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Design and evaluation of combined solar and biomass dryer for small and medium enterprises for developing countries

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A small scale demonstration model consisting of a combined solar and biomass cabinet dryer with 3 equally spaced drying trays was designed, constructed and evaluated. The results, obtained using fresh yam chips as test material over a four day test period, were satisfactory and useful for optimization purposes. Maximum tray temperature of 53°C was obtained in combination with solar and biomass heating sources even though the ambient temperature for the test period was between 24 and 30°C. An optimal drying rate of 0.0142 kg/hr was achieved with the combined solar and biomass dryer, compared to the lower drying rate of 0.00732 kg/h for the solar drying and 0.0032 kg/h for the biomass drying. This study proved that the efficiency of agricultural dryers could be increased through the use of a combination of solar and biomass heating sources, compared to conventional dryers with only solar or only biomass heating sources. It implies that improvements in the design and construction of the various components of the system would lead to more efficient dryers for use in small and medium business enterprises for sustainable development of developing countries. Using combined solar and biomass dryers have the potential to increase the productivity and resultant economic viability of small and medium-scale enterprises producing and processing agricultural produce in developing countries. African countries, with large quantities of natural resources, like forests and solar radiation, could make the most use of these types of dryers.

Key words: Solar biomass dryer, drying rate, moisture loss, preservation, yam chips, solar radiation, small and medium-scale enterprises.

INTRODUCTION

Although most tropical regions of Africa experience high levels of solar radiation throughout the year, much of this radiation is absorbed by frequent rain and persistent cloud cover. Due to inadequate preservation techniques available to farmers in developing countries, large quantities of agricultural output with high moisture contents are lost annually due to decomposition by micro-organisms. This results in reduction of the net agricultural output and subsequent reduction in the gross domestic product (GDP) of the developing countries.

Dehydration is one of the oldest techniques employed in food or agricultural products storage and preservation (Montero et al., 2010; Montero, 2005; Mujumdar, 2000; Corvalan et al., 1995). The most common method of dehydration is by open air sun drying but this often results in food contamination and nutritional deterioration

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(Ratti and Mujumdar, 1997). Food dehydration technology employs direct and/or indirect mixed mode systems with natural or forced distribution of heated air. According to Madhlopa and Ngwopa (2007), direct heating mode systems consist of direct heating of the items by direct sun radiation through transparent material enclosing the items while indirect heating mode systems consist of heating of air in a separate solar collector and circulating the same through the drying bed where it picks moisture from the crop. The mixed mode drying system combines the features of the two above mentioned systems. The study of solar drying and design of solar dryers are not new but the advent of the renewable energy industry has sparked renewed interest in these fields. There are many sources of literature on solar drying. Ekechukwu (1999) and Ekechukwu and Norton (1999 a, b) have presented overviews of drying principles, theories and solar drying technologies, with a description of low temperature air-heating solar collectors for crop drying applications.

Owing to intermittent solar radiation throughout the day, continuous drying of agricultural products can be accomplished through a combination of solar and non-solar heating sources in a mixed mode system. Thermal storage systems can also be used to increase the efficiency of solar dryers. These thermal storage system range from hybrid modes where, electrical resistances have been used to increase the heating of the air (Prasad and Vijay, 2005; Prasad et al., 2006) to the use of biomass as auxiliary heating source for the drying chamber. Auxiliary heating sources are used to provide uninterrupted supplies of thermal energy for the continuous operation of dryers, during periods of limited solar radiation like night time and cloudy The heated air from the auxiliary heating source passes through pipes or channels and then into the drying chamber via convection. Auxiliary heating source could be powered by electricity or biomass. However, biomass is the most widely used due to its availability and cost effectiveness in rural areas of developing countries. Many solar hybrid dryers have been designed, constructed and tested. Some of these have reached advanced and commercial stages, while some are still undergoing improvements. At the Asian Institute of Technology (AIT), Thailand (Elepaño et al., 2005) a hybrid dryer based on solar and biomass heat sources has been developed and commercialized. This dryer is constructed of bricks and mortar, and is more efficient than a conventional solar cabinet dryer made of steel or aluminum. The dryer has been tested with products such as banana and mushroom. Similarly in Nepal, the Research Centre for Applied Science and Technology (RECAST) developed a similar hybrid dryer based on combined biomass solar drying. These designs were constructed with concrete and bricks. It was capable of drying 10 kg of fresh agricultural products such as radish, carrot, ginger, mushroom, potato and pumpkin.

In Nigeria, some advances have been made in the development of solar hybrid dryers. Danshehu et al. (2008) evaluated a 150 kg kerosene-assisted solar cassava dryer which improved the dehydration process compared to open air solar drying. Similarly, Oparaku et al. (2003) evaluated a solar cabinet dryer with auxiliary heater where appreciable result was obtained. The problems facing the development of this technology in Nigeria include poor design and construction of the dryers, little or no mathematical modeling and poor choice of materials for construction. As a result of these reasons commercial solar dryers are yet to be realized in Nigeria. This has necessitated a search for suitable and efficient dryers based on local technology rather than importing dryers not suited for Nigerian conditions. Nigeria's geography, with tropical forests in the south and high solar radiation levels in the north 3.55 $\text{kWh.m}^{-2}\text{.day}^{-1}$ (Sambo, 2009), holds great potential for combined solar and biomass drying schemes. Utilising Nigeria's geography and natural resources for solar and biomass drying, could increase the durability and resultant availability and price stability of agricultural and aquatic products throughout the country. It is therefore the objective of this study to design, construct and evaluate the performance of a solar combined with biomass heating dryer for use in developing countries. This preliminary study of the authors utilizes fresh yam chips as test samples in a four day test period.

THEORY

Determination of the heat contribution in drying

The quantity of heat Q_w required, to evaporate moisture of mass m_w is estimated using the basic heat equation.

$$Q_w = m_w L_{vap} \tag{1}$$

where L_{vap} [kJ/kg] is the latent heat of evaporation of water, which can be calculated by the method of Youcef-Ali et al. (2001) as:

$$L_{vap} = 4.186\,(597 - 0.56T_{pr})\ \text{kJ/kg} \tag{2}$$

where T_{pr} [°C] is the product temperature, which can be assumed as the ambient temperature at the coldest weather condition.

$$Q_w = 4.186\,m_w\,(597 - 0.56T_{pr})\ \text{kJ} \tag{3}$$

This represents the heat energy required to dry the items in the dryer to appreciable moisture content status. The sketch below represents the various sources of heat to the drying chambers of the system. Total heat required, Q_w is the sum of the heat which enters the system from the collector, Q_c, the biomass stove, Q_s and the body of the drying chamber, Q_g (Figure 1).

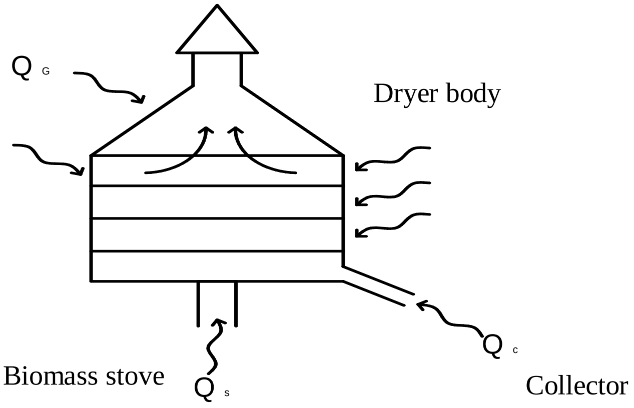

Figure 1. Sketch of the possible heat sources of the dryer.

$$Q_w = Q_c + Q_s + Q_g \tag{4}$$

where the quantity of the heat from the stove, Q_s is the product of the mass of biomass fuel used, m_c and the heating value of the biomass, H_v.

$$Q_s = \eta m_c H_v \quad \text{kJ} \tag{5}$$

According to Duffie and Beckman (1991), the useful energy output of a flat plat collector of area A_c is the difference between the absorbed solar radiation and the thermal loss. If I_T is the solar radiation incident on the collector, U_L the overall heat transfer coefficient of the collector and Q_u the heat output of the collector, then,

$$Q_u = A_c[I_T - U_L \Delta T], \tag{6}$$

Where ΔT = T - T_a the difference between the absorber plate temperature and the ambient temperature. Due to difficulty in estimating the absorber temperature because it depends on fluid flow characteristics, it has been suggested that the heat output of the collector be based on the heat removal factor F_R of the collector. But

$$F_R = \frac{m C_p (T_o - T_i)}{A_c[I_T - U_L(T_i - T_a)]} \tag{7}$$

The heat removal factor is a function of the collector efficiency factor F´ which can modify the heat removal factor as

$$F_R = \frac{m C_p}{A_c U_L}\left[1 - \exp\left(-\frac{A_c U_L F'}{m C_p}\right)\right] \tag{8}$$

A graphical representation of the ratio of these factors are provided in Duffie and Beckman (1991) which can be used to estimate the heat removal factor. In order to minimize the heat losses for maximum heat output, it is assumed that both the collector plate and the moving working fluid (air current) should be at the same temperature. Hence the maximum heat output of the absorber plate is

$$Q_u = A_c F_R\, [I_T - U_L(T_i - T_a)] \tag{9}$$

From above this is equivalent to the percentage of the total heat expected from the solar collector to remove m_w of moisture to dry the stuff. The solar radiation component of the Equation 9 can be estimated by the models suggested by Hottel and Wortz (1942) which were improved by Liu and Jordan (1963) as:

$$I_T = I_b R_b + I_d\left(\frac{1+\cos\beta}{2}\right) + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{10}$$

This is the total solar radiation on the tilted surface for 1 h. According to Ulgen (2006) maximum annual energy availability is obtained when the slope of the collector is equal to the angle of latitude of the location for low latitude countries ($\varphi \leq 40^\circ$). Hence, in Nsukka, solar collectors are tilted to the angle of latitude 7°. The heat developed by the direct solar radiation through the transparent body of the dryer can be estimated by the method of Harkness and Mehta (1978) and Okonkwo and Nwoke (2008). This method proposes that the heat developed through the transparent glass material can be estimated by

$$q_c = UA(T_o - T_i) \tag{11}$$

and

$$q_t = (I_D A_s \tau_1 + I_d A \tau_2), \tag{12}$$

Where q_c and q_t are heat transfer by conduction and solar radiation through the glass material respectively. The sum of these components gives the estimated total heat through the glass. From this the total area of the glass (A_s) can be calculated.

MATERIALS AND METHODS

The hybrid solar and biomass dryer (Figure 2) consists of a solar drying section and a biomass stove section. The dryer has the shape of a home cabinet with tilted transparent top, consisting primarily of a drying chamber, biomass stove, and solar collector. The dryer is provided with two heated air inlets: one at the top of the solar collector for the heated air leaving the collector, and the other at the base of the drying chamber for the heated air exiting the biomass stove. The chimney has a height of 180 cm from the ground and is located at the top of the drying chamber and serves as the air outlet. The drying chamber is 59.6 by 59.6 cm in

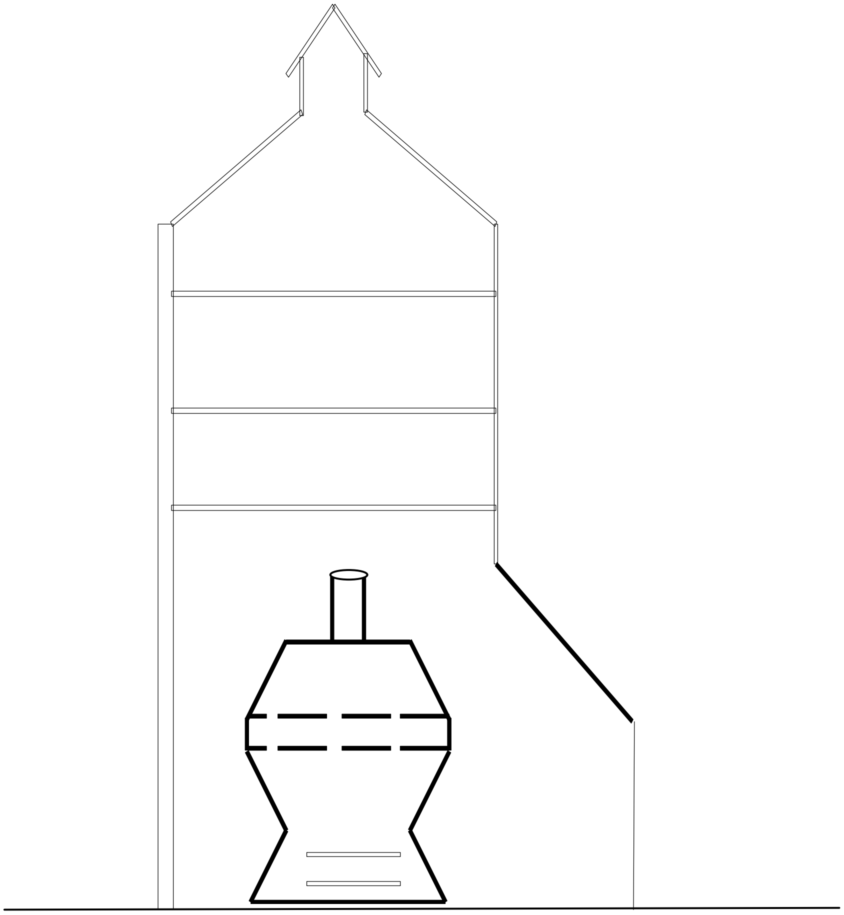

Figure 2. Dimensionless sketch of the combined solar and biomass dryer.

cross-section and has a height of approximately 104 cm. It has three tray levels, and is fitted with a piping system that channels the heat exiting the biomass stove to the different trays.

The biomass stove consists of three main components: the fuel chamber which doubles as the combustion chamber, the primary air inlet and frustum-shaped lid with a little pipe protrusion. The stove is approximately 43 cm in height. The flat plate solar collector of size 0.61× 0.64 m, consists of an absorber, insulation and cover plate. The movement of air from the inlets to the outlets, when the dryer is placed in the path of airflow, brings about a thermo-siphon effect which creates an updraft of solar heated air, which removes moisture from the drying chamber. Ambient air is used as source of air. The performance test of the dryer was carried over a period of four days. The first day consisted of measuring the temperature distribution across the trays of the dryer with no load. The second day consisted of measuring the moisture loss of yam chips on the dryer trays with only solar heating during the day, and then with only biomass heating during the night. The rest of the test period consisted of measuring the moisture loss of the yam chips on the dryer trays with a combination of solar and biomass heating. In all tests yam chips were placed in the open air to dry under direct sunlight as control. The yam chips were prepared from fresh yam purchased from the local market of Nsukka in Nigeria. The chips were washed to ensure that no impurities were involved in the experiment. Equal portions of yam chips of 120 g were weighed out using micro weighing balance and spread in the trays and open sun as control. Temperature changes were monitored using mercury thermometers fixed in the trays while ambient temperature was monitored with k-type thermocouples.

RESULTS AND DISCUSSION

Temperature distribution

The first test was conducted over a period of four hours from 14:00 to 18:00. Figure 3 compares the temperature distributions across the dryer trays over time with no load and with only direct solar radiation as heating source. Within the first hour the temperature of the three trays increased steadily from 38°C (tray 1) to the maximum of 44°C in tray 3. The collector and the transparent glass body performed well as this was reflected in the wide temperature difference between the ambient temperature and the temperature of the trays.

Moisture loss with solar drying

On the second day the system was evaluated with fresh

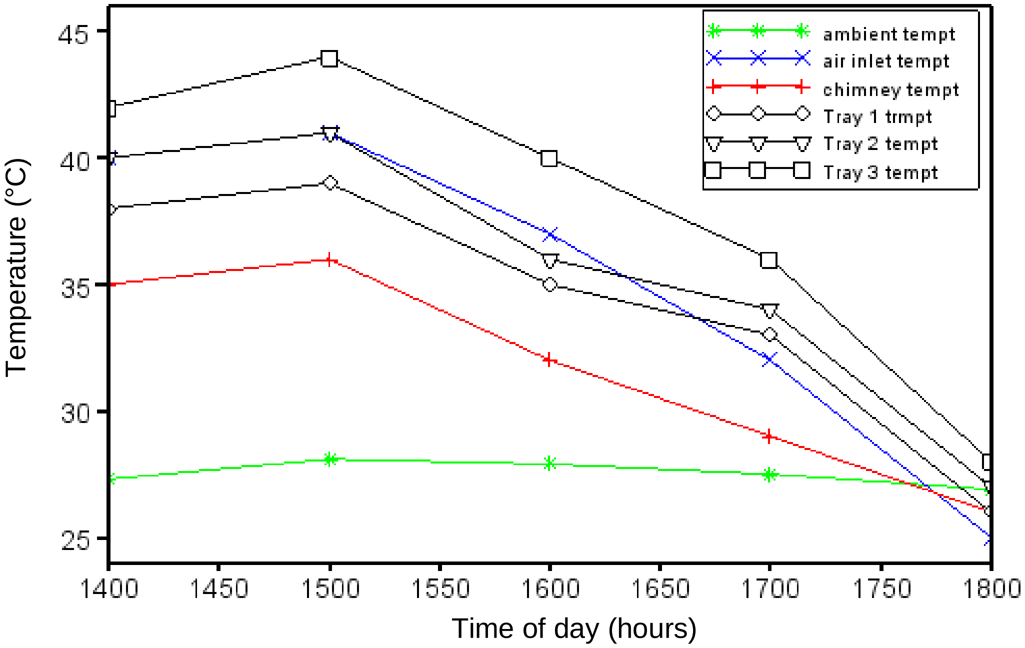

Figure 3. Temperature distribution across the dryer with no load and solar heating only on day one.

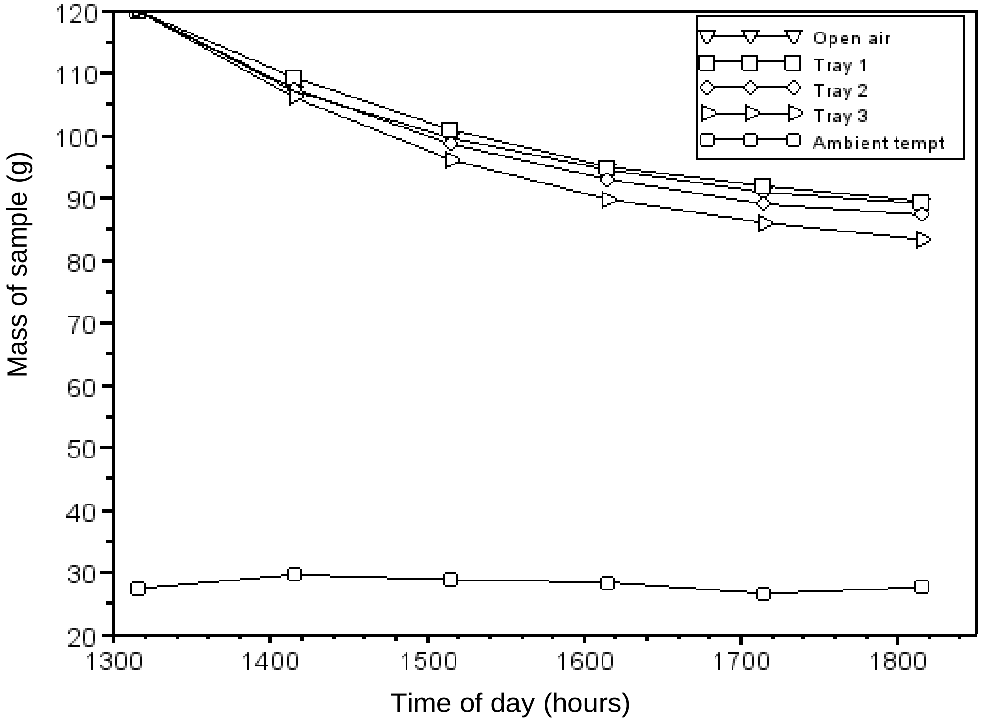

Figure 4. Mass loss of yam chips in the open air compared to yam chips in the dryer with only solar heating on day 2 starting from 13:15.

yam chips whose drying (mass loss) mechanism is shown in Figure 4. A high degree of moisture loss was achieved over the first hour. The mass loss in the open air was greater than in tray 1. This higher drying rate

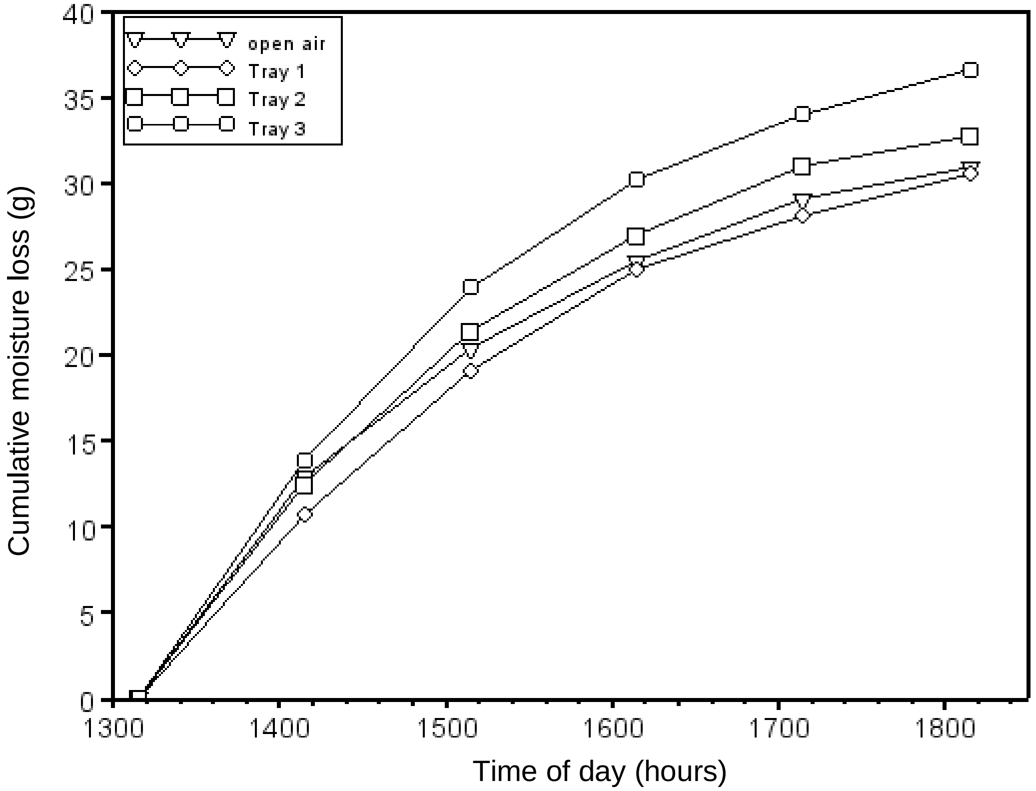

Figure 5. Cumulative moisture loss (removal) with solar drying only.

could have been caused by wind. Surface moisture from the yam chips was lost at a faster rate than its internal moisture, because it takes less energy to evaporate. The rate of total moisture loss slowly reduced after the surface moisture was lost and it took longer to evaporate the internal moisture of the yam chips. The drying effect in the dryer can be observed by the much slower drying rate of the yam chips in the open air compared to the drying rate of yam chips on the dryer trays, until dusk, when the tray temperatures dropped and returned to ambient conditions. The drying rate of 0.00732kg/hr obtained is comparable to 0.009 kg/h obtained by Ajao and Adedeji (2008) using a box type solar dryer for yam drying. The total (cumulative) moisture loss of the yam chips dried in the open air compared to those dried in the solar heated dryer is shown in Figure 5. The cumulative moisture loss in the open air was comparable to the first tray. This could be due to the fact that the first tray did not receive more solar radiation than those dried in the open air, because it was shaded by the upper two trays.

Moisture loss with biomass drying

Figure 6 shows the effect of adding an additional biomass heat source to the drying of the yam chips when solar radiation was not available. The marked moisture loss between 18:00 and 18:30 is expected due to the additional heat source which resulted in increase in temperature of the drying chamber. Within this period, the ambient temperature decreased and there was no sunshine. This implies that additional moisture removal was achieved through the biomass heat addition to the system.

Moisture loss with combined solar and biomass drying

Figures 7 – 9 present the results obtained when biomass was combined with solar drying in the day time. Figure 7 shows the rapid mass loss over the first 30 min while the maximum mass loss of 9.3 g of water occurred after one hour on tray 1. Combining solar heating with additional biomass heating improved the efficiency of the dryer compared to the drying modes where only solar or biomass heating was used. Combining solar and biomass drying reduced the moisture content of the yam chips to 70.83% in 2.5 hours (Figure 7), compared to the moisture content of 75% (Figure 4) of the yam chips with solar drying in 5 hours and 94.44% (Figure 6) in1.25 hours with biomass drying. Comparing this in terms of drying rate, using the tray with the largest cumulative moisture removal, we obtain 0.0142, 0.0032 and 0.00732 kg/h

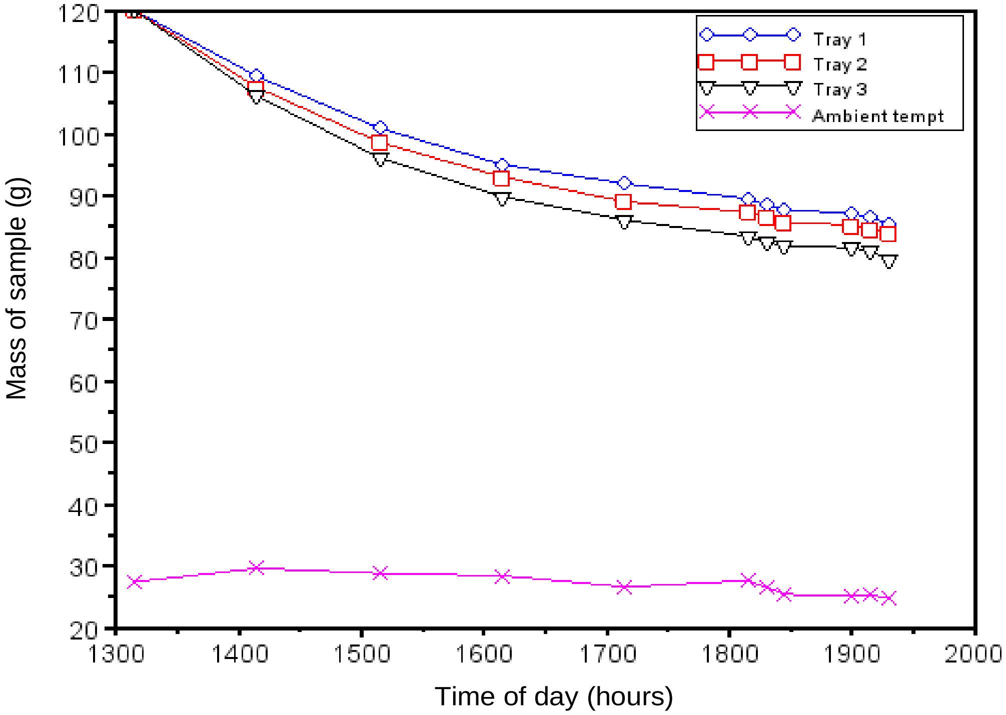

Figure 6. Mass reduction on solar drying in the day and biomass drying in the evening on day 2.

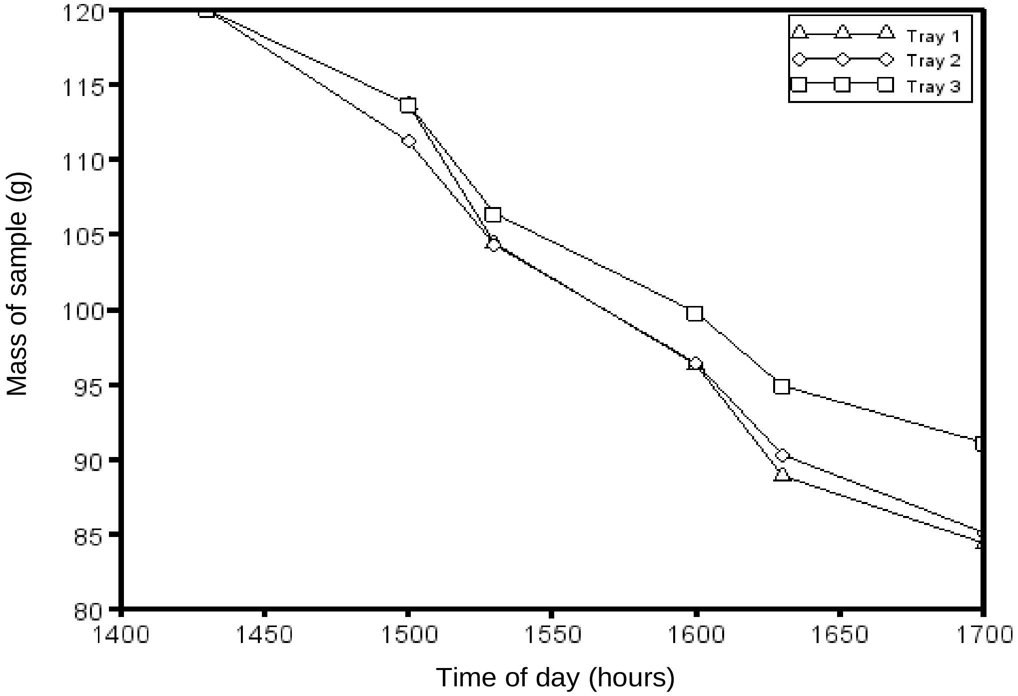

Figure 7. Mass loss with combined biomass and solar drying.

respectively for solar combined with biomass, biomass heating and solar heating only.

Figure 9 also shows that combined solar and biomass heating increased the maximum tray temperature to

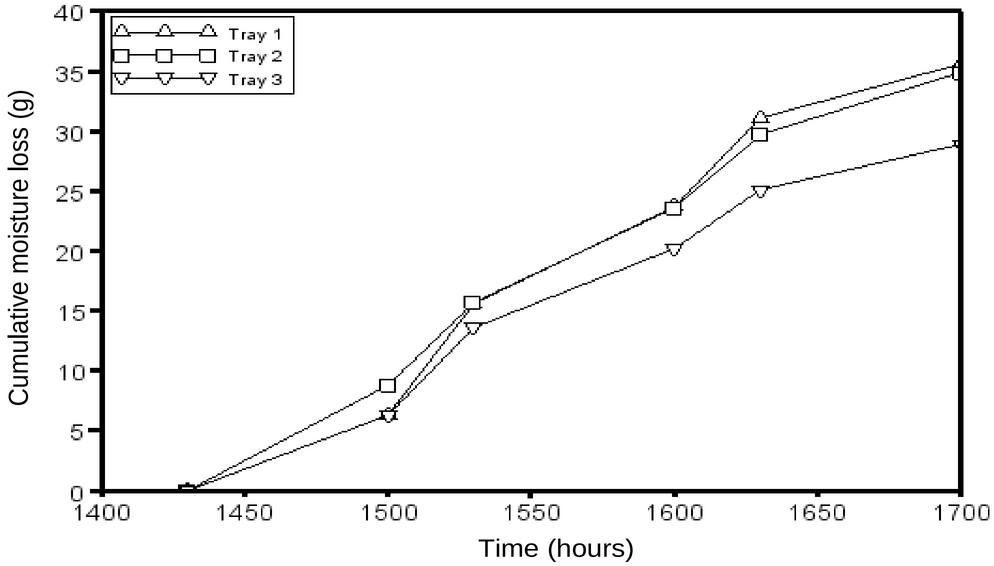

Figure 8. Cumulative moisture loss with combined biomass and solar drying.

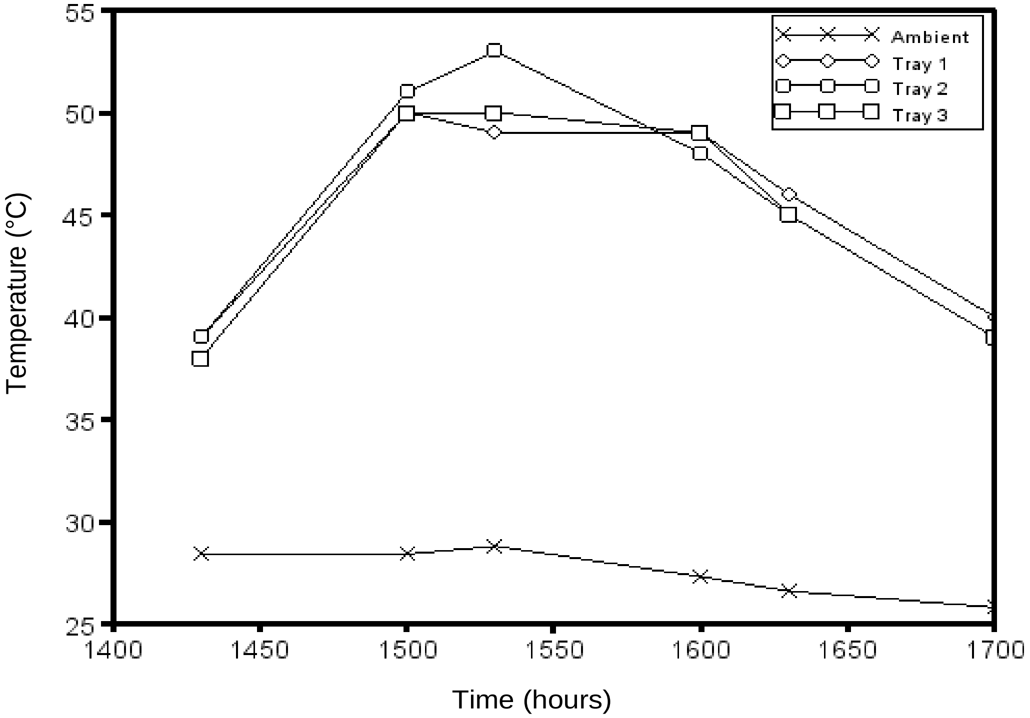

Figure 9. Temperature distribution in the trays with combined biomass and solar drying.

53°C, compared to 44°C with biomass heating and 32°C with solar heating (Figure 3).

Conclusion

This study proved that the efficiency of agricultural dryers could be increased through the use of a combination of solar and biomass heating sources, compared to conventional dryers with only solar or only biomass heating sources. Using combined solar and biomass dryers have the potential to increase the productivity and resultant economic viability of small and medium-scale enterprises producing and processing agricultural produce in developing countries. Countries, like Nigeria, with large quantities of natural resources, like forests and solar radiation, could make the most use of these types of dryers. It is believed that improvements in the construction of the various components of the system will improve the performance of the dryer for use in small and medium business enterprises.

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