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Performance study of two designs of solar dryers

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Abstract

Two solar dryers (chimney and cabinet) were fabricated and tested in Mubi, Adamawa State, Nigeria. Both have the same basin area. For the solar chimney dryer, the vapor formed due to evaporation, is taken away by the air entering into the drying chamber from one end and escapes through the chimney provided at the top with the aid of the supplied dc fan, while for the solar cabinet dryer, the vapor escapes through hole provided at the side of the system. Both dryers were used to perform experimental test in drying 50kg of tomatoes, pepper and bitter leaves. With solar chimney dryer, results reveal that these quantities of tomatoes, pepper and bitter leaves can be dried within 129, 105 and 84h, respectively giving an average 51% of the time spent for the natural sun drying. With solar cabinet dryer, the same quantities of tomatoes, pepper and bitter leaves can be dried within 138, 129 and 90h, respectively with an average 79% of the time spent for the natural sun drying. It was finally observed that solar chimney dryer yields the best result. The color and the flavor of the food stuffs dried with this dryer are comparable to that of a high quality dried in markets. They are free from microbiological contamination.

Keywords: Solar Dryers; Vapor; Experimental Test; Microbial Contamination.

INTRODUCTION

Drying is a simple, low-cost way to preserve food that might otherwise spoil. Drying reduces the moisture content of a product to a level below which deterioration does not occur and thus prevents fermentation or the growth of molds. It also slows the chemical changes that take place naturally in foods, as when fruit ripens. Surplus grain, vegetables, and fruit preserved by drying can be stored for future use. Drying depends upon the rate at which the moisture within the product moves to the surface by a diffusion process depending upon the type of the product [1]. Drying for other spices like chili and pepper, is not only for preservation purposes but also for modifying the tastes and flavors in order to increase their values in market. Studies on drying of agricultural products using the sun have been carried out. These studies include that of Anwar and Timani [2], Komolov et al [3], Zaman and Bala [4], Brooker et al [5], Garg and kumar [6] and Goyal and Tiwari [7] to mention but a few.

In most of the developing countries, people have been drying agricultural products for decades by placing the agricultural products on mats in open air. This is considered as drying under primitive condition. Primitive condition drying practiced on a large scale in the rural areas of the developing countries suffers from high product losses due to inadequate drying, fungal growth, encroachment of insects, birds and rodents, etc. The unexpected rain or storm further worsens the situation. Further, over drying, insufficient drying, contamination by foreign materials like dust, dirt insects and micro-organisms as well as discoloring by Ultraviolet Radiation [8, 9] are observed for open sun drying. Furthermore, open air drying is often not possible in humid climates. Generally, open sun drying does not fulfill the international quality standards and therefore it can not be sold in the international market.

Properly designed solar dryers may provide a much-needed appropriate alternative for drying of some of the agricultural products in developing countries [10-12]. Artificial drying is economically feasible, especially when used on large farms. Nevertheless, the acquisition and operational costs of these dryers significantly increase the costs of the dried product. Therefore, since solar dryers use solar energy (a renewable and low pollutant source of energy) to dry agricultural products, they in turn present an interesting and promising alternative. Considerable efforts have been made to design and develop solar dryers for drying of agricultural products [13-15]. A large number of solar food dryers have been developed over the past few years [16-24]. Although solar dryers involve an initial expense, they produce better looking, better tasting, and more nutritious foods, enhancing both their food value and their marketability.

Most of the modern drying technologies available are expensive and not appropriate for a developing country like Nigeria, particularly in the areas where prerequisites for these, such as electricity are simply not available adequately; an alternative is to develop a simple inexpensive and more scientific methods for preservation of agricultural products.

The aim and objectives of this research are to develop a Solar Chimney and a Solar Cabinet Dryers for crops and to investigate their performances. Both dryers are relatively inexpensive compared to systems used in developed countries.

2. Description and Operation the Dryers

2.1. Solar Chimney Dryer

A solar chimney dryer was designed, fabricated and installed at the Department of Physics, Adamawa state University, Mubi, Nigeria. Figure 1 shows a schematic diagram of the designed solar chimney dryer, which basically consisted of a drying chamber, an absorbing surface, wooden frames, wire mesh, glass cover, chimney, a dc fan and a 40 W photovoltaic module. The drying chamber consists of an absorber plate made of aluminium sheet, and painted to form a matt black surface (absorptivity of about 0.96 and emissivity of about 0.06 from absorbed energy). The absorber plate is insulated from the bottom to prevent heat losses. Glass wool was used between the aluminium sheet and the wooden frames at the bottom of the drier as an insulation material to reduce the heat loss from the bottom of dryer. A wire mesh was then placed on top of the absorber plate serving as the drying area. A plastic chimney containing a dc fan was fixed on top of the dryer. The top of the dryer is covered with 3mm thick transparent glass (transmissivity of about 0.88). The glass is tilted to the angle of latitude of Mubi, Adamawa State – Nigeria,$10^0 15^'$, to ensure maximum transmission of solar radiation into the dryer. Also tilted to the latitude of Mubi, on top of the dryer is photovoltaic module as a power source to operate the fan. The drying chamber can be opened easily for operation and transportation from one place to another. The edges of the glass are sealed with headlamp gum so that the entire dryer becomes air tight. The entire material is made of quality material designed to withstand the harsh conditions produced by sunlight and it is placed on a wooden stand.

A part of incidence solar radiation on the glass cover is reflected back to atmosphere and remaining is transmitted inside the drying chamber. Further, a part of transmitted radiation is reflected back from the surface of the crop on the wire mesh. The remaining part is absorbed by the surface of the crop. Due to the absorption of solar radiation, crop temperature increases and the crop starts emitting long wavelength radiation which is not allowed to escape to atmosphere due to presence of glass cover unlike open sun drying. Thus the temperature above the crop inside drying chamber becomes higher. The glass cover serves one more purpose of reducing direct convective losses to the ambient which further becomes beneficial for rise in crop and drying chamber temperature respectively. However, convective and evaporative losses occur inside drying chamber from heated crop. The moisture, that is the vapor formed due to evaporation, is taken away by the air entering into the drying chamber from one end and escaping through the chimney provided at the top with the aid of the supplied dc fan as shown in Figure 1.

2.2. Solar Cabinet Dryer

A solar cabinet dryer was also designed, fabricated and installed at the Department of Physics, Adamawa state University, Mubi, Nigeria. The schematic diagram of the designed solar dryer is shown in Figure 2. The size and the description of the system is the same as that of solar chimney dryer with the exception of the chimney which contains the fan and the photovoltaic module.

The operation of the solar cabinet dryer is also similar to that of solar chimney dryer except that the vapor formed due to evaporation (moisture), is taken away by the air entering into the drying chamber from one end and escaping through hole provided at the side of the system as shown in Figure 2.

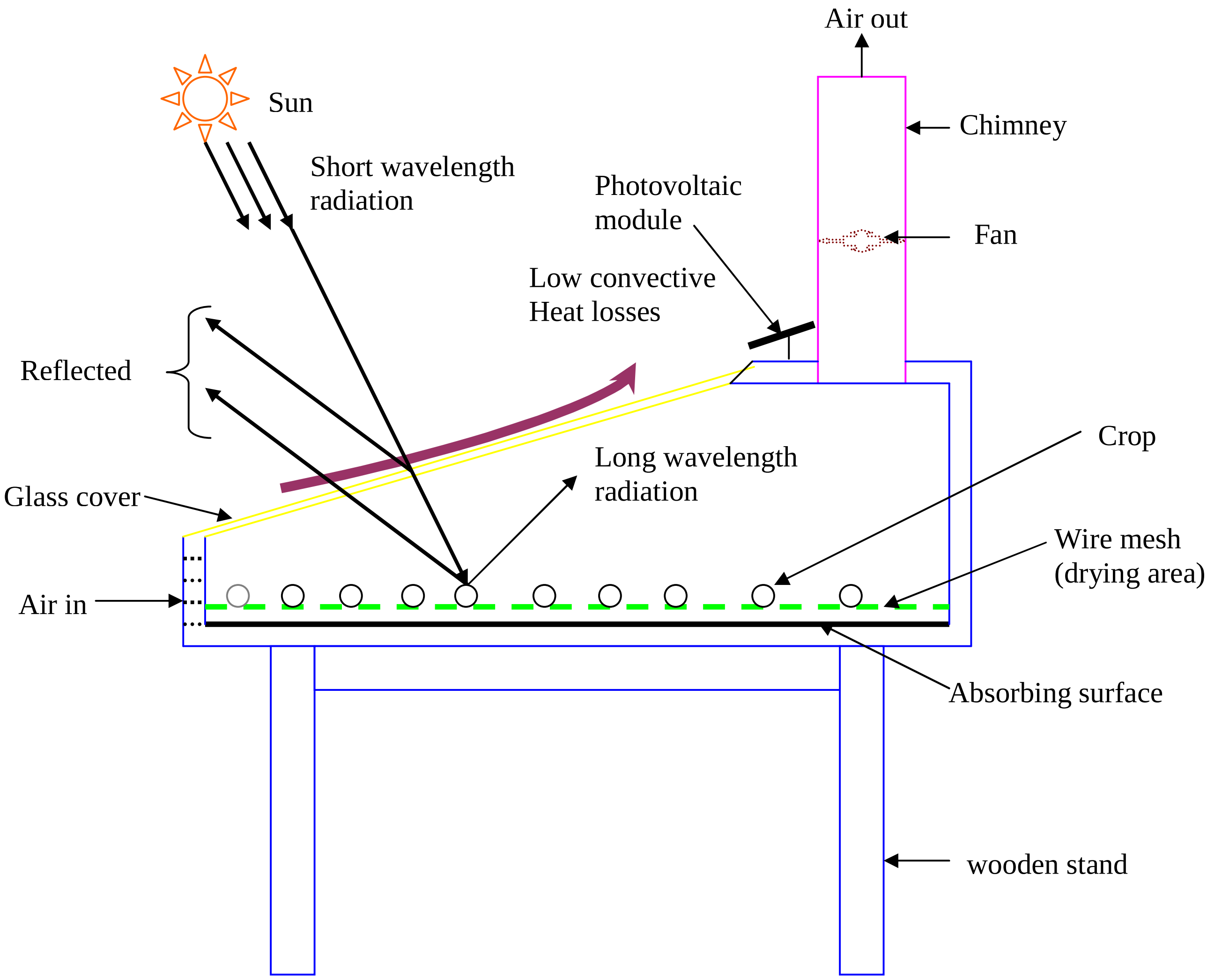

Fig. 1: Schematic of Solar Chimney Drier

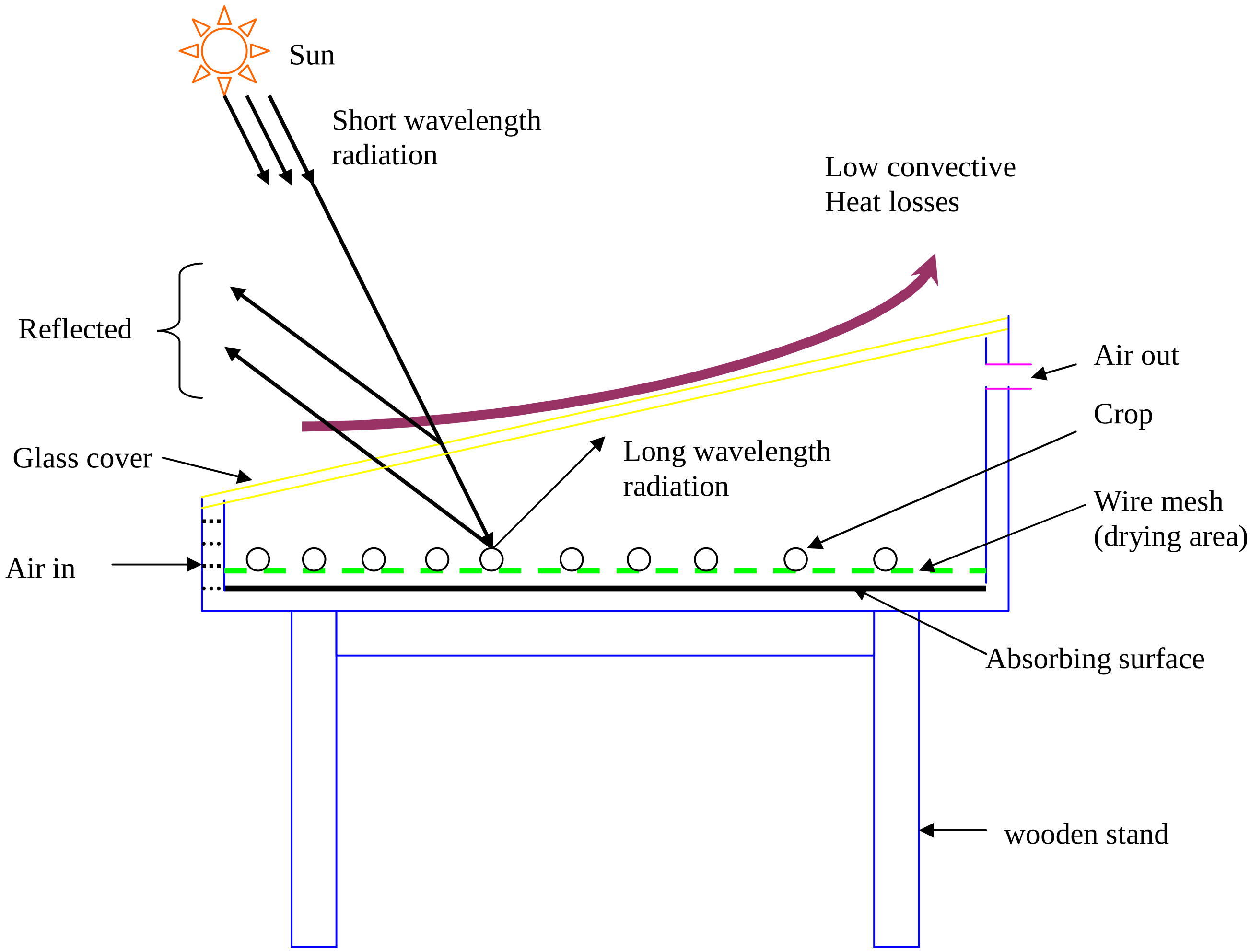

Fig. 2: Schematic of Solar Cabinet Drier

3. Theoretical Considerations

In evaluating the performance of any solar drying system the two basic criteria usually used are the kinetics and the drying effectiveness.

The re-absorption and the night moisture losses of the products are also decisive. The drying kinetics can be expressed by the drying equation [18]

$$\frac{dM}{dt} = -k(M_t - M_e) \qquad (1)$$

The moisture content on dries basis M_t is the weight of the moisture present in the product by unit dry weight matter in the product obtained in the equation

$$M_t = \frac{m_t - m_d}{m_d} \qquad (2)$$

This can also be calculated in percentage as

$$M_t = \frac{m_t - m_d}{m_d} x100 \qquad (3)$$

For instantaneous moisture content at any time

$$M_t = \left[(M_i + 1)\frac{m_t}{m_i} \right] \qquad (4)$$

The nocturnal moisture re-absorption or loss R_n is defined as the ratio of the rise in moisture content over the night period to the moisture content value at the sunset of the preceding day. R_n can be calculated in percentage from equation [4]

$$R_n = \frac{M_{sr} - M_{ss}}{M_{ss}} x100 \qquad (5)$$

Positive values of R_n mean moisture re-absorption, but negative values indicate further moisture loss.

The solar heat collector's performance is evaluated in relation to its thermal effectiveness, defined as the ratio of the useful energy on the incident solar radiation, for one period. This useful energy is closely related to the thermal losses of the system and its environment, resulting from conductive, convective and radiative exchanges. The thermal effectiveness can be expressed as [25]

$$\eta = \frac{\dot{m} C_p \int_{t1}^{t2} (T_o - T_i) dt}{A_c \int_{t1}^{t2} I_t dt} \qquad (6)$$

According to Hottel–Whiller–Bliss equation, a solar dryer thermal performance is given by [26].

$$\eta = \frac{Q_u}{A_c I_c} = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_\alpha}{I_T} \qquad (7)$$

where

$$F_R = \frac{\dot{m} C_p}{A_c U_L}\left[1 - e^{A_c U_L F' / \dot{m} C_p} \right] \qquad (8)$$

Comparing Eq. (6) and Eq. (7), the air increasing temperature in the drying chamber is given by

$$(T_o - T_i) = \frac{A_c F_R (\tau\alpha) I_T}{\dot{m} C_p} - \frac{A_c F_R (T_i - T_\alpha) U_L}{\dot{m} C_p} \qquad (9)$$

$$(T_o - T_i) = \frac{A_c F_R (\tau\alpha) I_T}{\dot{m} C_p} - \frac{A_c F_R (T_i - T_\alpha) I_{th}}{\dot{m} C_p} \qquad (10)$$

where

$$U_L = \frac{I_{th}(\tau\alpha)}{T_i - T_\alpha} \quad (11)$$

I_{th} is the threshold level of incident radiation [27].

MATERIALS AND METHODS

The experimentation were measurement of the mass, moisture content of the products to be dried and taking the solar irradiance of the environment where the products were dried. The drying tests were conducted for tomatoes, peppers and bitter leaves. At the initial drying tests, each product receives a pretreatment [28]. The tomatoes and peppers were cut into two parts and the seeds removed, and the leaves of bitter leaves were removed. After these procedures, the products were divided into two samples. The first sample was submitted to natural sun drying the second sample was dried inside the solar chimney drier and the third sample was dried inside the solar cabinet dryer. The mass of the products is determined by the electronic balance throughout the drying process. For the drying tests, 50kg of tomatoes with an initial moisture content of about 90% was used for each drying test. 50kg of peppers and bitter leaves with initial moisture contents of 80% and 60% respectively were also prepared for the drying test. Experimental data are noted every three hours at regular intervals between 6:00 a.m. to 6:00 p.m. and the fan was started at about 6:00 a.m. and it was stopped at 6:00 a.m. The fan was started again in the next morning and the process was repeated until the least moisture was reached. During these processes, insolation was taken (measurement of solar radiation) with a reliable model pyranometer (RMP001) constructed and data at 1 minute intervals was recorded using a data logger. The logger has a USB interface with proprietary software for communicating with a computer. The data was stored in a propriety binary format and later saved as a text file that was imported into excel.

RESULTS AND DISCUSSION

The experimental tests were performed in May, 2009 in Mubi, Adamawa State – Nigeria. This month is in the wet season. During this period, the town is under the influence of Inter Tropical Discontinuity (ITD) and most of the days cloudy. The variations of solar radiation are shown in Fig.3. Analysis of this figure revels that the highest and the lowest daily average irradiance occur on 20th and 14th of that month with values of 553.84 Wm^{-2} and 270.27 Wm^{-2} respectively.

Drying tests for tomatoes, peppers and bitter leaves were performed. During the test, 1kg of the product sample was taken from each dryer and weighed at 3hour interval. The products in the dryers were stirred manually three times every day to ensure uniform drying of the products until the desired final moisture content was reached.

Variation of the moisture contents of tomatoes, peppers and bitter leaves using the solar chimney and natural sun drying are shown in Fig.4, Fig.5 and Fig.6 respectively. The tests revealed that the time required for drying inside the solar chimney was lower than that required for cabinet and natural sun drying. It was observed from the figures that the moisture contents decrease on the first and second day, then rapidly decreased on the third day and slowly again on the following days. This can be explained in terms of drying kinetics as follows. The drying in the first two days is a constant rate drying phase. The product surface is constantly fed out of interstitial water by capillary forces. This is known as isenthalpic phase since the energy received by the product is entirely used for the vaporization of surface waters. In this phase, all the products remain at the drying chamber temperature. On the third day, when the surface of the products reaches the hygroscopic threshold, drying enters into a first step of deceleration. At the beginning of this phase, the drying rate decreases rapidly. The evaporation zone is now inside the product. From each side of the evaporation zone, there are two methods of transport. Upstream, in the centre of each of the products, there are always migrations of free water by capillarity and the temperatures of the products are always equal to hygroscopic temperature. Downstream, the migrations are due to the diffusion phenomena (vapor) or diffusion-sorption (water dependent) and there are increasing temperatures in this zone. In the remaining subsequent days, the products are in hygroscopic field. Water does not exit any more but in dependent form and in vapor form. The drying rates decrease very slowly and tend toward zero. These values are reached when the moisture content balance of the surfaces in contact with air are obtained. The drying processes are then finished.

The comparison of tomato's drying curves inside the two solar dryers with the natural sun drying (to a final moisture content of 58%) is shown in Fig.4. The natural sun drying was completed in 198h, while the drying inside the chimney and cabinet solar dryers were completed in 129h (55% of the time spent for the natural sun drying) and 138h (70% of the time spent for the natural sun drying) respectively.

Fig.5 presents the drying curves of the pepper. The natural sun drying occurred over a period 162 h, while the drying of the pepper inside the solar chimney and cabinet dryers occurred in 55% (105h) and 88% (129h) of this time respectively.

The drying curves of the bitter leaves in the sun and in the two solar dryers are presented in Fig.6. The bitter leaves needed 114h to be dried when directly exposed to the sun, while the time required in the solar chimney and cabinet dryers were only 84h and 90h, about 74% and 79% respectively of the time required for natural sun drying. From these results obtained, it is observed that solar chimney dryer yields the best result

Microbial contamination of the dried products was not observed. All dried products presented acceptable flavor, texture and color.

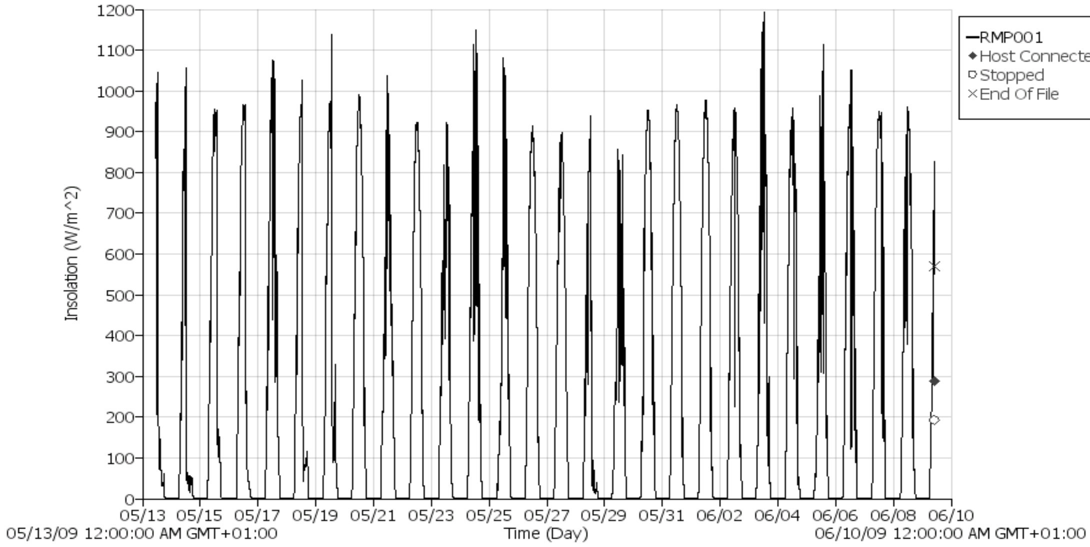

Fig. 3: Variation of solar radiation in May/June, 2009, when the drying tests were performed

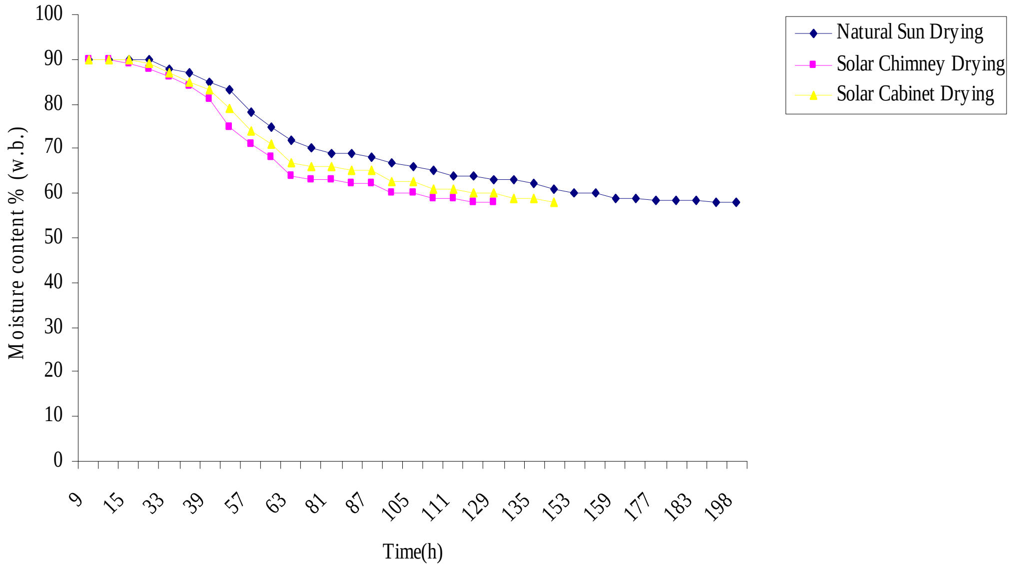

Fig. 4: Variation of the moisture contents of tomatoes using the solar chimney and natural sun drying

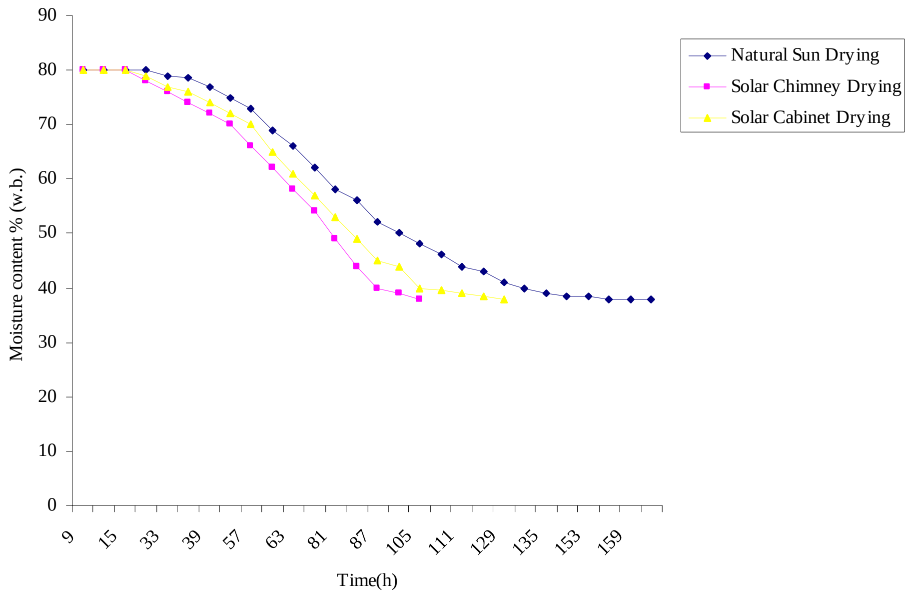

Fig. 5: Variation of the moisture contents of pepper using the solar chimney and natural sun drying

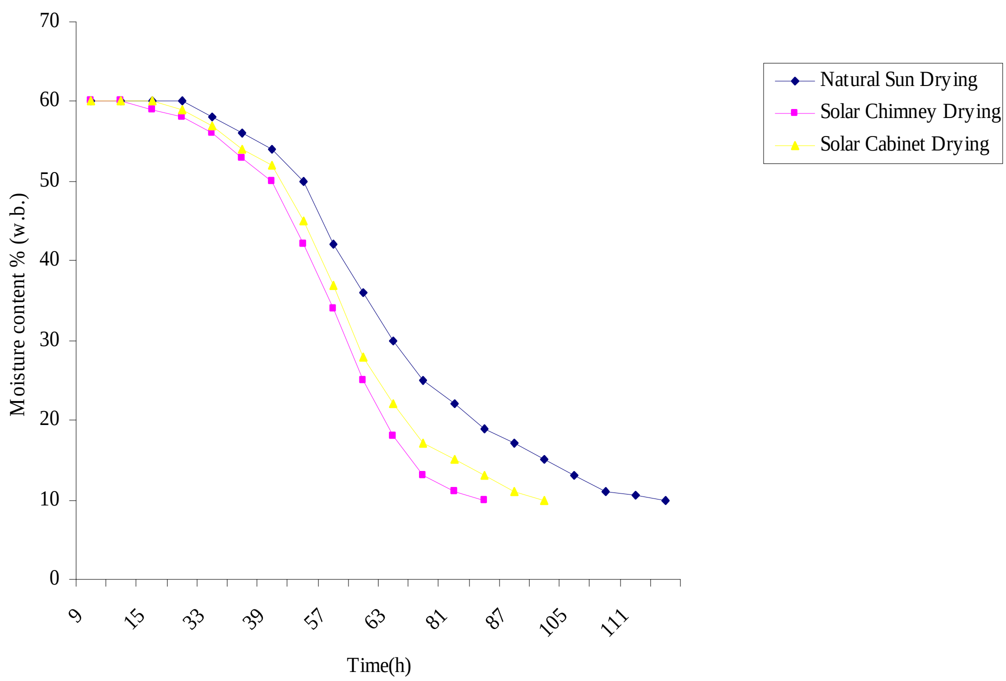

Fig. 6: Variation of the moisture contents of bitter leaves using the solar chimney and natural sun drying.

CONCLUSION

A solar chimney and cabinet dryers have been developed and tested in Mubi, Adamawa State, Nigeria. The dryers were inclined to the angle of latitude of Mubi, $10^{0}15^{'}$, to ensure maximum transmission of solar radiation into the dryers. Both dryers were used to perform experimental test in drying 50kg of tomatoes, pepper and bitter leaves. With solar chimney dryer, results reveal that these quantities of tomatoes, pepper and bitter leaves can be dried within 129, 105 and 84 h, respectively giving an average 51% of the time spent for the natural sun drying. With solar cabinet dryer, the same quantities of tomatoes, pepper and bitter leaves can be dried within 138, 129 and 90h, respectively with an average 79% of the time spent for the natural sun drying. The products being dried are completely protected from rains and insects. Dried products of high quality are obtained.

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Nomenclature

A_c = collector area(m^2)

C_p = specific heat(J/kgK)

F_R = heat removal factor of collector

I_T = incident radiation(W/m^2)

M = product moisture content(%)

M_{sr} = moisture content at sunrise(%)

M_{ss} = moisture content at sunset(%)

m = weight of product(kg)

m_d = weight of dried product(kg)

m_t = weight of product to be dried at any time(kg)

$\dot{m}$ = air mass flow(kg/s)

Q_u = useful energy gain of collector(W/m^2)

R_n = nocturnal moisture re – absorption or losses(%)

t = drying time(h)

T = temperature(^0C or K)

U_L = global heat loss coefficientflow(W/m^2K)

α = absorption coefficient

τ = transmission coefficient

η = efficiency(effectiveness)

Subscripts

e = equilibrium

i = inlet, initial