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Performance Study of A Solar Chimney Dryer for Preservation of Agricultural Products

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Abstract

The agricultural products that are dried under the sun exposed to the environment, especially high moisture crops are often unprotected from insects, pests, unexpected rain, contamination and are prone to fungus infection, which degrade the quality of the products. To alleviate this, a solar chimney dryer was developed. It is constructed in local materials then tested experimentally in food stuffs drying tomatoes, pepper and bitter leaves. With this dryer, 50kg of tomatoes, pepper and bitter leaves can be dried within 125, 102 and 84 h, respectively giving an average 65% of the time spent for the natural sun drying. The dryer reduces drying losses as compared to sun drying and show lower operational costs than the artificial drying. 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: Agricultural Products; Solar Chimney; Operational Costs; Microbiological Contamination.

Introduction

The preservation of surplus crops and foodstuffs can be regarded as one of the first and most important techniques of food processing. Among them, one of the most commonly used methods is drying. Drying is one of the most important post-harvest operations for agricultural products. It is mainly aimed in reducing the moisture content of a product to a level below which deterioration does not occur and the product can be stored for a definite period. According to Sodha et al [1] 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. For some spices such as chili and pepper, drying is not only for preservation purposes but also for modifying the tastes and flavors in order to increase their market values. The drying of agricultural products using the sun has been studied. Examples of such study include that of Anwar and Timani [2], Komilov 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.

People have been drying agricultural products for thousands of years by placing the agricultural products on mats in open air. This is considered as drying under primitive condition and there is a considerable loss due to various reasons such as rodents, birds, insects and micro-organisms. 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 characteristics for open sun drying. Furthermore, open air drying is often not possible in humid climates. In general, open sun drying does not fulfill the international quality standards and therefore it can not be sold in the international market.

Solar food dryers represent a major improvement upon this ancient method of drying foods. 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. Many solar food dryers have been developed over the past few years [10-18]

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. They also are faster, safer, and more efficient than traditional sun drying techniques. An enclosed cabinet-style solar dryer can produce high quality, dried food stuffs in humid climates as well as arid climates. It can also reduce the problem of contamination. Drying is completed more quickly, so there is less chance of spoilage. Fruits maintain a higher vitamin C content. Because many solar dryers have no additional fuel cost, this method of preserving food also conserves non-renewable sources of energy.

Since 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, a simple inexpensive and more scientific method could be a useful alternative for preservation of agricultural products.

The objectives of this work are to develop a Solar Chimney Dryer for crops and to investigate its performance. This dryer is relatively low-cost compared to systems used in developed countries.

System Description and Operating Principle

A solar chimney drier 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 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 drier. 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.

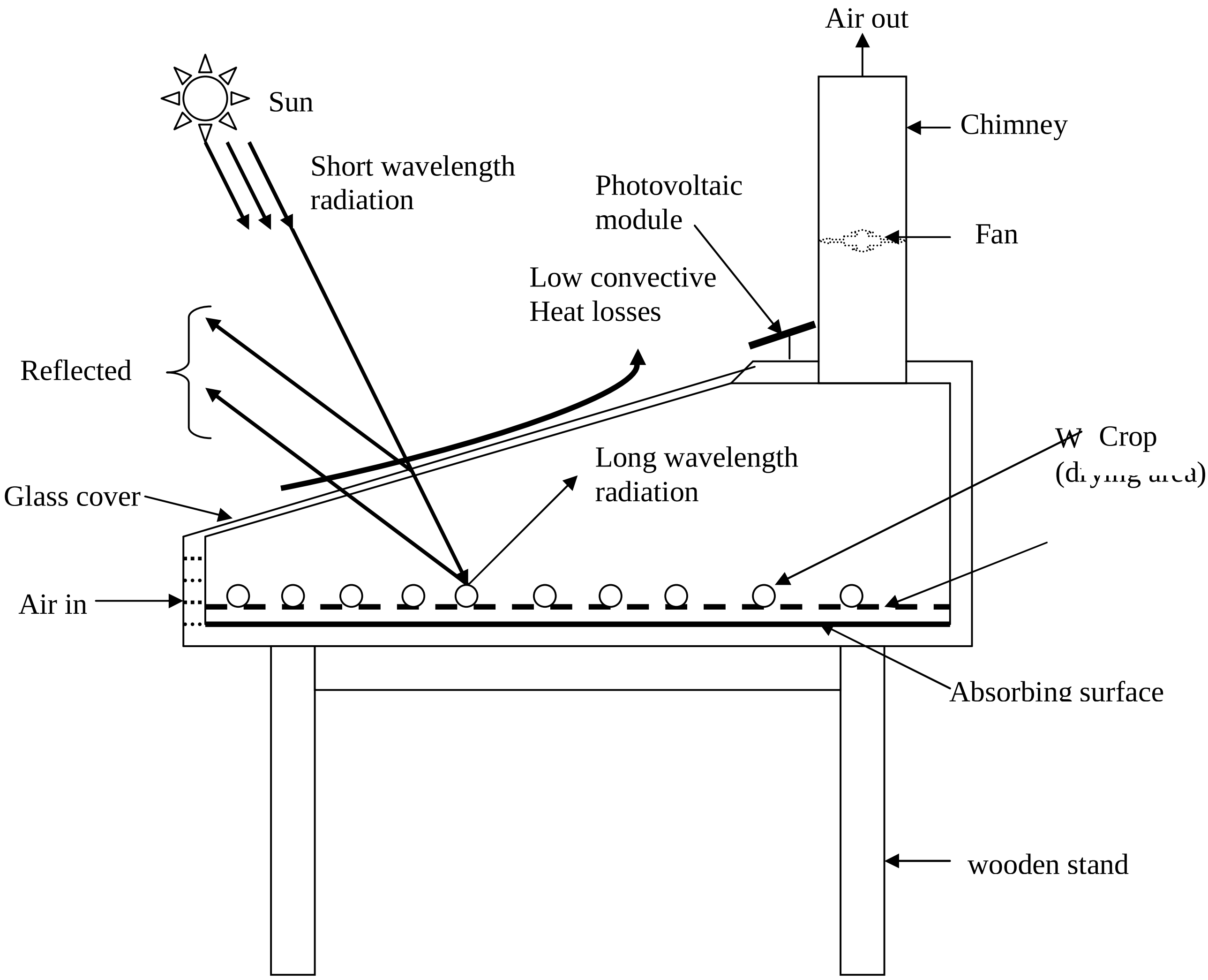

Fig. 1: **Schematic of the System**

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.

Theoretical Analysis

The principal criteria usually used to evaluate the performance of any solar drying system 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 [12]

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

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

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

In percentage, the moisture content can calculated as

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

For instantaneous moisture content at any time

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

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]

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

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

The performance evaluation of a solar heat collector is related 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 [19].

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

Using Hottel–Whiller–Bliss equation, a solar dryer thermal performance is expressed by [20].

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

where

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

By substituting Eq. (6) into Eq. (7), defined air increasing temperature in the drying chamber by

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

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

where

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

I_{th} is the threshold level of incident radiation [21].

Experimental Details

The experiment consisted of measuring the mass, moisture content of the products to be dried and taking the solar insolation of the environment where the products were dried. The materials used for drying tests were tomatoes, peppers and bitter leaves. Before beginning of the drying tests, each product receives a pretreatment, according to Aguirre and Gasparino Filho [22]. 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 and the second sample was dried inside the solar chimney drier. 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 measured with a pyranometer (model CMP3) 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 November, 2008 in Mubi, Adamawa State – Nigeria. This month is in the dry season, most of the days are sunny with sporadic clouds. The variations of solar radiation are shown in Fig.2. Analysis of this figure revels that the highest and the lowest daily insolation measured in that month were 965.26 Wm^{-2} and 872.72 Wm^{-2}.

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

The drying curve of tomatoes, peppers and bitter leaves are displayed in Fig.3, Fig.4 and Fig.5 respectively. In all the tests, the time required for drying inside the solar chimney was lower than that required for natural sun drying. From the figures, it was observed that the moisture content 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 phase is also called isenthalpic phase since the energy received by the product is entirely used for the vaporization of surface waters. During 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.

Fig.3 compares the tomato's drying curves inside the solar dryer with the natural sun drying (to a final moisture content of 58%). The natural sun drying was completed in 196 h, while the drying inside the dryer was completed in 125 h (64% of the time spent for the natural sun drying).

The drying curves of the pepper are presented in Fig.4. The natural sun drying occurred over a period 165 h, while the drying of the pepper inside the solar chimney dryer occurred in 62% of this time (102 h).

Fig. 5 shows the bitter leaves' drying curve in the sun and in the solar dryer. The bitter leaves needed 122 h to be dried when directly exposed to the sun, while the time required in the solar chimney dryer was only 84 h, about 69% of the time required for natural sun drying.

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

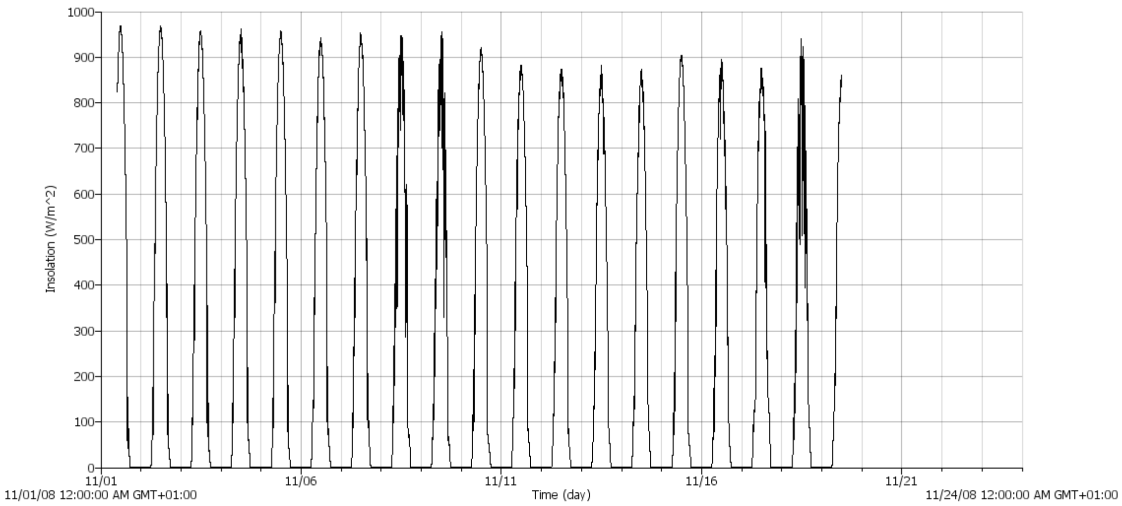

Fig. 2: **Variation of solar radiation in November, 2008, when the drying tests were performed**

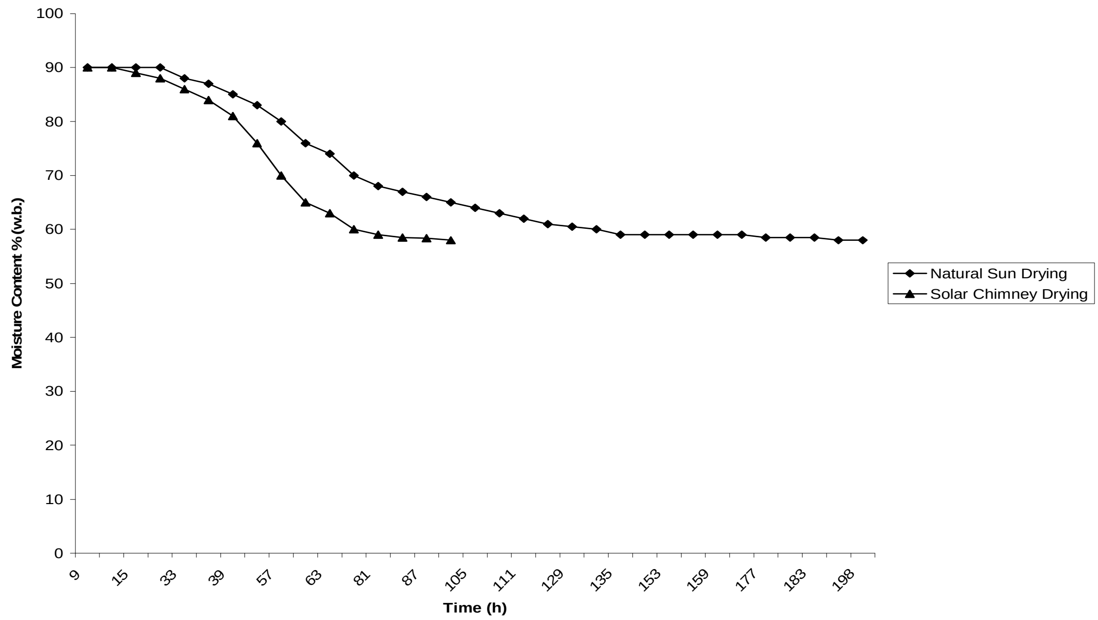

Fig. 3: Variation of the moisture contents of tomatoes using the solar chimney and natural sun drying

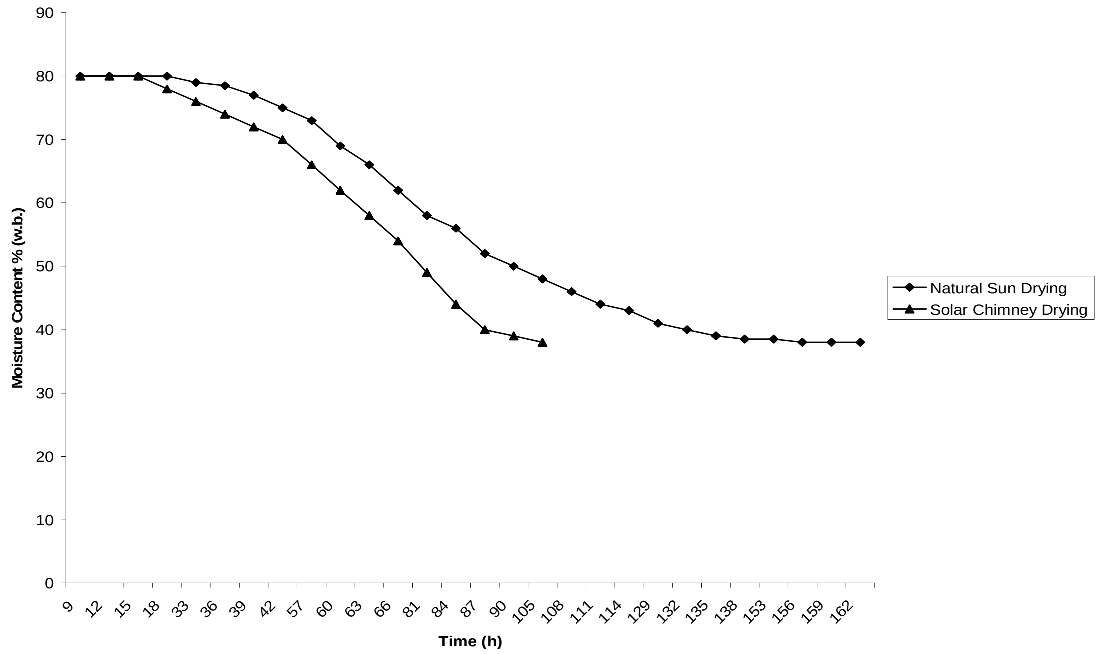

Fig. 4: Variation of the moisture contents of pepper using the solar chimney and natural sun drying

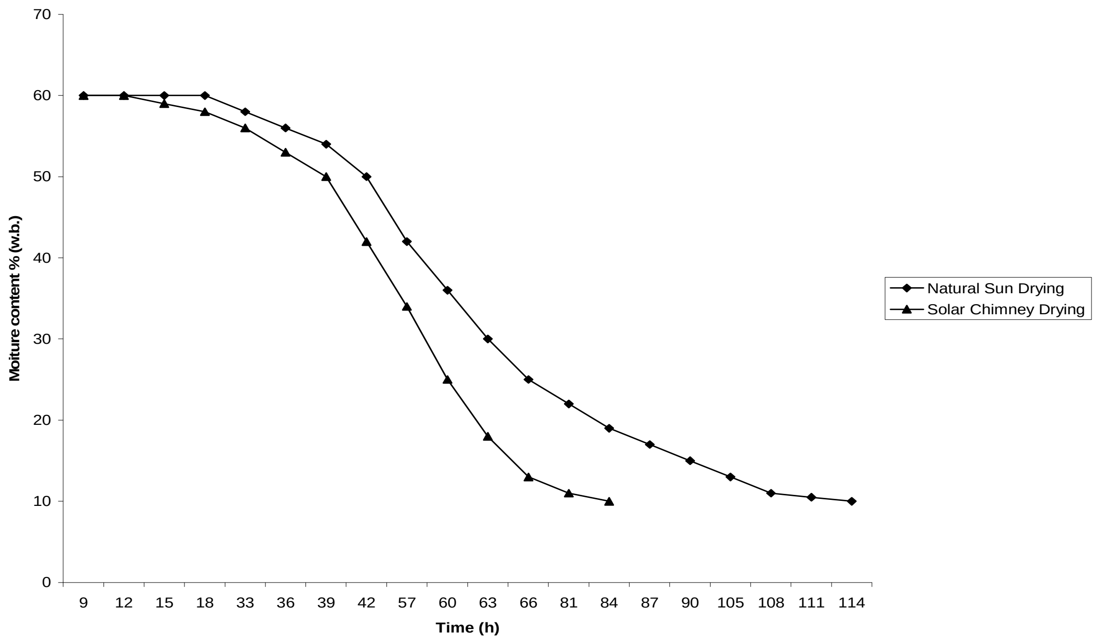

Fig. 5: Variation of the moisture contents of bitter leaves using the solar chimney and natural sun drying.

Conclusion

A solar chimney dryer has been developed and tested in Mubi, Adamawa State, Nigeria. The dryer was used to perform experimental test in drying tomatoes, pepper and bitter leaves. With this dryer, 50kg of tomatoes, pepper and bitter leaves can be dried within 125, 102 and 84 h, respectively giving an average 65% 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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$$A_c = collector \quad area(m^2)$$

$$C_p = specific \quad heat(J/kgK)$$

$$F_R = heat \quad removal \quad factor \quad of\, collector$$

$$I_T = incident \quad radiation(W/m^2)$$

$$M = product \quad moisture \quad content(\%)$$

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

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

$$m = weight \quad of \quad product(kg)$$

$$m_d = weight \quad of \quad dried \quad product(kg)$$

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

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

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

$$R_n = nocturnal \quad moisture \quad re-absorption \quad or \quad losses(\%)$$

$$t = drying \quad time(h)$$

$$T = temperature(^0C\, or\, K)$$

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

$$\alpha = absorption \quad coefficient$$

$$\tau = transmission \quad coefficient$$

$$\eta = efficiency(effectiveness)$$

Subscripts

$$e = equilibrium$$

$$i = inlet, initial$$