Design and performance evaluation of a solar-biomass greenhouse dryer for drying of selected crops in western Kenya

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Abstract: Solar drying systems are not able to achieve the best drying rates given the intermittent nature of solar energy and poor airflows. To address this problem, a solar-biomass dryer, measuring 8 m long, 4 m wide and 2.6 m high, with two layers of beds, was developed for use by medium scale processors in Kenya. It had a bimodal biomass heating system to back up the solar energy, and four provisions for air ventilation; chimney, turbo ventilators, lower opening and fans. It was constructed and preliminary tests on it undertaken at Khwisero in Kakamega County, Kenya. Six commonly grown crops; arrow roots (*Maranta arundinacea*), cassava (*Manihot esculenta*), sweet potatoes (*Ipomoea batatas*), kales (*Brassica oleraceae var acephala*), bananas (*Musa spp.*) and spider plant (*Chlorophytum comosum*) were utilised for the trials. Temperature, relative humidity, weight change and radiation data were collected in October 2017 to monitor the performance of the dryer. This was done under three modes of the greenhouse dryer; natural ventilation, forced convection and solar-biomass (hybrid). The difference between the inside of the dryer and ambient temperatures within the first three hours was 13.1°C, 20.8°C and 17.9°C under the natural, forced and the hybrid modes, respectively, with the inside of dryer temperature being 49.3°C, 53.8°C and 53.2°C, respectively. The average solar radiation over the same time was 545, 668, 594 W m^{-2}, respectively. The monitored air velocity was controlled to 0.7 m s^{-1} for hybrid mode and 0.4 m s^{-1} for forced mode. The comparative higher air velocity for the hybrid mode led to a lower inside air temperature, making it nearly equal to that of forced convection; but the hybrid mode drying rate was 18%-19% higher than the other modes. This implies that the hybrid system improved the drying conditions through higher heat supply. As expected, the relative humidity reduced during drying, with the inside of the dryer and the ambient relative humidity being 21.5% and 35.5%, 18.1% and 44.0%, and 19.5% and 35.3% for the natural, forced and hybrid modes, respectively. There was no marked difference in temperatures between lower and upper beds under the three modes. Overall, the study indicates that the efficiency of greenhouse solar dryers could be increased through improved ventilation and backup energy.

Keywords: solar-biomass, greenhouse dryer, ventilation, performance, Kenya

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1 Introduction

Sun drying of crops is the most widespread method of food preservation in most parts of Kenya and the world in general due to solar irradiance being very high during sunny periods that are experienced in these regions. Solar drying is an advancement of sun drying and entails the use of a closed system that achieves relatively higher temperatures and provides hygienic and less pest damage than that realised through sun drying. Several attempts have been made in recent years to use solar energy for drying mainly to preserve agricultural produce and get

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the benefit from the energy provided by the sun (Olaniyan and Adeoye, 2014; Akinjiola and Uthamalingam, 2012; Ronoh et al., 2010). These efforts emanate from the fact that most small-scale farmers and entrepreneurs cannot afford the commonly available electricity and fossil fuels forms of energy for drying. Several designs of solar dryers have therefore been developed and introduced to farmers and entrepreneurs in an attempt to popularise the use of solar energy. These systems have not achieved the desired efficiencies due to a number of challenges such as poor designs and intermittent nature of solar energy. Solar energy is only available during the day time and also when daytime weather is favourable. This limitation has reduced the uptake of solar technologies. To overcome this challenge, it would be ideal to support the solar dryers to dry produce at night or during bad weather, this calls for use of hybrid systems that have alternative heat supply.

A number of fruits and vegetables are grown in Kenya and the two play an important role in food security, nutrition, and income generation for resource-poor farmers and consumers. The study focused on six crops that are grown in Western Kenya where the developed dryer was piloted: cassava (*Manihot esculenta*), sweet potatoes (*Ipomoea batatas*), and arrow roots (*Maranta arundinacea)* – the three representing root crops and tubers; kales (*Brassica oleraceae var acephala*), and spider plant (*Chlorophytum comosum*) – representing vegetables, and bananas (*Musa spp*) – representing fruits. Root crops and tubers are the second most important food crops after cereals while the African leafy vegetables (ALVs) such as spider plants are becoming popular in most households in Kenya. Kales is a widely consumed vegetable in Kenya. Amongst the fruits, the banana has emerged as an important food crop and income earner in Kenya that is grown in most regions countrywide. Food losses are common among these crops and it is a major factor limiting food security. In 2016, the production of sweet potatoes, cassava and bananas in Kenya was 1.15, 1.12 and 1.81 million tonnes repectively (KNBS, 2017). Waste was reported to be about 10%, 3% and 15% of these productions, respectively. The waste from vegetables was reported to be about 10%. Such losses lead to reduced incomes for farmers, and this justifies the need for promotion of loss reduction technologies.

The RE4Food (Renewable Energy for Food Processing) was a collaborative project funded by UK-AID for 3.5 years (2013 – 2016). The project addressed research challenges associated with increasing food security and reducing reliability on fossil fuels. The solar drying technology was introduced through this project to address the realised challenge of an inefficient system for food preservation. Through the project, a multipurpose solar-biomass dryer was developed and piloted with the Khwisero Integrated Community Umbrella Development (K-INCUD) group, Kakamega County (Kanali et al., 2017). This study, therefore, aimed at evaluating the performance of the designed solar-biomass greenhouse dryer for drying of selected crops in the western region of Kenya.

2 Review of literature

A number of solar, biomass systems have been introduced by different researchers. In general, the systems lead to improved drying. Shyam et al. (2015) reported that the industrial cabinet solar-biomass dryer they introduced lowered cost of operation, and increased the output capacity of the industry by approximately 100 per cent. The product quality was also superior.

Dhanushkodi et al. (2015) simulated a forced solar, biomass hybrid cabinet dryer and the research found out that a uniform temperature distribution was achieved and that a temperature of 60°C – 70°C was obtained in the drying chamber. The findings reported that with an increase in the drying temperature, relative humidity takes lower values and these would enhance the drying rate with drying occurring in a short span of time.

Hybrid systems have been found to be economical and faster than using standalone fuel and solar energy systems, respectively. Yuwana and Sidebang (2017) developed a plastic house equipped with; a drying chamber with the trays inside, two heat collectors, a furnace embedded in a heat exchanger and a chimney. The solar drying option dried the produce in 16.6 hours and achieved 10.6°C higher than ambient temperatures. The coconut shell biomass energy option achieved temperatures of 28.2°C higher than ambient, drying the fish in 8.6 hours with energy consumption of 0.375 kg per kg of wet fish. The hybrid system, raised the temperature by 25.6°C and dried in 9.1 hours with a biomass consumption of 0.29 kg per kg of wet fish. Gunasekaran et al. (2012) designed an integrated biomass energy hybrid type of solar dryer. The dryer was an indirect solar dryer and with an air recycling and mixing provision. The dryer was tested and evaluated for drying Coleus stems. The results showed that the integrated hybrid model produced the best optimum results. After drying for a uniform time, the moisture contents of the hybrid model, solar dryer and biomass dropped from 87% to 12.3%, 33% and 19.6%, respectively, over the same period. Generally, the literature indicates that biomass systems would provide improvement in solar drying. The identified studies do not explore the use of bimodal heating systems and the use of combined ventilation systems in improving the performance of the solar dryers.

3 Materials and methods

3.1 Description of the solar-biomass dryer

A gable roof greenhouse solar-biomass dryer, measuring 8 m long, 4 m wide and 2.6 m high was designed and constructed for K-INCUD group in Kwishero, Kakamega County. The design calculations were based on drying of sweet potatoes. The size of the dryer was based on an average size of a dryer for fruits, vegetable, root crops and tubers, identified through an earlier study (Ndirangu et al., 2018). The site is located at 34.58336° E, 0.13921° N and is at an altitude of 1405 m above sea level. The area lies in the Lower Midland 1 (LM1) agro-ecological zone, with average rainfall ranging between 1250 and 1750 mm per annum (Jaetzold and Schmidt, 1982). The average monthly maximum average temperature in the county ranges from 23°C to 32°C, with an estimated average of 26°C, while the minimum one ranges from 13°C to 17°C, with an average of about 15°C (Worldweather, 2018). The average monthly wind speed varies from 4 to 12.6 km h^{-1} with an estimated average of 8 km h^{-1} (Worldweather, 2018). The average daily incident shortwave solar energy varies between 5.3 and 7.4 kWh within the year (Weatherspark, 2018). The tested dryer is shown in Figure 1 and it had two turbo ventilators, a chimney on the roof of the dryer, and two direct current fans at the inlet and at an outlet in operation for the forced and hybrid mode. In these farmers' trials, the lower vents provided extra ventilation under the three modes. The fans were not switched on for the natural convection mode. The biomass unit comprised a bimodal heating system with two ducts; one carrying heated exhaust air that indirectly heated the crop through heat exchange with the inside air stream and the other carrying heated air that heats crop directly. It had two rows of drying beds of 1 m width with each bed having two layers.

Figure 1 *Left*: Stakeholders viewing the drying of sweet potatoes and other crops. *Right*: The biomass heater for the hybrid dryer

The temperatures and relative humidity inside the dryer were monitored with portable temperature sensors at three points for each layer. The moisture change was taken through the regular measuring of the weight of samples from three points in each layer of the dryer and by use of digital scale has an accuracy of ±0.01 g. The drying was done until there was minimal change in weight. The velocity of air at the inlet and outlet of the dryer was measured with the help of vane type anemometer having ±0.1 m s^{-1} accuracy. Radiation was measured using Photosynthetically Active Radiation (PAR) meter and the readings were converted to W m^{-2} using a factor of 2.2 based on findings from earlier studies (Pashiardis et al., 2017; Wang et al., 2014; Ren et al., 2018; Anjorin et al., 2014).

3.2 Design consideration

3.2.1 Amount of water to be removed from cassava

The mass of water (m_w) to be removed was calculated based on what is stated by Ichsani and Wulandari (2002).

$$m_w = m_i \left(\frac{M_o - M_f}{100 - M_f} \right) \quad (1)$$

Loading density of 8 kg m^{-2} for sweet potatoes was used, with initial and final moisture contents of 78% and 10%, respectively.

3.2.2 The amount of heat required

The amount of heat required to dry, for instance, sweet potatoes is given by Ajala et al. (2015):

$$H = m_p \times C_{sp} \times \Delta T + \{m_w \times 4.186 \times (597 - 0.56\, T_p)\} \quad (2)$$

The specific heat of sweet potatoes of potatoes was taken as 3.67 kJ $kg^{-1}\cdot K^{-1}$ and the optimum desired temperature used was 60°C.

3.2.3 Mass and volumetric airflow

The mass of air was calculated according to the formula stated by Ichsani and Wulandari (2002).

$$m_a = \frac{m_w}{(\Delta W_{fi} \times n)} \quad (3)$$

The volumetric flow rate of the drying air was based on the equation by Olaniyan and Adeoye (2014).

$$m_v = m_a \times v_s \quad (4)$$

By use of psychometric chart, ΔW_{fi} and m_a were calculated.

The friction loss was calculated using the following equation for galvanized steel circular duct (Engineering Toolbox, 2018a):

$$\Delta p = (0.109136\, u^{1.9}) / d_e^{5.02.} \quad (5)$$

A length of 7 m for the 0.3 m diameter double ducting and 1 m of a 0.47 diameter duct was used. The equivalent length method was used to estimate the pressure drops for the 4 bends and an L/D value = 20 was selected (Wilson, 2014). The total pressure drop was factored in fan selection.

An average ambient minimum and maximum day time temperature of 20°C and 26°C, respectively, were used; average relative humidity used was 70% (Weatherspark, 2018; Worldweather, 2018). A pickup factor of 0.25 was used (Olaniyan and Alabi, 2014) and a drying time of 8 h as desired.

3.2.4 The amount of energy required

The energy required for drying was determined based on the following formula:

$$H = m_p\, C_p\, \Delta T + m_w\, L_w \quad (6)$$

3.2.5 The amount of biomass required

The amount of biomass (firewood) needed to be burned in the biomass heater was determined using the following equation (Olaniyan and Adeoye, 2014).

$$Q_w = \frac{H}{C_w} \quad (7)$$

Calorific value of 18,230 kJ kg^{-1} was used.

3.2.6 Ducts and lower opening design

Minimum area of lower opening for use with natural ventilation is calculated as:

$$A_v = \frac{M_v}{V_w} \quad (8)$$

Average wind speeds at Kakamega have been used, and the mesh glazing openings have been estimated at 50% and assuming all volumetric flow rate is achieved with wind under natural ventilation and a one direction wind flow.

Ducts selection was based on a management guide by Foster et al. (2015) with the cross-sectional area selected such that air velocity in the duct is 7.62 m s^{-1} or less.

3.2.7 Selection of the outlet fan

Turbo ventilator capacity

Turbo ventilator exhaust capacity was based on a guide by Ampelair (2008). For the Kakamega region, the average wind speed of 8 km h^{-1}, stack heights of 3 m and temperature differences of 6°C – 12°C were used and for a 0.5 m throat diameter ventilator. A capacity of 1000 cfm was therefore used.

Chimney capacity

The airflow rate created by natural draft due to the temperature difference between the outside air and inside of dyer was calculated according to Equation 9 (Engineering Toolbox, 2018b).

$$q = \pi d_h^2 /4 \left[(2 g (\rho_o - \rho_r) h)/(\lambda l \rho_r/d_h + \Sigma \xi \rho_r)\right]^{1/2} \quad (9)$$

With the air density at given temperature calculated based on following formula:

$$\rho = (1.293 \text{ kg m}^{-3}) (273 \text{ K}) / (273 \text{ K} + t) \quad (10)$$

Exhaust fan size

This was calculated based on the following expression:

$$EFS = LFC - LTVC - LCC \quad (11)$$

According to Wheeler and Both (2004), for a well-designed greenhouse, the static pressure difference is approximately 0.05-inches of water with an acceptable operating range of 0.03 to 0.13-inches. The fan selection was based on calculated cfm, and by factoring a 0.08 pressure drop and 5% margin (Arora, 2010).

3.2.8 System design after factoring radiation

The total heat energy gained and temperature rise due to solar radiation was then calculated. Variant expression of collector efficiency has been given by Azimi et al. (2012), Hossain and Gottschalk (2007) and Almuhanna (2012). The later gives;

$$\eta_d = \frac{m_a \, C_{pa} \, (T_i - T_a)}{\tau \, R \, A_d} \quad (12)$$

Studies have given different values of thermal efficiencies; for greenhouses it has ranged from 18.00% - 60.11% according to Ayyappan and Mayilsamy (2010) and Almuhanna (2012), while Hossain and Gottschalk (2007) gave efficiency ranges of 17%-52%, with an average of about 45% for an indirect dryer and based on global radiation. The thermal efficiency of 50% has been assumed.

The average solar radiation in Kenya is between 4 to 6 kWh m^{-2} day^{-1} (Wasike et al., 2014) or an average of 700 W m^{-2} (Wasike et al., 2014). The radiation R is estimated from proportions of global radiation received on a gable roof dryer (Dragicevic, 2011) and estimates from studies by McAneney and Noble (2012). With this, the North and South roof is estimated to receive 90% of global radiation on a horizontal surface, West wall and East wall receiving 50% of the radiation while North wall and South wall receive 30% of radiation. Total radiation RA_d was then calculated.

Equation 12 was used to estimate the average increase in ambient temperature; using C_{pa} = 1.007 kJ kg^{-1} K^{-1}; calculated m_a and τ = 0.9 (Saravanapriya and Mahendiran, 2017). On the other hand, Equation 6 was used to determine the heat required to raise temperature to estimated temperature and evaporate water while Equation 7 was used to establish the weight of wood after factoring radiation.

Drying rate

The drying rate (DR) was calculated based on the following equation (Chakraverty, 2000).

$$DR = \frac{dM}{dt} = \frac{M_{t+dt} - M_t}{t} \quad (13)$$

A summary of key design output data for the developed solar-biomass dryer is presented in Table 1.

Table 1 System design key output data

Item	Value
Lower vents opening	0.2 m
Ducts cross section area	0.09 m^2
Blower fan capacity adjusted for 0.675 inches water gauge/100 ft of duct	3916 cfm
Average estimated rise in temperature inside the dryer solely due to solar radiation	8.4°C
Biomass required at average solar radiation (kg of firewood/kg wet produce)	0.1 kg
Extractor fan capacity	1508 cfm

4 Results and discussion

The moisture reduction with time under the three modes (viz., natural, forced convection and hybrid modes) is shown in Figures 2, 3 and 4. The drying rate of kales and spider plant both of which had higher initial moisture content was higher than that of the other crops. The drying rate is slower in arrow roots, sweet potatoes, bananas, and cassava and this could be attributed to a number of factors such as; the difference in initial moisture content, which is high in fruits and vegetables; varied moisture diffusivity and thermal conductivity of different crops. These parameters in many instances have been reported to affect each other with the latter two being influenced by other factors such as shape and size of material being dried as well as shrinkage during drying (Srikiatden and Roberts, 2007; Kumar et al., 2015; Njie et al., 1998). From Figures 3 and 4, under the hybrid mode, most crops were able to reach low moisture contents of 200% dry basis and below within 3 h compared to 4 and 6 h under the natural and forced convection modes, respectively. From the results, the drying rate and the drying time could be projected to be lower than the estimated design time of 8 h per batch. This could be attributed to the higher average solar radiation during trials than the design radiation.

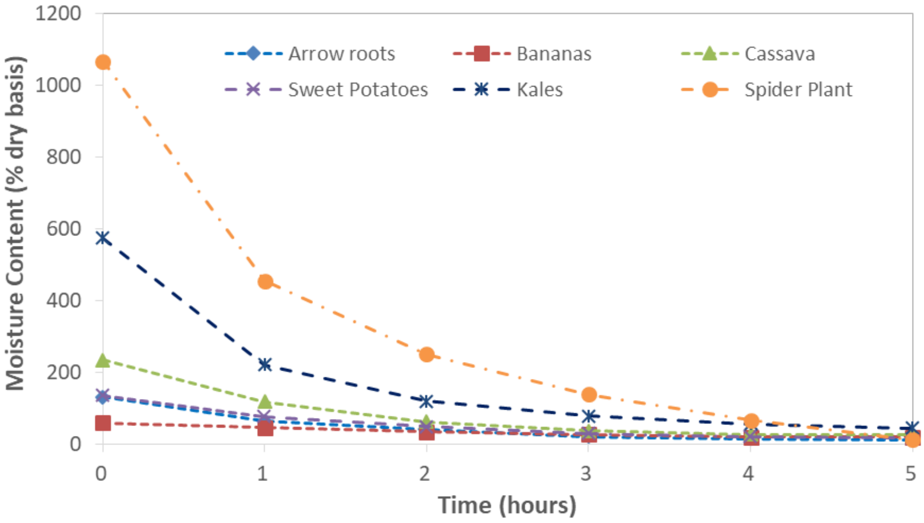

Figure 2 Variation of moisture content with time under natural convection

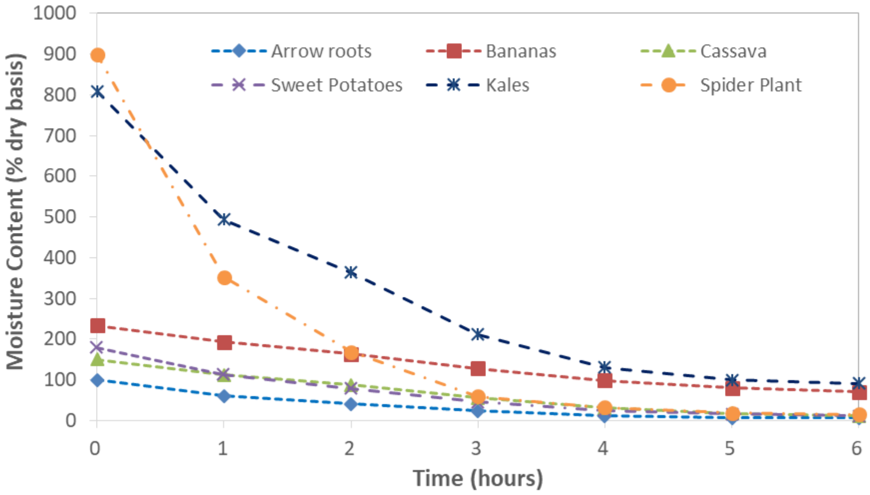

Figure 3 Variation of moisture content with time under forced convection

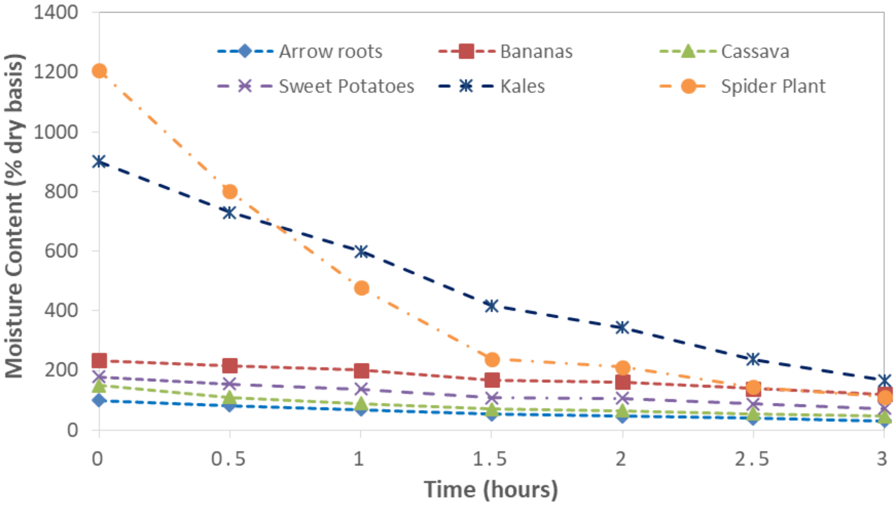

Figure 4 Variation of moisture content with time under hybrid mode.

The temperature and radiation changes with time in the dryer under the three modes are shown in Figures 5, 6 and 7. The hybrid mode was operated for three hours; therefore, comparison of performance is based on the first three hours of operation for each mode. From the results, it can be observed that the average temperature changes within the first three hours were 13.1°C, 20.8°C and 17.9°C under the natural, forced and the hybrid modes, respectively. The average radiation over the same time was 545, 668, 594 Wm^{-2}, respectively. The temperature changes, increased with an increase in solar radiation. Further, a declining trend of solar radiation with time led to a decrease in air temperature change. This shows that solar radiation has a direct influence on air temperature. The average temperatures in the dryer were 49.3°C, 53.8°C and 53.2°C under natural, forced and hybrid modes, respectively. The average monitored air velocity in the hybrid system was higher at an average of 0.7 m s^{-1} compared to 0.4 m s^{-1} under forced convection; this varied as air velocity was manually increased to control the temperatures inside the dryer. The temperatures inside the dryer were almost equal for both hybrid and forced convection despite the solar radiation in the forced convection mode being 12.5% higher than in the hybrid mode. It is worth noting that the lower mesh openings along the bottom section of the side walls were left unclosed even in the hybrid mode as was the case in the other modes. Significantly higher temperatures inside the dryer could be achieved if the lower mesh openings are closed or replaced with polyethylene cover, especially when the dryer runs on hybrid mode as per design. The high air velocity in the hybrid mode compared to that of the forced convection, led to comparative lower temperatures. All these show that the biomass heater led to an improved drying condition inside the hybrid mode, mainly due to increased heat supply which resulted in the higher drying rates.

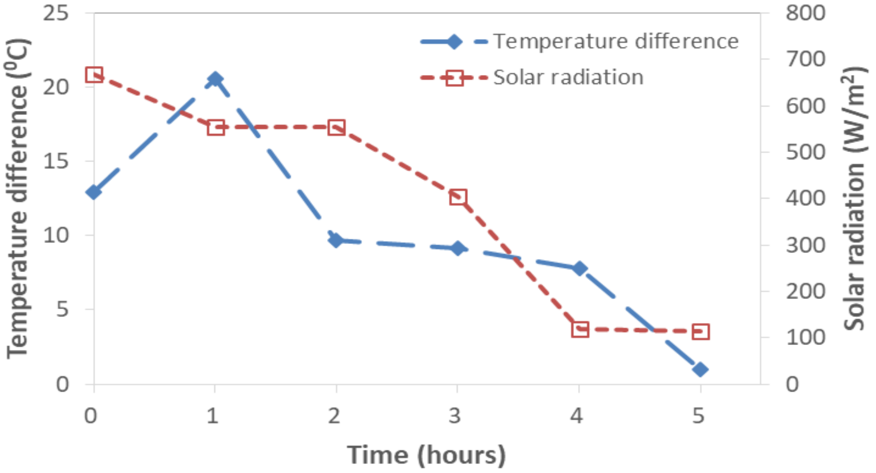

Figure 5 Variation of the difference between ambient and inside air temperatures and solar radiation under natural convection.

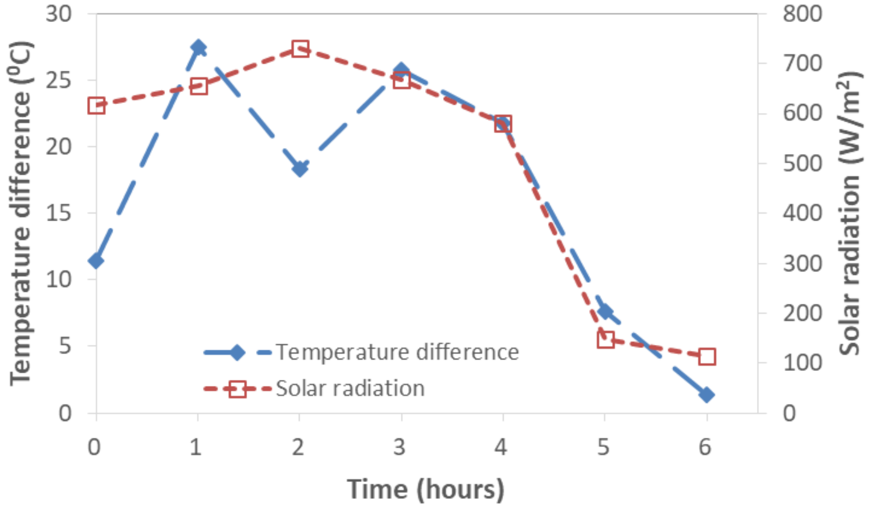

Figure 6 Variation of the difference between ambient and inside air temperatures and solar radiation under forced convection.

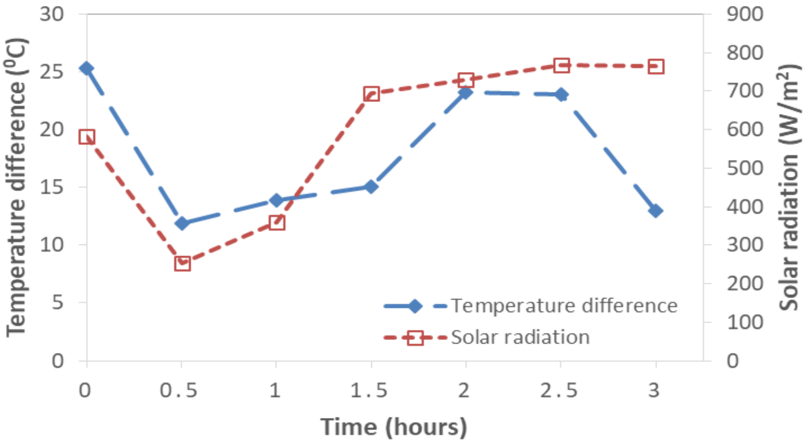

Figure 7 Variation of the difference between ambient and inside air temperatures and solar radiation under hybrid mode.

There was no marked difference between lower and upper drying beds in terms of temperatures under the three modes; with lower beds having a slightly lower temperature by 1.9°C and 1°C for the natural and hybrid modes, respectively. However, the lower bed temperatures were marginally higher by 0.2°C in the forced convection, an indication of proper mixing of air inside the dryer. The drying rate under the hybrid mode was, on average, about 19.0% higher than of the natural mode, while that of forced mode was 1.1% higher than of natural mode. Analysis of drying rate in the first three hours shows that on average, for all the crops, the hybrid dryer exhibited a higher drying rate of 0.03425 kg water per kg dry matter per second compared to 0.0288 and 0.0285 kg water per kg dry matter per second under natural and forced convection modes. However, the difference in the ambient conditions led to the reduced reflection of the actual performance. The prevailing temperatures were different and this must have influenced slightly the drying rates in the three modes; with the average ambient temperature in first three hours being 36.2°C, 33.0°C and 35.3°C under the natural, forced and hybrid modes. As expected, the relative humidity reduced during drying when temperatures increased. The inside of the dryer and the ambient relative humidity were 21.5% and 35.5%, 18.1% and 44.0%, 19.5% and 35.3%, respectively for the natural, forced and hybrid modes.

Biomass used

The biomass used was blue gum (*Eucalyptus globulus*). About 0.045 kg of biomass per kg of wet produce was used, translating to about Kshs 0.9 (US$ 0.009) per kg of wet produce, within the 6 hours of biomass utilization. This was lower than the calculated quantity mainly because the radiation and ambient temperatures during drying were higher than the average radiation used in design calculations and due to a varied loading of the dryer. Also, a higher biomass use would have increased the inside temperatures close to the desired temperatures.

5 Conclusions

A multipurpose solar-biomass greenhouse dryer was developed and tested for use by small to medium enterprises in Kenya. From the results of this study, the system performance improves when solar energy is backed up with biomass energy. The drying, increased by about 18%-19% using the solar-biomass mode compared to both the natural and forced convection modes. The amount of biomass used in the developed system is low and would not substantially increase the cost of drying. Overall, the hybrid mode has a great potential in improving the greenhouse dryer performance and even further by closing, as per the design, the lower mesh openings on the bottom section along the side walls of the dryer. However, more tests still need to be undertaken to fully analyse the dryer’s performance, especially in optimising the biomass use in order to achieve desired temperatures.

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Nomenclature

Parameters	Meaning
A_d	surface area of the dryer (m^2)
A_w	area of lower openings of the dryer (m^2)
C_p	specific heat capacity of product (kJ kg^{-1} K^{-1})
C_{pa}	specific heat of the air (kJ kg^{-1} K^{-1})
C_{sp}	specific heat of sweet potatoes (kJ kg^{-1} K^{-1})
C_w	calorific value of wood (kJ kg^{-1})
d_e	equivalent duct diameter (inches)
d_h	hydraulic diameter (m)
DR	drying rate (kg water per kg dry matter per h)
dM	change in moisture content (kg water per kg dry matter)
dt	change in time (h)
Δp	friction (head or pressure loss) (inches water gauge/100 ft of the duct)
EFS	exhaust fan size
g	acceleration of gravity (9.81 m s^{-2})
h	height between the outlet and inlet air (m)
H	heat required/ energy required (kJ)
I	solar radiation (W m^{-2})
η_d	overall thermal efficiency (-)

l	length of duct or pipe (m)
LCC	lowest chimney capacity (cfm)
LFC	lowest fan capacity (cfm)
LTVC	lowest turbo ventilator capacity (cfm)
Lw	latent heat of evaporation of water (J kg^{-1})
λ	Darcy-Weisbach friction coefficient (0.015 for PVC pipes)
m_a	mass flow rate (kg s^{-1})
m_i	initial mass of the product (kg)
M_o	initial moisture content of the product (w.b, %)
M_f	final moisture content of the product (w.b, %)
m_p	mass of the product (kg)
M_t	moisture content at time t (kg water per kg dry matter)
M_{t+dt}	moisture content at time $t+dt$ (kg water per kg dry matter)
Mv	volumetric flow rate under natural ventilation (m^3 s^{-1})
m_v	volumetric flow rate (m^3 s^{-1})
m_w	mass of water (kg)
n	pickup factor (-)
t	total time (h)
T_i	inside temperature (^{o}C)
T_a	ambient temperature (°C)
T_p	product temperature (°C)
τ	transmittance of cover material (-)
q	air volume (m^3 s^{-1})
Q_w	quantity of wood (kg)
u	air volume flow (cfm)
R	total solar radiation incident on a horizontal surface (W m^{-2})
ρ_o	density outside air (kg m^{-3})
ρ_r	density inside air (kg m^{-3})
$\Sigma\xi$	minor loss coefficient -summarized (-)
V_w	wind flow rate (m s^{-1})
v_s	specific volume of dry air (m^3 kg^{-1})
ΔW_{fi}	change in humidity ratio (g of moisture/kg of dry air)