irrigation and water pumping, refrigerated food, vaccine and drug storage etc. They also recommended the expansion of solar energy supply schemes to the rural areas in Nigeria.

Eze and Agbo (2011), in their comparative study of the research topic on sun and solar drying of peeled and unpeeled ginger, was able to find, the moisture content of the solar dried unpeeled ginger was drastically reduced to 7.0% (w.b). This falls within the acceptable international market standard of 6%-9%. The experiments also show that, open-air sun-dried crop produce retain its colour and aroma more than the solar dried samples.

Ugwu *et al.* (2011) in their experimental study on impact of vehicle emissions and ambient atmospheric deposition common in Nigeria on the Pb, Cd and Ni content of fermented cassava flour processed under the sun discovered, the higher the concentration of the emissions on the fermented cassava, the higher its effects. The average concentration of the element in sun-dried samples were greater ($p \leq 0.01$) while when it was on the roadside, they were 185% in Pb, 53% in Cd and 176% in Ni greater than atmospheric condition. The results also showed that, Pb emissions from petrol. diesel with dust is among those considered as the major source of Cd, Ni and other extraneous factors including metals adsorbed on pavements surfaces. Open-sun drying of wet foodstuff on the bare surface of roadside could potentially lead to high levels of Pb, Cd and Ni in food produce when compared to drying under conducive conditions or oven-drying.

In the research topic on the design and fabrication of a direct natural convection solar dryer experiment carried out for tapioca by researchers Ogheneruona and Yusuf (2011), they determined, a minimum of 7.56 m^2 solar collector area is the right area to dry a given batch of 100 kg tapioca in 20. In the experiment, the final moisture content of the drying material - tapioca was 10% (w.b.) which falls from the initial moisture content of 79% (w.b.). During the experimental research study by Okoroigwe *et al.* (2013) in their research evaluation regarding to the design and evaluation of combined solar and biomass dryer for developing countries, it was found by them that, the drying efficiency of the solar dryers where greatly maximized when it was combined with biomass as a source of its heating. The results showed that, the optimal drying rate of 0.0142 kg h^{-1} was actualized when with combined solar and biomass dryer as when it was only solar drying or biomass drying which happen to have drying rates of 0.00732 kg h^{-1} and 0.0032 kg h^{-1} respectively. In the performance evaluation of a solar wind-ventilated cabinet dryer experiment (Figure 10) carried out by Bolaji *et al.* (2011) shows that, the dryer performance depends on the proper air circulation through the system. Comparatively, the increase in the air velocity through the system leads to a significant increase in the system efficiency.

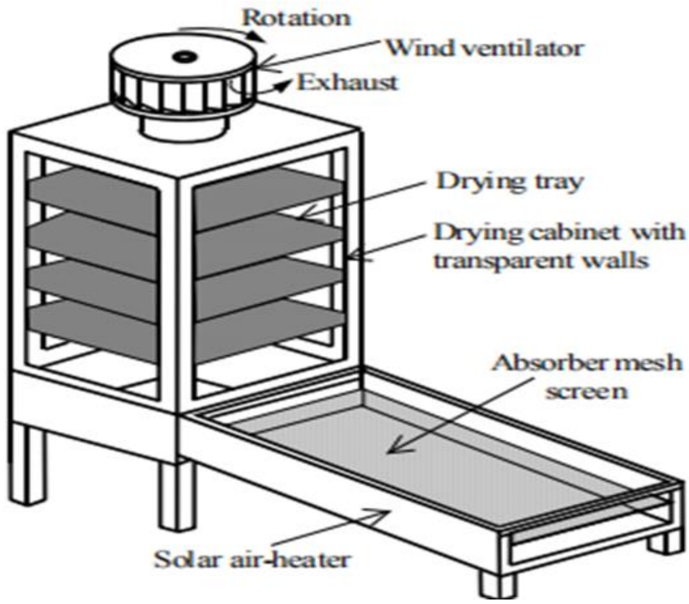


Figure 10. Solar wind-ventilated cabinet dryer (Bolaji *et al.*, 2011).

Alonge and Adeboye (2012) in their evaluation study of the drying rates of some given fruits and vegetables, obtained that direct passive solar dryer gives better results when the fruits like pepper, okra and vegetables were dried as regards to indirect passive solar dryer. The experiment also helped in confirmation of other research works carried out by showing that, the drying rate of the crops occurred in falling rate period.

Babagana *et al.* (2012) research on design and construction of forced/natural convection solar vegetable dryer with heat storage discovered that the drying rate and time of the forced mode solar dryer used for drying tomato, onion, pepper, okra and spinach vary significantly from natural mode solar dryer. The collector efficiency was 45% and useful heat of 48.9 W $m^{-2}K^{-1}$ was used for about 6 h in drying during the night. Hussein *et al.* (2017) research on the design, construction and test of a hybrid photovoltaic solar dryer showed that, it took 6 h to reduce the moisture content of tomato slices from the initial value of 94.22% to the final value of 10% (w.b.). This is different to the 9 h it took to achieve same moisture content when solar dryer was used. Average drying rate and efficiency determined during the experiment were 0.800 kg h^{-1} and 71% for hybrid solar dryer and 0.0578 kg h^{-1} and 65% for combined solar-energy dryer.

Eze and Ojike (2012) experimental study on effect of different dryers on vitamin content of tomato, the concentrations of Vitamin A, C and E between the fresh samples and dried samples for all drying systems was able to show significant difference. The study also showed that, Vitamin A and E are increased significantly with open-air sun drying system having the highest value in Vitamin C concentration. Latitudinal box dryer (Figure 11) on the other hand gave the best result in terms of vitamin A and E retention in direct comparison with greenhouse solar dryer (Figure 12) and sun-tracking solar dryer (Figure 13). It proved drying tomatoes using solar dryer enhances the concentration of fat-soluble vitamins in direct comparison to open-air sun drying system which enhances water soluble vitamins better.

Figure 11. Latitudinal box solar dryer (Eze and Ojike, 2012).

Figure 12. Greenhouse solar dryer (Eze and Ojike, 2012).

Figure 13. Sun manual tracking solar dryer (Eze and Ojike, 2012).

Aliyu *et al.* (2013) in experimental study of the performance evaluation of a village-level solar dryer for tomato under savanna climate discovered that, the drying temperature and drying rate was higher than the natural open-air sun drying method. Results showed drastic reduction of the tomato moisture content to 4% (w.b) while on the otherhand, the solar dryer efficiency was 64%, air flow rate 0.025 kg s^{-1} and drying rate of the crop produce 0.03906 kg h^{-1}. Nwoke *et al.* (2011) experimental study on the analysis and survey of the application of solar dryers in Eastern Nigeria, were able to find on the domestic and industrial level, the practical use of solar dryers is absent. These results were gotten from oral interview and administration of questionnaire to the local farmers as well as the rural populace. Also, there was great enthusiasm among the farmers in the use of solar crop dryers if their performance is satisfactory with respect to quality and quantity of products although the rejected the idea of establishing a communally maintained and operated solar drying system. Preference for commercialized solar drying system where payments would be made per unit quantity of products dried was commonly agreed by the farmers. Recommendation on the establishment and development of affordable solar crop dryers with auxiliary heat sources to mitigate the effects of daily and seasonal fluctuation in solar system was reached by the researchers.

Oko and Nnamchi (2013) in their experimental research study on coupled heat and mass transfer in solar grain dryer, they noticed, good agreement between the theoretical and experimental results at specified Biot and Posnov numbers in addition to varying Fourier number. From their study, it could be used to specify the design parameter for solar grain dryers. In the experimental set up by Anyanwu *et al.* (2012) to investigate a photovoltaic-powered solar cassava dryer, they discovered, the system is structurally and functionally operative which is capable of handling 50 kg of fresh corn per batch. Despite the active solar dryer being expensive, it happened to be suitable for application in rural, off-grid agricultural settlements in Nigeria.

Eke (2013) in his experimental study discovered that, when direct mode natural convectional solar dryer (Figure 14) was used to dry tomatoes, okra and carrots, over 50% gain was obtained in the drying time when compared with open-air sun drying carried out at the same time. Also, even though the solar dryers' efficiency ranges between 21%-25% for the vegetables, it was far better than open air sun drying which has highest system drying efficiency of 15.9%. The experimental results show that, onions cannot be dried in the open air due to loss of its aroma and the best way to preserve vegetables is by using solar dryers.

Figure 14. The direct mode natural convection solar dryer for carrot, tomato and okra (Eke, 2013).

Eke (2014) in his investigation, on the research topic: low-cost solar collector for vegetable drying in rural areas (Figures 15-18) determined that, mud as a material for building the solar collector is cheaper and readily available in the Northern region of Nigeria in comparison with metal, wood or cement materials. The evaluated data obtained from the drying of sliced tomatoes on the solar dryers constructed with these materials shows that, metal plate solar collector offers the highest system drying efficiency of 27.24%.

Figure 15. Solar dryer constructed with metal plate solar collector (Eke, 2014).

Mustapha *et al.* (2014) in their experimental research study on the proximate analysis of fish dried using solar dryers, was able to notice the final moisture content of the 2 species of fishes dried being around 10.77% (w.b.)-11.20% (w.b.) (*C. gariepinus*) and 6.80% (w.b.)-7.82% (w.b.) (*O. niloticus*). Other analysis showed that, the fiber was low in the two species, with regards to fat, it was 8.19-8.96 (*C. gariepinus*) and 6.80-7.82 (*O. niloticus*), in protein, was 64.88-66.48 (*C. gariepinus*) and 58.75-63.28 (*O. niloticus*). It shows nutrient compositions of the species dried with solar dryers were very high, hygienic, better, more preserved and acceptable. Ezeanya *et al.* (2018) research on the modelling of a thin layer solar drying kinetics of cassava noodles (Tapioca), found the Modified Aghbashlo Model was the best fitted to the drying data of tapioca. Data obtained using a forced convection solar dryer with the treatment combination of the experiment comprises air flow velocities (V) of 1.5, 2.5 and 3.5 m s^{-1}, in the drying layer, thickness (B) of 0.48 cm and 0.72 cm and lastly, in the initial moisture contents (M_i) of 297%, 186% and 122% (d b).

Figure 16. Solar dryer constructed with wood solar thermal collector (Eke, 2014).

Figure 17. Solar dryer constructed with cement thermal solar collector (Eke, 2014).

Figure 18. Solar dryer constructed with mud solar thermal collector (Eke, 2014).

Ugwu *et al.* (2014) in their study of a mixed mode solar kiln with black-painted pebble bed for timber seasoning (Figure 19) found out that, it was an efficient system for wood seasoning. During the peak periods, timber stacked in the drying chamber receives hot air flow from the collector and the transparent roofs simultaneously with the maximum drying chamber temperature being 61.7°C. Kiln drying reduce the timber moisture content of the dryer from the initial moisture content of 66.27% (d.b.) to 12.9% (d.b.) while on the other hand, open-air sun drying was reduced to 20.1% (d.b.) in 360 h of drying process. The rapid rate of drying in kiln showed, the ability to dry timber to the barest level without defects when compared to open-air sun drying.

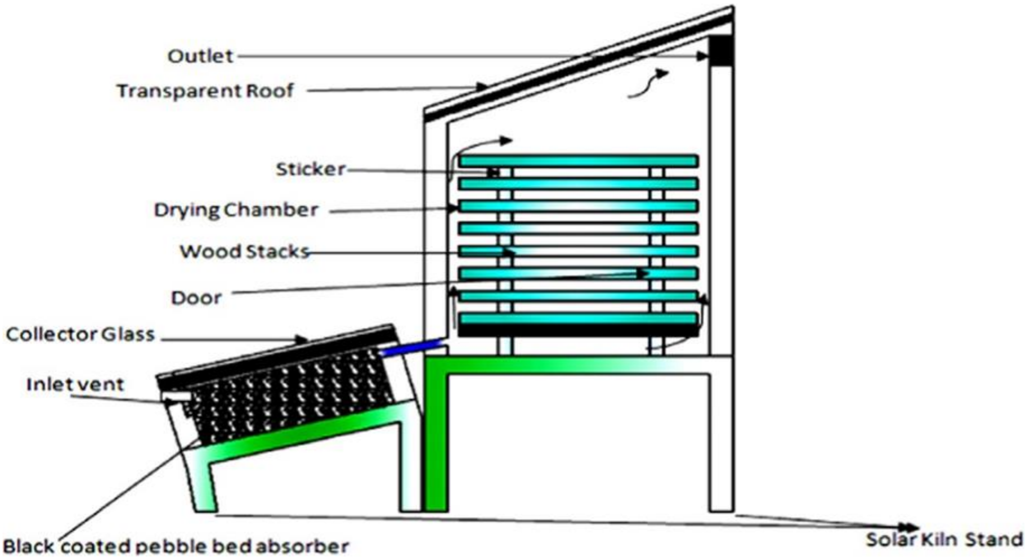


Figure 19. Cross-sectional view of mixed-mode passive solar dryer with pebble bed (Ugwu *et al.*, 2014).

Ibrahim *et al.* (2015) research on the drying of chili pepper using solar dryer with a backup incinerator under Markudi humid climate showed drying occurs under a falling rate period. The drying efficiencies for solar dryer and combined solar-incinerator dryer were 99.6% and 92.9%, respectively. In the study on integral type natural-circulation solar-energy tropical dryer done by Ekechukwu and Norton (1995), it was discovered a direct linear correlation of the measured data for a grouped parameter of ambient and crop properties against moisture content. This helped in forming solar dryer design charts. Ogunkoya *et al.* (2011) research study on development of a low-cost solar dryer found out that it cost approximately $40 (US Dollar) for a solar dryer fabricated with locally sourced materials. In addition, Abubakar *et al.* (2018) previously studied on development and performance of a mixed-mode solar dryers with and without thermal storage, efficiency of the dryers with storage materials enhanced greatly by 13% which was as a result of the thermal storage used. Okoroigwe *et al.* (2013) research study on design and evaluation of combined solar and biomass dryer for small and medium enterprises for developing countries, dryers have potential to increase the productivity and resultant economic viability of small and medium scale in developing countries. An optimal drying rate of 0.0142 kg h^{-1} was achieved with the combined solar-biomass dryer when it happened to be compared to the lower drying rate of 0.00732 kg h^{-1} for solar drying and 0.0032 kg h^{-1} for biomass dryer. Adeuwa *et al.* (2014) in the study on the development of hot air supplemented dryer took 13 h to dry yam slices in comparison to the solar dryer which took 18 h. The average thermal efficiency for both solar dryer and hot-air supplemented solar dryer are 31.45% and 42.10% respectively when the measurement was carried out.

Okeke *et al.* (2015) in research study on drying of Nsukka beans using a solar dryer found that, result was achieved when a 10 kg beans were successfully dried and reduced to 6 kg. The system drying efficiency was 40%. In the study carried out by Ikrang *et al.* (2015) research on the development of a direct passive solar dryer for crayfish, it was discovered that, crayfish exposed to open sun drying were infested with maggots as a result of contamination by flies and microorganism. In different drying with solar dryer, good crop produce was obtained which had good appearance and better colour. Their experimental result also showed that, it took approximately 3 days (at 9 hourly drying) to reduce the moisture content of the crayfish from initial moisture content of 76.60% to final moisture content12.00% (w.b.) when solar dryer was used unlike 5 days that was obtainable in open-air sun drying.

Adepoju and Osunde (2017) in their experimental study regarding to the effect of pre-treatment and drying methods on some qualities of dried mango fruits, discovered that, sun and solar drying of pre-treated mango slices took 8 h while on the other hand, the oven drying took 6 h at an average temperature of 32°C, 41°C and 65°C respectively. From the result, pre-treated methods used did not have effect on the drying rate. Also, proximate composition of the pre-treated dried mango samples revealed rich Vitamin C and B carotene (antioxidant) which makes them healthy and nourishing.

In the experimental study on effect of drying methods on the yield, phytochemical composition and antioxidant activities of potato and sweet potato carried out by Kolawole *et al.* (2018), it showed the floor yield varied significantly when evaluated using open-air sun drying and solar drying. The total antioxidant activities in the crop produce was significantly affected by the drying methods in the experiment. The effect of open-air sun-drying was less favorable on the white fleshed sweet potato samples in direct comparison with solar drying method. From their study, it was discovered, the direct dependency of the tubers on drying methods on yield, phytochemical and antioxidant activities of the sample. Iwe *et al.* (2018) in the experimental evaluation towards the mathematical modelling of a thin layer solar dryer of Ighu (dried cassava slices used to prepare a meal commonly called African salad) determined, the effects on drying time by applying different air plenums, different loading densities as well as different moisture contents in direct relation to open-air sun drying method which was used as the control experiment. The experimental moisture ratios of the samples obtained during the experiment was fitted to nine drying models. The testing of the mathematical models with the drying behavior of Ighu, the Page model and Modified Page model happened to be the best model based on statistical parameters of coefficient of determination, root mean square error and reduced mean square errors. This is applicable towards predicting moisture content of Ighu samples during solar drying and open-air sun drying.

Abubakar *et al.* (2018) built a mixed-mode solar crop dryers with and without thermal storage materials and tested under Nigerian climatic conditions (Figure 20). The dryer consists of solar collector, drying chamber, chimney and shelves. According to the results, drying efficiencies were found 28.75% and 24.20% with and without thermal storage, respectively.

Komolafe and Waheed (2018) designed and fabricated a 10 kg capacity forced convection solar dryer integrated with thermal energy storage materials. The dryer consists of a solar collector, drying chamber and photovoltaic components (Figure 21). The maximum collector and drying chamber temperatures reached to 91.3ºC and 70.8ºC at higher solar radiation values. In drying experiments of cocoa beans, drying time was 10 h, while it was 58 h for natural sun drying. So, the solar dryer was capable for drying products within short time.

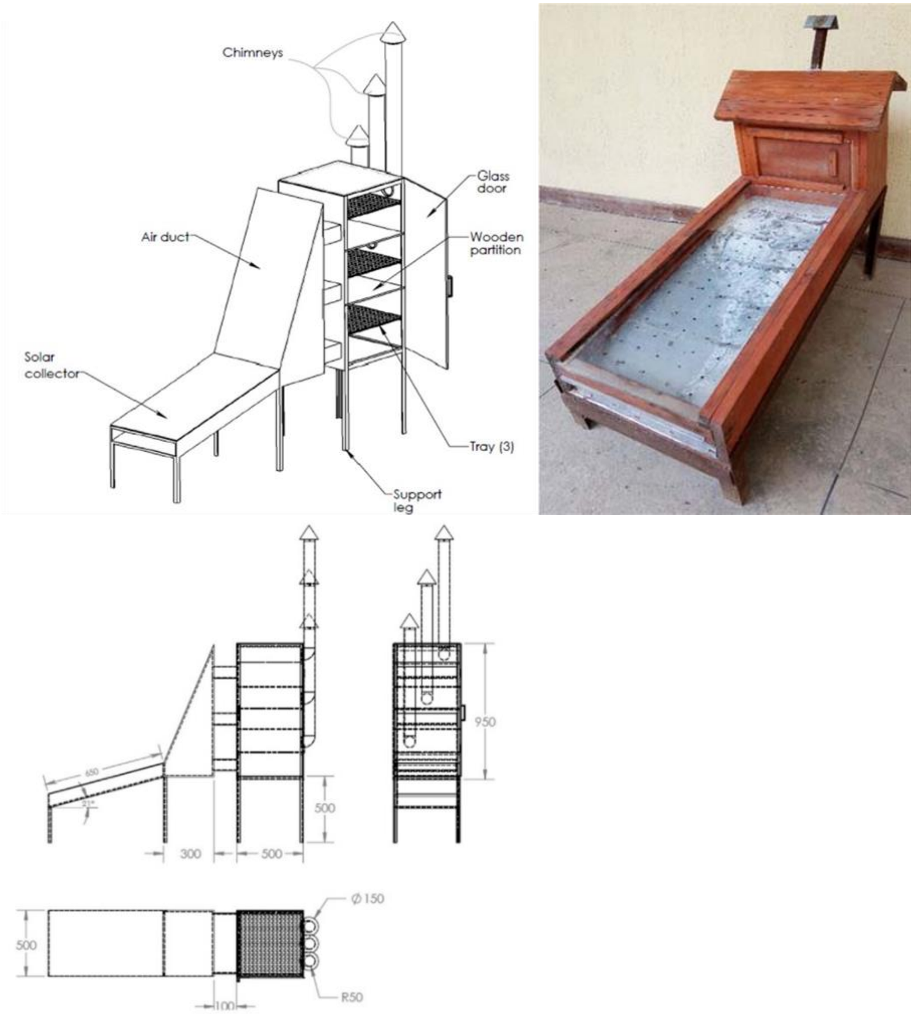
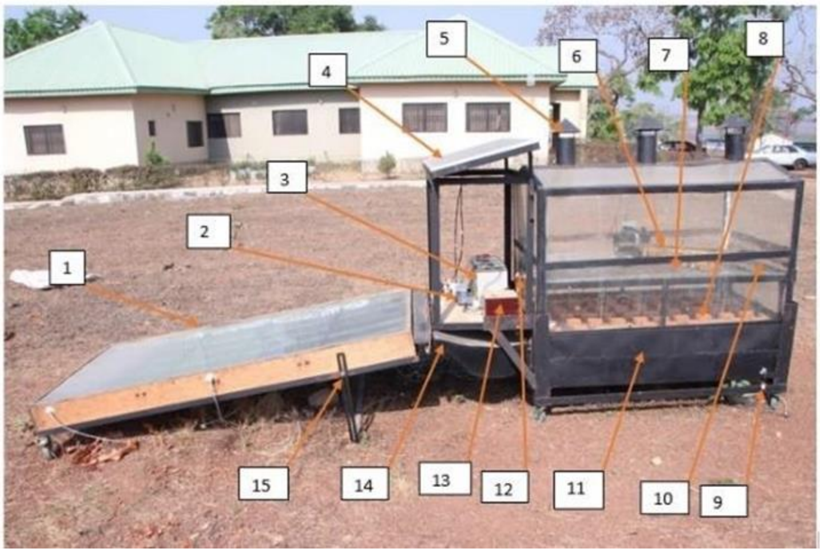


Figure 20. Mixed mode solar dryer (Abubakar *et al.*, 2018).

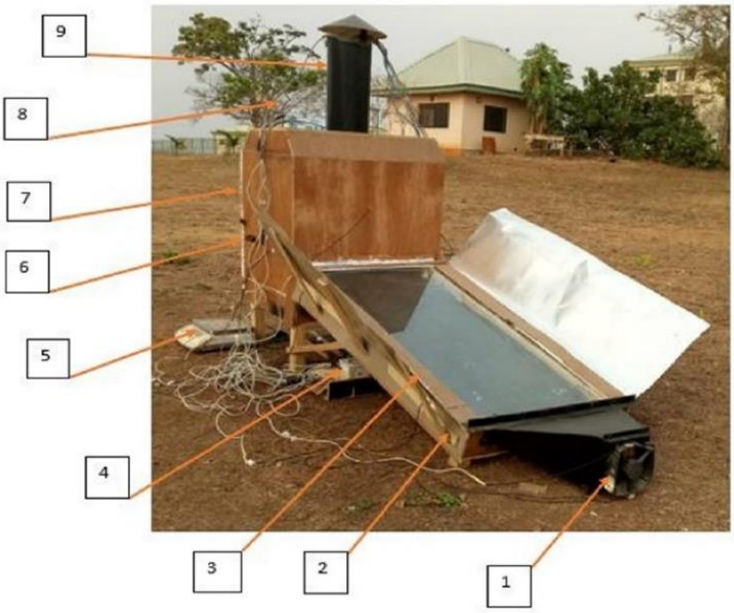


(1-Solar collector box; 2-Charge controller; 3-Battery; 4-Solar cell; 5-Chimney; 6-Stirrer; 7-Drying tray; 8-Thermal storage material; 9-Supporting frame; 10-Drying chamber; 11-Plenum chamber; 12-Thermostat; 13-Stirrer control box; 14-Air duct with blower; 15-Collector box supporting hanger).

Figure 21. Picture of the fabricated solar dryer (Komolafe and Waheed, 2018).

Kilanko *et al.* (2019) designed, constructed and evaluated the performance of solar dryer with a dimension of 1000x410x700 mm (Figure 20). In experiments, fresh scotch bonnet pepper was dried to the safe moisture content. According to the results, the mean dryer efficiency was found as 28.4%. In addition, the use of solar dryers has growing interest for the agricultural sector especially in locations of high solar insolation. The quality of produce obtain via this method provides longer shelf life and greater sale value.

Komolafe *et al.* (2019) investigated the thin layer drying behaviour of locust beans under forced and natural convection mode solar dryer with thermal storage materials (gravel) (Figure 22).



1-Blower; 2-Solar collector; 3-Reflector; 4-Data acquisition system; 5-Weighing balance; 6-Thermostat; 7-Drying chamber; 8-Temperature and humidity sensors; 9-Chimney.

Figure 22. Forced convection solar drying system (Komolafe *et al.*, 2019).

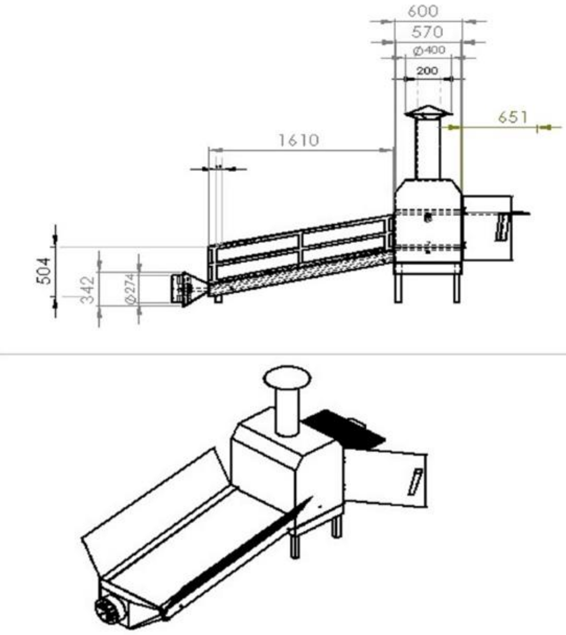
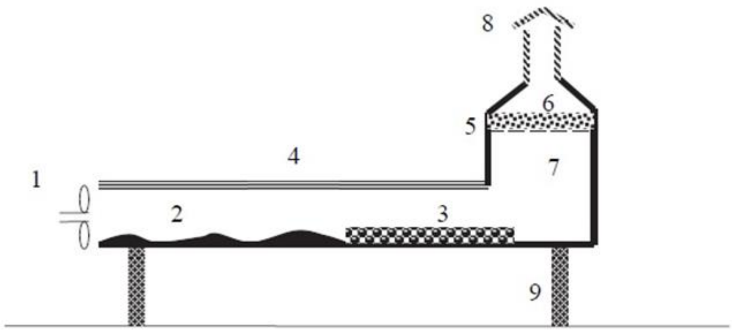


Figure 22. Continue (Komolafe *et al.*, 2019).

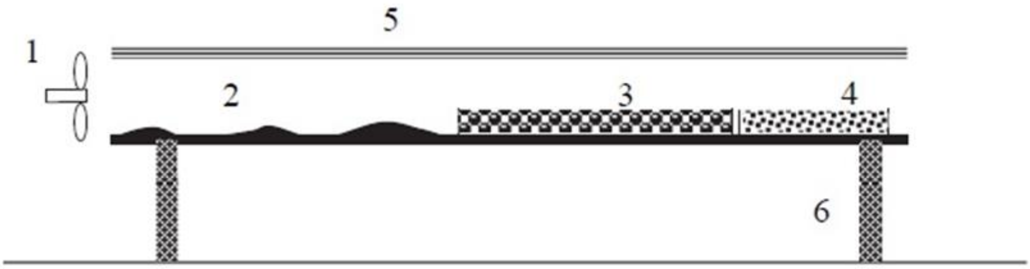
Itodo *et al.* (2019) emphasized that, humid tropical regions with nearly more than 70% ambient relative humidity for whole year, require desiccant augmented dryers. So, three types of non-regenerative desiccant solar crop dryers, indirect-active desiccant dryer (IADD) (Figure 23 and 24), direct-active desiccant dryer (DADD) (Figure 25 and 26), and the direct-passive desiccant dryer (DPDD) (Figure 28 and 29) were evaluated than compared with open air sun drying (OASD) by the drying rate (kg h^{-1}) and dryer performance coefficient (DPC). The desiccant used was a composite of rice husk ash (RHA) and calcium chloride binded with cement in the ratio of 1:1:1 by weight. According to the results, the drying rates were 0.23, 0.19, 0.16, and 0.13 kg h^{-1} for the DADD, DPDD, IADD, and OASD, respectively. The drying rate of the OASD was not significantly different from that of the IADD. The DPC was 1.53, 1.40, and 1.15 for the DADD, DPDD, and IADD, respectively. The DPC of the dryers were significantly different. The direct active desiccant dryer had the highest temperature of 45°C, the lowest relative humidity of 50% at the drying unit and the highest rate of moisture absorbed by the desiccant of 0.24 kg h^{-1}. The non-regenerative RHA desiccant had maximum moisture absorption of 28% of its weight. The direct active desiccant dryer is recommended for further development for use in humid tropical locations.



1-Fan; 2-absorber; 3-desiccant bed; 4-transparent cover; 5-grain tray; 6-grains; 7-drying chamber; 8-chimney; 9-wood support.

Figure 23. Cross-sectional view of the indirect-active desiccant solar crop dryer (Itodo *et al.*, 2019).

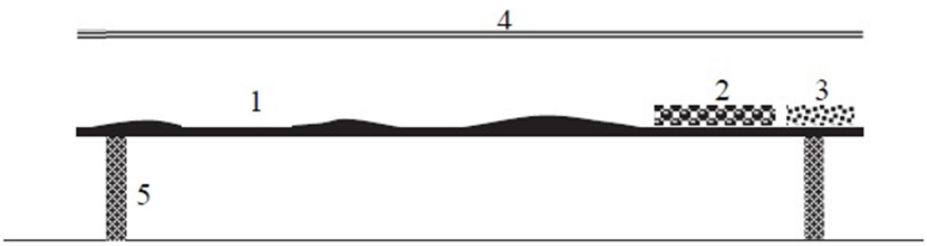
Figure 24. The indirect-active desiccant solar crop dryer (Itodo *et al.*, 2019).



1-Fan; 2-absorber; 3-desiccant bed; 4-grain; 5-transparent polythene cover; 6-wood support.

Figure 25. Cross-sectional view of the direct-active desiccant solar crop dryer (Itodo *et al.*, 2019).

Figure 26. The direct-active desiccant crop dryer (Itodo *et al.*, 2019).

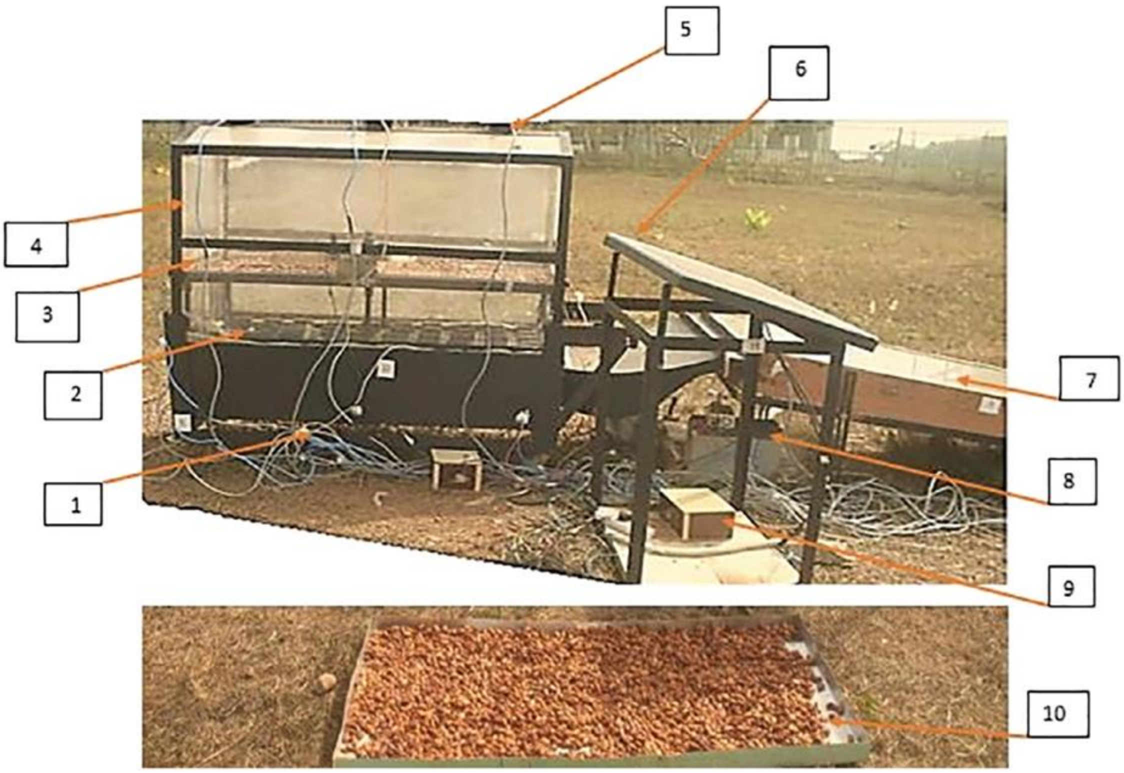


1-Absorber; 2-desiccant bed; 3-grains; 4-transparent polythene cover; 5-wood support.

Figure 27. Cross-sectional view of the direct-passive desiccant solar crop dryer (Itodo *et al.*, 2019).

Figure 28. The direct-passive desiccant solar crop dryer (Itodo *et al.*, 2019).

Komolafe *et al.* (2020) dried cocoa beans using open-sun and a force convective solar drying (SD) system with a capacity of 10 kg.



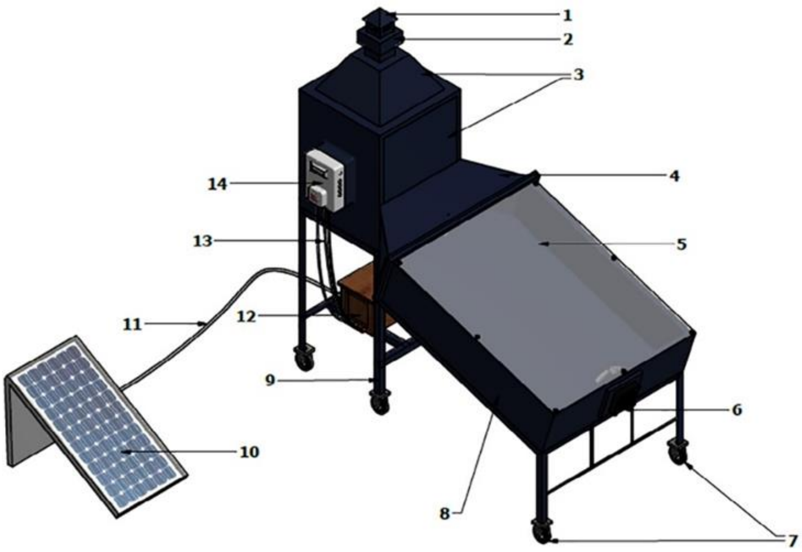
1-Temperature and humidity sensor cables; 2-Heat storage materials platform; 3-Drying chamber; 4-Supporting frame; 5-Chimney; 6-Solar panel; 7-Solar collector; 8-Battery/inverter/charge controller; 9-Data logger housing; 10-Open-sun drying.

Figure 29. Pictorial view of the experimental set-up (Komolafe *et al.*, 2020).

Ndukwu *et al.* (2020a) investigated the drying of potato slices with an active mix-mode wind-powered fan and with a passive mix-mode non-wind-powered solar dryers with and without thermal energy storage. Results showed that, active mix-mode wind power fan solar dryer with energy storage took shorter drying time. The energy consumption changed between 4.10 to 4.98 MJ, while the specific energy consumption ranged from 2.85 to 3.69 kWh kg^{-1}. The drying efficiencies ranged from 25.03% to 31.50%. This naturally powered fan with any place without electricity would supply shorter drying times and also saving about 15.3 to 290.4 $ per year (Figure 30).

Figure 30. Developed prototype solar dryer without and with a wind generator (Ndukwu *et al.*, 2020a).

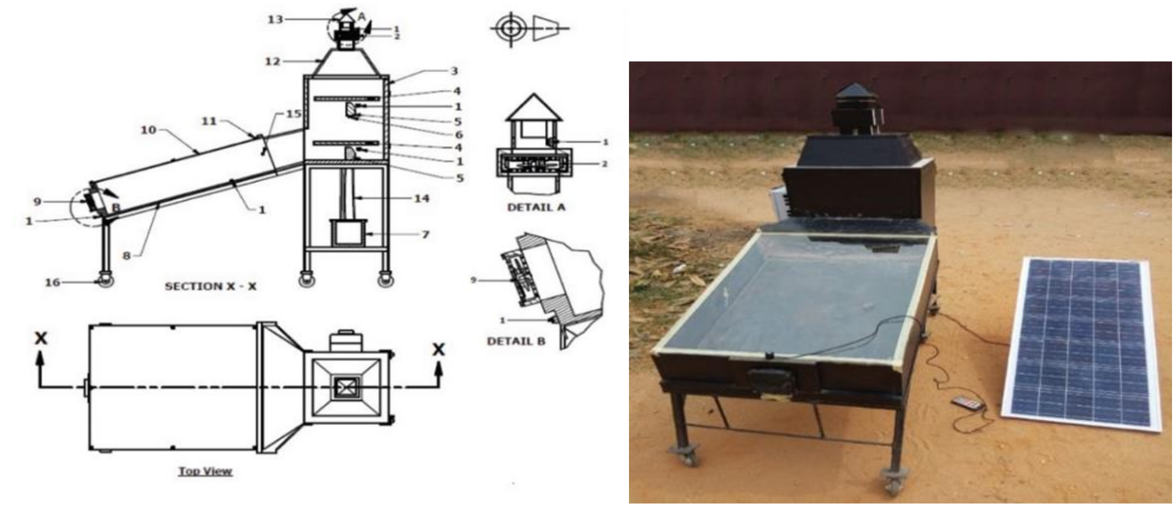
Nwakuba *et al.* (2020a) used an active hybrid solar-electric dryer to dry tomato slices (Figure 31). The study examined the effects of varying process parameters such as drying air temperature, sample thickness and air velocities on the total and specific energy requirements, drying time, lycopene content, ascorbic acid and color properties. The results showed that, the total and specific energy requirements for a batch of tomato varied from 7.82 to 125.48 kJ h^{-1} and 6.70 to 179.83 kJ hg^{-1}. In addition, optimum drying conditions were found as 57.28°C, 14.08 mm, and 1.3 m s^{-1}, and the specific energy requirement, lycopene content, ascorbic acid content, nonenzymatic browning index, brightness, redness to yellowness ratio, and drying time were 103.3 kJ hkg^{-1}, 58.7 mg $100mg^{-1}$ dry matter, 2.9 mg g^{-1}, 0.51 absorbance unit, 60.07, 0.77 and 61.88 minutes, respectively. It was announced that, the improved dried tomato quality could be obtained together with higher dryer energy efficiency and cost-effectiveness.



1-Chimney; 2-Outlet/Exhaust fan housing; 3-Drying chamber hood; 4-Heating chamber; 5-Plain glass; 6-Inlet sensor fan; 7-Rollers; 8-Solar collector; 9-Angle iron support; 10- Solar panel; 11-Solar panel cable; 12-Inverter/Battery unit; 13-Control unit cable; 14-Control unit.

Figure 31. Isometric view of the hybrid solar dryer (Nwakuba *et al.*, 2020a).

Nwakuba *et al.* (2020b) developed hybrid solar-electric dryer (HSED) and investigated during the rainy season (Figure 32). In this study, thermal characteristics, drying efficiency of the dryer at diferent conditions for 1.5 kg fresh sliced tomato samples. According to the results, the total and specific energy consumption of tomato slices changed between 5.61-120.31 kJ h and 5.18-167.59 kJ hg^{-1}, respectively. The energy contribution by solar and electric heat units varied between 44.57-56.24% and 43.76-55.43%, respectively. Drying time and drying efficiency ranged between 130 and 330 min and 4.33-36.38%, respectively. The average energy efficiency of the hybrid system increased from 15.67 to 38.17%. According to the results of economic analysis, an amount of about 1490 $ could be saved per year by using this solar dryer with a payback period of 0.72 years.



1-Temperature/Humidity sensors; 2-Exhaust fan; 3-Door frame; 4-Drying racks; 5-Weighing balance; 6-Iron bar (support); 7-Battery/Inverter assembly; 8-Solar collector; 9-Inlet fan; 10-Plain glass; 11-Screw bolt; 12-Drying chamber hood; 13-Chimney; 14-Cable; 15-Heating element; 16-Roller.

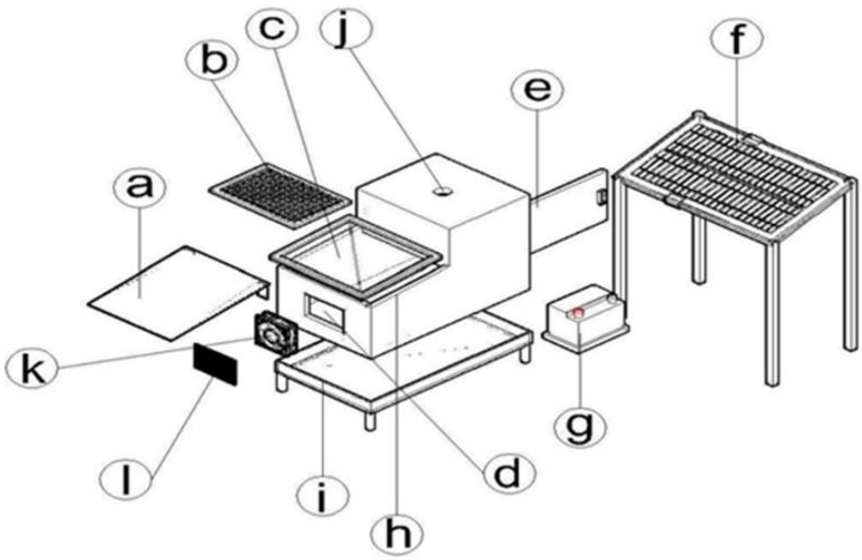
Figure 32. Hybrid solar-electric dryer (Nwakuba *et al.*, 2020b).

Ndukwu *et al.* (2020b) designed, fabricated and tested a low-cost hybrid solar drying system with and without biomass heater (Figure 33). The results showed that, drying time could be reduced between 27.78% and 58.33% by using solar dryer when compared to open sun drying method for 5 mm thick plantain slice. The average drying efficiency was found between 8.4% and 14.64% for solar dryers.

A-solar dryer without biomass heater; B-side view of the array of the two solar dryers with the biomass heater furnace open; C-solar dryer showing the biomass heater furnace covered and the door open; D-the biomass heater with the cylindrical pipe in place to create the flue gas duct during feedstock loading; E-biomass furnace revealing the connection of the exit pipe into the combustion chamber; F-sun drying of the plantain slices

Figure 33. Prototype of the indirect solar dryer (Ndukwu *et al.*, 2020b).

Etim *et al.* (2020) designed and constructed active indirect solar dryers for drying of banana. The dryers were constructed with different air inlet shapes. Total of 52 dryers were required for the experimental design (Figure 34 and Figure 35). According to the results, the dryers were able to conserve almost 40% of the total drying time for the products when compared to natural open sun drying. The efficiency of the driers changed between 13.85 to 31.84%. It was observed that the air inlet area of the dryer had significant effect on the efficiency of drying. Increasing the air inlet area correspondingly enhanced the performance of the dryer and vice versa.



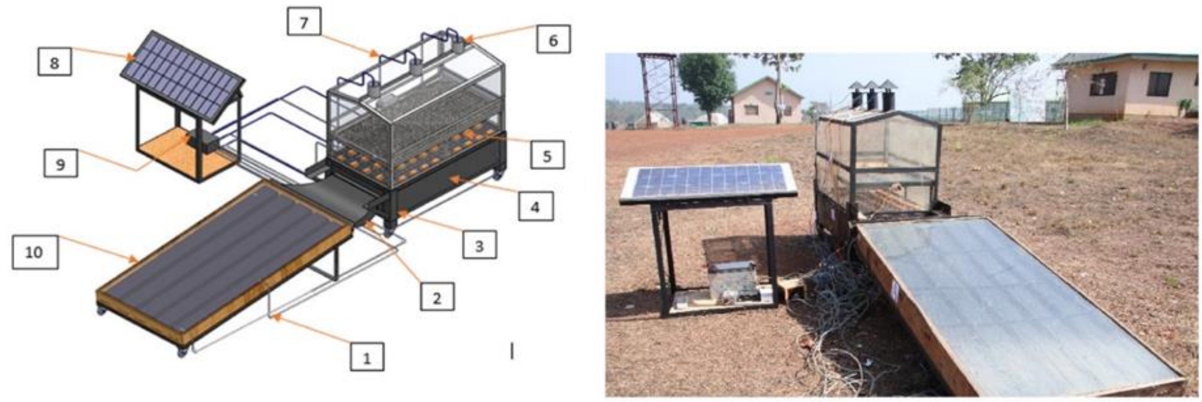
a-Absorbent plate; b-drying tray; c-transparent cover material; d-air inlet area; e-drying chamber door; f-solar panel; g-DC battery; h-drying cabin; i-dryer telescopic leg; j-air outlet; k-blower; l-solar charge controller.

Figure 34. Exploded view of the dryer (Etim *et al.*, 2020).

Figure 35. Aerial view of the experimental set up (Etim *et al.*, 2020).

Komolafe *et al.* (2021) examined forced convective solar drying system for cocoa beans incorporated with thermal energy storage to increase the dryer's operation period (Figure 36). The drying process of cocoa with the developed dryer is a combination of convective heating of the hot air and the direct radiation through the Perspex glass cover. It took 50 h to decrease moisture content from 0.60 to 0.059 g g^{-1} w.b.

Oni *et al.* (2022) compared modern fabricated solar dryer (MFSD) (Figure 37), hybrid biomass dryer (HBD) (Figure 38) and open-air drying (OAD) methods of maize to prevent aflatoxin-contamination. According to the results, a faster drying process with a reduction of aflatoxin in solar dried maize samples were obtained.



1-One of the temperature cables; 2-connecting duct; 3-supporting frame; 4-plenium chamber; 5-drying chamber; 6-chimney; 7-one of the relative humidity sensor; 8-solar panel; 9-data acquisition system; 10-solar collector.

Figure 36. Schematic and pictorial view of the experimental set-up indicating all the major components of forced convective solar dryer (Komolafe *et al.*, 2021).

Figure 37. Modern fabricated solar dryer (Oni *et al.*, 2022).

Figure 38. Solar biomass dryer (Oni *et al.*, 2022).

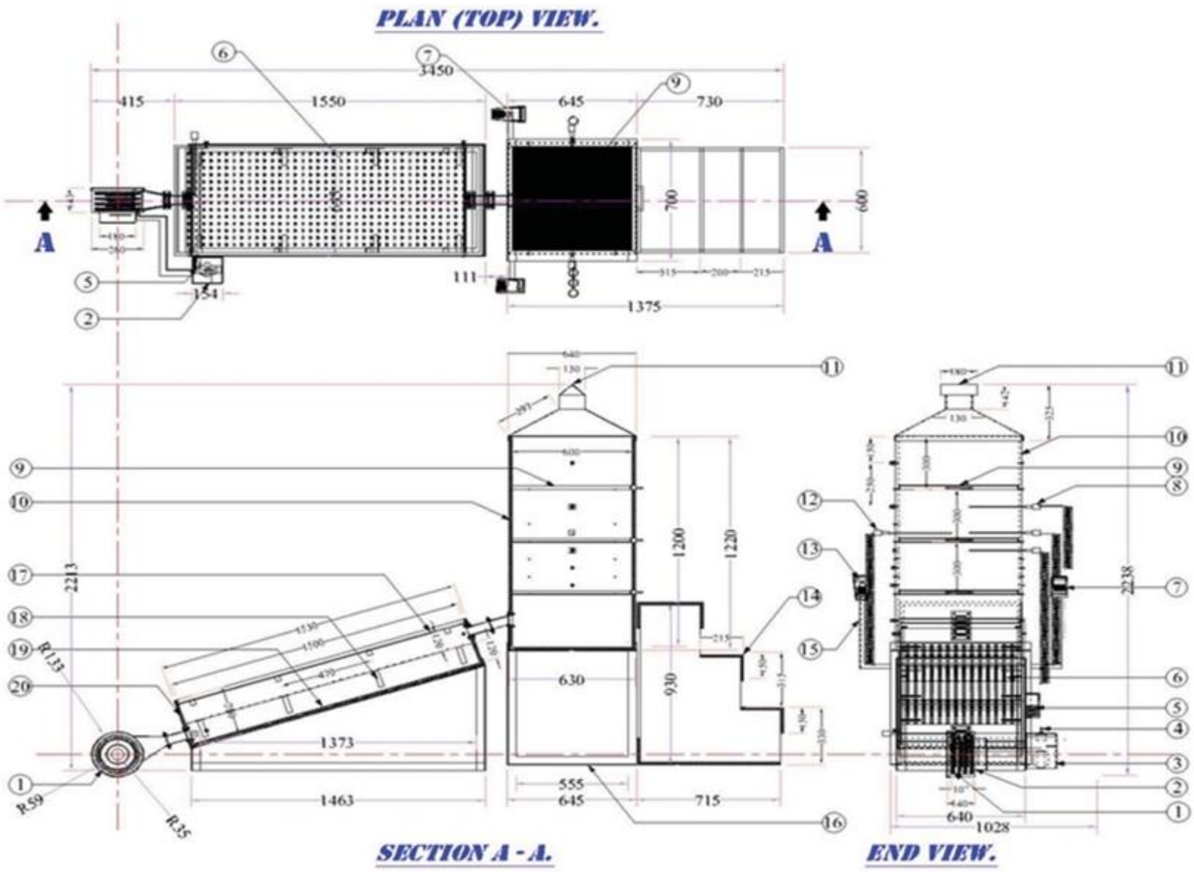
Kuhe *et al.* (2022) developed and tested a mixed-mode active solar crop dryer with a transpired solar air heater and conducted experiments for maize drying (Figure 39 and Figure 40). According to the results, the grain samples are dried faster at higher air mass flow rates. The drying efficiencies ranged between 55.3-82.2%. The drying efficiency reached its highest value at air mass flow rate of 0.038 kg s^{-1} and the minimum value at air mass flow rate of 0.026 kg s^{-1}. The developed system is suitable for drying 6 kg of maize in one batch in six hours.

Figure 39. Complete assembly of the active transpired indirect solar cabinet dryer (Kuhe *et al.* (2022)).

CONCLUSION

In Nigeria, part of the challenges of sustainable food for its citizens is as a result of loss of crop produces to wastage due to inadequate preservation techniques. This challenge had led to the introduction of solar dryers as a preservation appliance in Nigeria over the past few decades. They all could be used for drying different products according to the climatic conditions of Nigeria in the drying industry, they could improve product quality then produced by sun drying.

In as much as the fact that solar drying appliances is not as popular as the traditional open-air sun drying being used, there has been a considerable study carried out those dryers with most documented in leading articles. This article, on the review of most of the research works carried out using solar dryers in drying various crop produce shows that, there is great potential for its usage in Nigeria.



1 Fan, 2 Blower fan housing, 3 Fan regulator casing, 4 Fan Regulator, 5 Solarimeter, 6 Transpired Absorber Plate, 7 Thermocouple, 8 Thermocouple probe, 9 Trays, 10. Drying cabinet, 11 Vent, 12 Air flow probe,13. Air flow metre, 14 Staircase, 15 Probe hanger, 16 Frame, 17 Glass cover, 18 Absorber plate hanger, 19 Insulated lining, 20 Solar box collector.

Figure 40. Detailed drawings of solar dryer (Kuhe *et al*., 2022).

RECOMMENDATIONS

The research experiments reviewed so far shows great potentials for its application in Nigeria. The government should key into this initiative through establishment of support bodies for the local farmers rather than leaving the cost and its associated expenses in setting up large scale solar dryers to the local farmers. Also, efforts should be made to encourage the commercialization of the solar dryers fabricated using the locally available materials. Lastly, sensitization of the local farmers should be carried out across the country on the benefits associated with using a solar dryer for the drying of their agricultural products over the traditional open sun drying which they are used to over the years.

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DECLARATION OF COMPETING INTEREST

The authors declare that they have no conflict of interest.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Henry Okechukwu Okonkwo: Contributed to literature research, evaluation and writing of the paper

Can Ertekin: Contributed to supervising, evaluation, editing and reviewing of the paper.

ETHICS COMMITTEE DECISION

This article does not require any ethical committee decision.

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