A STUDY ON THE PERFORMANCE OF A POLYVINYL CHLORIDE (PVC) PASSIVE SOLAR DRYER FOR PERISHABLE CROPS

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ABSTRACT

This research aimed to design, develop, and evaluate a passive solar dryer for perishable crops. The dryer consisted of a drying tray, cover sheet, absorber plate, insulator, and drying chamber. It was designed to operate as a batch dryer, with heat energy for drying supplied by concentrating solar radiation on the collector. Heat transfer to the drying materials and mass transfer from the drying materials were achieved through a natural convective process (passive operation mode). The study demonstrated that both okra and pepper could be effectively dried using solar dryers and traditional sun drying methods, with okra generally drying faster than pepper. The solar dryer removed 0.243 kg of water from okra and 0.133 kg from pepper, achieving efficiencies of 15.63% and 35.52%, respectively. In contrast, the sun drying method removed 0.225 kg of water from okra and 0.137 kg from pepper, with efficiencies of 34.21% and 33.50%, respectively. The solar dryer was evaluated using only pepper and okra, which might limit the generalization of the findings to other fresh horticultural materials. The developed solar dryer can be improved by optimizing its design variables (drying chamber size, collector area size, and material) and process variables (maturity level and size of horticultural materials to be dried), as these factors can significantly influence the efficiency and effectiveness of the passive solar dryer.

Keywords: Passive solar dryer, Perishable crops, Polyvinyl chloride, Drying efficiency, Horticultural materials

1 INTRODUCTION

The development and function of the human body rely on various vitamins and minerals abundantly supplied by fruits and vegetables like tomatoes, peppers, carrots, pineapples, and leafy greens. Advances in nutritional and medical sciences have significantly increased the demand for these foods, especially due to the recognized benefits of antioxidants. Fruits such as tomatoes, peppers, and garden eggs are rich sources of dietary fiber, essential vitamins (such as C, B6, and E), and minerals (such as potassium, iron, and calcium), offering substantial health benefits [1]. Antioxidants, including tocopherols, tocotrienols, phenolic compounds, and carotenoids, help reduce the risk of major diseases and promote overall health [1, 2]. Vitamin A and carotenoids are vital for vision, immune function, and skin health, with carotenoids providing antioxidant protection. Additionally, dietary fiber from fruits and vegetables supports digestive health, lowers cholesterol, and regulates blood sugar levels, reducing the risk of cardiovascular disease and type 2 diabetes. The diverse nutrients in fruits and vegetables play a crucial regulatory role in many body systems [2]. Post-harvest losses in developing countries, particularly in sub-Saharan Africa, range between 20% and 50%, posing a serious challenge to global food security and resulting in lost income and livelihoods for farmers [3, 4]. These losses in fresh horticultural products are

attributed to rudimentary post-harvest management practices, inadequate handling and storage facilities, microbial infestation, mechanical injuries, and environmental factors [5, 6]. Studies have investigated techniques and measures to efficiently and sustainably mitigate post-harvest losses globally [7]. Recommended measures include cold storage and refrigeration, atmosphere modification (e.g., controlled/modified atmospheres), drying, and processing fruits into juices, purees, and powders, as well as canning/packaging [3].Various drying techniques have been developed over the years, including open-air sun drying [9, 10], heat pump drying, hot air drying, vacuum drying [9, 11], and spray drying [12]. These techniques have been widely evaluated and are noted for their throughput capacity and thermal efficiency (except for open-air drying). However, the dryers used in these techniques are typically costly to procure and operate, which can hinder their adoption by subsistence farmers and processors. Given that most farmers in Nigeria and other developing countries are subsistence farmers, these techniques may not be suitable for mitigating post-harvest losses in fresh fruits and vegetables [4]. Open-air drying is common in Nigeria and other developing countries due to the free and readily available solar energy in the tropics. Nigeria, located in the high solar radiation belt of the world, receives an annual average of about 3.5 kW h/m²/day in the coastal latitudes and about 7.0 kW h/m²/day in the extreme northern part of the country [13]. However, open-air drying faces challenges such as dependence on the time of year and meteorological variables (air temperature, relative humidity, wind speed, and cloud cover). It also exposes agricultural materials to contamination from pathogenic microorganisms and loss to reptiles and birds. Several studies have examined the development and performance of various operational modes of solar dryers for drying horticultural materials in different environments [6, 14, 11]. [15] designed, developed, and evaluated a solar dryer for drying agricultural by-products, comparing the suitability of different modes (passive, active, and hybrid). Their results identified the forced-hybrid mode as the most efficient, followed by passive and active modes. They also found that hybrid and mixed modes can reduce drying time by about 50%. However, their study focused only on olive pomace in Spain, which may not represent other horticultural materials or different meteorological conditions worldwide. [11] examined the drying performance and economic feasibility of novel hybrid passive-mode and active-mode solar dryers in East Africa. Specifically, they evaluated the performance of an improved solar dryer (ISD) under Ugandan conditions. Their active dryer included a photovoltaic-assisted, hot-air, active solar dryer and a solar photovoltaic and electric dryer (SPE), with conventional open-sun drying as the control. The economic analysis revealed that the cost of drying was lower with the ISD than with the SPE, and the payback period for the ISD was 2.4 times shorter than for the SPE. These results suggest the ISD is a better technology for resource-constrained farmers/agro-processors without electricity in Uganda and East Africa. A study by [15] documented the evaporative capability of the Nigerian climate by developing and evaluating a laboratory-scale solar grain dryer in Makurdi, Nigeria. Using fresh maize with a moisture content of 32.8% w.b., they found overall drying rates of 0.7 kg/day with traditional sun drying and 0.31 kg/day with a passive solar dryer. Higher collector temperatures and higher flow rates of drying air compared to ambient conditions were associated with higher drying rates and shorter drying times [11]. [6] recorded drying chamber temperatures of 33-59°C, compared to ambient temperatures of 25-31°C in Nsukka, Enugu State, Nigeria. Dryers have been developed and used to dry agricultural products in order to improve shelf life [16]. However, most of these dryers use expensive source of energy or a combination of solar and some other forms of energy [17]. Most of these innovations have not been adopted by the small-scale farmers, either because the final design and data collection procedures are frequently inappropriate or the cost has remained inaccessible and the subsequent transfer of technology from researcher to the end user has been a problem [18]. [19] designed and constructed a solar hot box and obtained about 180°C which could be regulated and used to dry agricultural produce. [20] designed a solar permanent drying system that can remove half of the moisture in an organic material, like the drying system required to dry peanut from 20 % to 10 % moisture content in 3 days. Ofi [21] designed and fabricated an indirect solar drying system consisting of a flat-plate collector made from corrugated galvanized iron sheets and achieved a max chamber temperature of about 50°C. [22] reported as cited by [23] that farmers in Nigeria have troubles with sun drying of vegetables most especially drying tomatoes. It was reported by [23] that indirect methods require the development of small temperature differentials, which affects drying. The process is achieved by circulation of air directed through the drying

trays to the products. [24] states that vegetable drying is facilitated by slicing and spreading out the product to increase their surface area to hot air; adopting a reliable heat medium; increasing the circulation of air around the product; insulating the areas that are not exposed to the same source of heat to avoid heat loss, avoiding direct heating since this affects the quality and appearance of the product and protecting the dried products against contamination, re-absorption of moisture from the environment and harmful effect of sunlight. It is against this background that a portable, low-cost, polyvinyl chloride (PVC) passive solar dryer for drying okra and sweet pepper was developed.

2 MATERIALS AND METHODS

The dryer was designed to operate on the principle of natural convection (i.e. passive solar dryer) following the procedures documented in [6, 25].

2.1 Material selection and dryer components

The following materials and equipment were used in the construction of the solar dryer, namely, circular saw, steel tape, carpenter's pencil, screw gun, paint gun, wire mesh, drilling machine, scissors, thermometer, timer, hygrometer, wind vane, digital weighing machine and sawing machine. The construction steps involved mapping out of dimensions based on the designed values, cutting out of mapped dimensions and joining/fastening of the various components. The dryer consisted of an absorber plate, polyvinyl chloride cover sheet, drying tray, insulator, air inlet and outlet ports.

2.2 Dryer design and evaluation method

Wood was selected for housing (casing) and for insulation because of its poor heat conductivity and it is relatively cheap. Mild steel sheet of 1mm thickness was used for the absorber plate, and it was painted black colour to enhance its heat absorption capacity. The dimension of the solar collector was 54 cm X 34 cm. Ultraviolet (UV) polyethylene sheet was used as a glazing/cover sheet because it allows for a unidirectional flow of heat from the atmosphere into the drying chamber but prevents the flow of heat from the drying chamber to the external environment. Heat transfer from the drying chamber to the ground surface was prevented by using wood as an insulating material. Given the small size of the solar dryer, a plywood of 2 cm thickness was used. The polyvinyl cover was cut to a dimension of 49 cmx 34 cm for each of the walls along the length of the dryer, while for the walls on each of the widths, a dimension of 28cm X 34 cm was used. The drying tray was constructed using wire mesh/net to allow for sufficient flow of air through the drying materials during the drying process. The dimension of the drying tray was 1836 cm^2. The wire mesh was also applied to the air inlet and outlet ports to prevent insects, flies and rodents from gaining access to the drying chamber as well as contaminating the drying materials. The required number of dryer tray was estimated using Equation 1.

$$T_n = \frac{A_D}{A_C} \tag{1}$$

Where T_n = Collector area (cm^2), A_D = Width of dryer (cm), A_C = Length of the dryer (cm). Mass of water removed from the drying materials was computed using Equation 2.

$$\Delta M = M_i - M_f \tag{2}$$

Where ΔM = Mass of water extracted/removed from the drying material (kg), M_i = Initial mass of sample (kg), M_f = Final mass of sample (kg).

2.3 Dryer evaluation procedures

The dryer was designed, developed and evaluated at the department of Agricultural and Environmental Engineering, Modibbo Adama University, Yola; Nigeria (9^o21^1N and 12^o29^1E) (See Figures 1-2 for the details of the Engineering drawing and for the picture of the developed solar dryer). Prior the drying test, the solar dryer was operated empty to determine the highest temperature that could be developed within the drying chamber; during which a maximum temperature of 44°C was recorded for the drying

chamber while the ambient environment recorded a maximum temperature and relative humidity of 37°C and 16%, respectively. The wind speed of the ambient environment for the stated location was 2.57 m/s. The actual drying test started at 10:40 am to 5:38 pm on Saturday (02 December, 2023) and continued on the next day (Sunday, the 3rd December, 2023) at 10:40 am to 5:38 pm); indicating a drying duration of 11 hours 48 minutes. The dryer was placed directly under the sun and was loaded with 0.63 kg fresh pepper and 0.315 kg of fresh okra. The drying materials were monitored intermittently until when they were completely dried. At the end of the drying process, the mass of the dried samples (pepper and okra) was determined. The efficiency of the developed dryer was estimated using Equation 3.

$$\eta_d = \frac{W_o}{W_{in}} \times 100 \tag{3}$$

Where η_d = Dryer efficiency (%), W_f = Final mass of material after drying (kg), W_{in} = Initial mass of material before drying (kg).

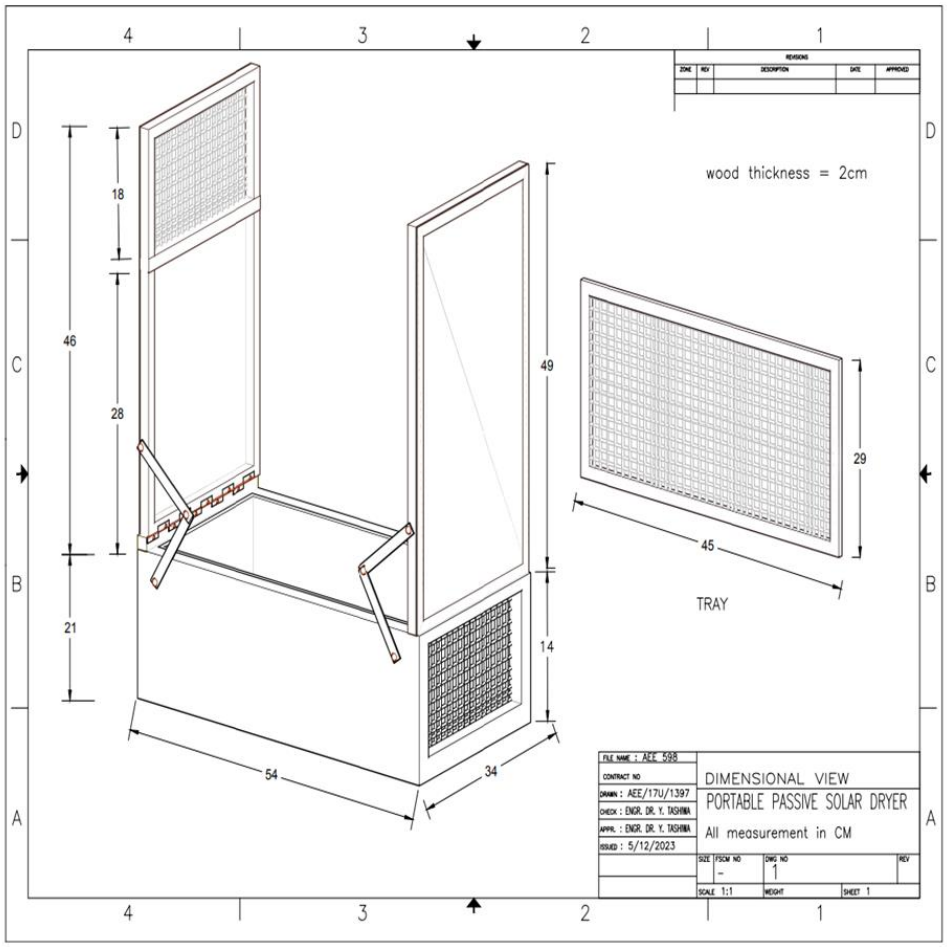

Figure 1. Dimensioned view of the designed passive solar dryer

Figure 2. Constructed passive solar dryer

3 RESULTS AND DISCUSSION

Figure (a, b, and c) presents the drying time, the amount of moisture extracted, and the overall drying rates under solar dryer and sun drying conditions, respectively. Starting with drying time, okra takes slightly longer to dry under solar conditions (9.8 hours) compared to sun drying (9.3 hours) (Figure 4a). This might be due to the polyvinyl chloride cover, which prevents drying to take place during the period when it is not under the sun, while the okra exposed to sun drying continues to experience moisture removal even during the night. This might be the reason why the drying time of the sun drying was less than that in the solar dryer. While pepper dries in about 11.8 hours in the solar dryer and 11.6 hours under sun drying. This indicates that okra generally dries faster than pepper, with sun drying showing a marginal advantage in reducing drying time for both crops. The reason sun drying was more effective in this study could be attributed to the fact that in sun drying moisture removal continues even during the night time. While in the solar dryer moisture removal is dependent on the hours it is exposed to the solar radiation. Examining the moisture removed, okra loses 243 grams of moisture under solar drying and 225 grams under sun drying (Figure 4b). Pepper, in comparison, loses 133 grams of moisture under solar conditions and 137 grams under sun conditions. Considering the overall drying rate, okra exhibits an overall drying rate of 24.8 g/hr under solar conditions and 24.2 g/hr under sun conditions. For pepper, the rates are 11.27 g/hr under solar conditions and 11.8 g/hr under sun conditions (Figure 4c). This confirms that okra maintains a consistently higher drying rate than pepper, reflecting its faster moisture removal per hour under both methods. In comparison to existing literature on the performance of passive solar dryers under the Nigerian climate, the results obtained from this study are encouraging. The maximum temperature developed within the drying chamber in this study was (44°C) is lower than the maximum temperature recorded in a similar study conducted in Enugu State, Nigeria (59°C) by [6]. Furthermore, the range of the overall drying rate recorded in this study (11.8 - 24.8 g/hr or 0.283 – 0.5952 kg/day) is consistent with the drying rate (0.31 – 0.70 kg/day) reported by [14] for a laboratory-scale grain solar dryer in Benue State, Nigeria. Additionally, interpreting the findings from this study in light of a similar study by [17], who observed a considerable reduction in drying cost with a passive solar dryer compared to a photovoltaic, active solar dryer, it can be suggested that with minor design refinements, a passive solar dryer like the one in this study would be highly beneficial to Nigerian vegetable farmers. The majority of these farmers (>70%) are subsistent in nature [4]. The passive solar dryer could save costs, increase revenues, and enhance food security by reducing postharvest loss of horticultural materials, which has been quite significant. Table 1 shows the initial design parameters for the passive solar dryer.

Table 1. The initial design parameters for the passive solar dryer

Items	Considerations
Latitude (Yola)	70 – 110 N
Longitude (Yola)	110 – 140 E
Products	okra and sweet pepper
Drying period	10:00am-5:00pm
Initial moisture content of okra	64% W.b
Final moisture content of okra	10% W.b
Initial moisture content of sweet pepper	68%
Final moisture content of sweet pepper	12%
Ambient air temperature, (Tam)	37 0C average for Yola
Ambient relative humidity (Rh)	16% average for Yola
Maximum allowable temperature (Tmax)	440C
Drying time (sunshine hours) (td)	11 hours (average for 2 days)
Daily mean global insulation (I)	539.9W/m2 (average Yola)
Air density	1.01Kg/m3
Air specific capacity (cp)	1.092KJ/KgK
Humidity ratio	0.0018kg H2o/Kg drying air

Figure 3. Fresh and dried materials: a) Pepper and okra before drying; b) Samples during the drying period; c) Sun-dried pepper; d) Solar-dried pepper; e) Sun-dried okra; f) Solar-dried okra

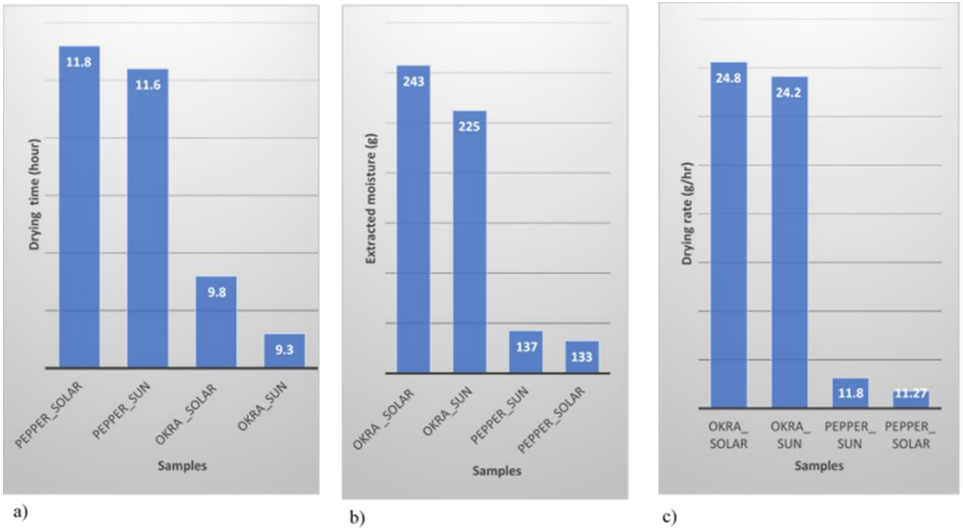

Figure 4. Drying duration and rates under solar and sun drying conditions: a) Drying time for the studied samples under solar and sun drying conditions; b) Extracted moisture under solar and sun drying conditions; c) Overall drying rate for the various samples and drying conditions

4 CONCLUSIONS

The study demonstrates that both okra and pepper can be effectively dried using solar dryers and traditional sun drying methods, with okra showing a generally faster drying rate than pepper. The solar dryer exhibited a slightly longer drying time compared to sun drying, but it achieved comparable moisture removal and drying rates. Which was attributed to sun dried products had longer time of air exposure and limited time for products in the dryer. If the products were subjected to same treatment by cover both after sun exposure, that in the solar dryer would have performed better due to increase in temperature in the solar dryer. These findings align with existing literature, suggesting that passive solar dryers are a viable option for vegetable drying under the Nigerian climate, offering potential benefits in cost savings, time reduction and postharvest loss reduction. There is the need for future researches to focus on optimizing the design of passive solar dryers to further enhance their efficiency and effectiveness. Investigating the impact of varying climatic conditions across different regions in Nigeria could provide insights into regional adaptability.

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