Development of a multi agricultural products dryer using biomass

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Abstract: Natural method of sun drying is weather dependent and time consuming which leads to spoilage and contamination of food crops. This research designed and experimentally tested a multi agricultural dryer using solar energy and biomass, capable of drying agricultural produce anytime of the day in a hygiene environment. The experimental setup consists of the biomass combustion chamber with inbuilt heat exchanger, the dryer and data collection instruments. Tomatoes, Okra and bitter leaf were dried, their relative humidity, moisture content, weight loss and temperature variation in the drying chamber were monitored. The maximum temperature reached in the drying chamber when drying tomato, okra and bitter leaf were 95.7ºC, 87.1ºC 73.4ºC respectively, with a drying rate of 0.1248, 0.1876 and 0.0780 kg h^{-1}, respectively at a steady air flow rate of 1.3 m s^{-1}. The dryer had an efficiency of 45% and effectiveness of the heat exchanger is 0.07 at an average combustion temperature of 1300ºC. The uniqueness of the machine is that it reduces the drying time and products are free from environment contaminations and rodents' invasion. Thus agricultural crop samples can be preserved year-round irrespective of weather conditions and at a faster rate with the developed machine.

Keywords: tomatoes, okra, bitter leaf, relative humidity, moisture content, weight loss, temperature

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1 Introduction

Food preservation helps in reducing wastage of surplus harvest, allow for storage of food in case of food shortages, and some instances help in the export of food to high-value market. Preservation of fruits, grains, vegetables, and meat has been practiced around the world for many years. There are various preservation methods which include: freezing, canning, pickling, curing (smoking and salting), and drying (Green and Schwarz, 2001). Drying is a process of removing moisture from an agricultural products through the application of heat to increase their shelve

life, make them easy to transport due to their weight loss, and reduce storage space, the removal of moisture hampers the growth and reproduction of microorganisms that result in decay and other deteriorative reactions (Dincer et al., 2002). The quality of the dried products depends on the duration, temperature, thickness of the product to be dried, and air velocity (Ertekin and Yaldiz, 2004; Fudholi et al., 2015). The traditional method of natural/open sun drying is a general practice everywhere in the world. Sun drying is an economical method commonly used by rural farmers for the drying of food products in developing countries. Some of the problems associated with sun drying include low drying rate, dependence on weather conditions, high crop losses

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due to inadequate drying, and inferior quality of the product dried due dust and dirt, non-uniform drying, and contamination caused by rodents, microorganisms, and insects (Hossain et al., 2008; Yassen and Al-Kayiem, 2015).

Biomass is a good substitute for the process of drying because it does not depend on weather conditions, making drying possible at all times. Biomass is a renewable energy source, largely obtained from agricultural waste. The heat energy gotten through the combustion of biomass can be directly used or supplied through carriers such as steam or hot air which in turn will be used to dry food products (Ghanchi et al., 2012). A number of literatures were reviewed with a view to establishing some knowledge gap, Bena and Fuller (2002) designed a direct-type natural convection solar dryer with a biomass burner for drying fruits and vegetables. The dryer dried 20-22 kg of 0.01 m thick pineapple slices with an overall efficiency of 9%. Ways to improve the performance of the dryer's solar and biomass compartments were suggested. Prasad and Vijay (2005) worked on a brace type solar dryer with biomass stove attached. Tests were carried out on the dryer using ginger, turmeric, and Guduchi. The moisture content of the ginger reduced from 319.47(d.b)% to 11.8(d.b)% within 33 hours while there was a reduction in the quantity of moisture in turmeric from 358.96(d.b)% to 8.8(d.b)% and that of Guduchi from 257.45(d.b)% to 9.67(d.b)% during a drying period of 36 and 48 hours respectively. The drying time of open sun and solar-only operation of the dryer was 72-120 hours and 192-288 hours respectively.

Madhlopa and Ngwalo (2007) designed and constructed an indirect type of natural convection solar dryer incorporated with collector-storage and biomass backup heaters. Pineapples were the agricultural product used to carry out tests of the dryer. Tests were carried out on the dryer using three operational modes which were solar, biomass, and solar biomass, the drying of the pineapples occurred fastest in the solar-biomass method. Gutti et al. (2012) worked on the design and construction of forced and natural convection solar vegetable dryer with heat storage. The collector unit, air inlet, energy storage unit, air outlet, and ambient temperatures obtained are 53ºC, 52ºC, 52ºC, 44ºC, and 36ºC respectively. The heat storage unit was only used during periods of low or no sunshine to ensure drying of the agricultural products is not hindered. The forced convective mode system took 14, 15, 12, 11 and 1 hour to dry tomato, onion, pepper, okra, and spinach while the natural convective mode system took 24, 27, 25, 21, and 2 hours to dry tomato, onion, pepper, okra, and spinach. From their results, it was evident that the forced mode system used for drying is better than the natural mode system.

Okoroigwe et al. (2013) designed, constructed, and evaluated the performance of a solar cabinet dryer combined with a biomass heater that can be used in developing countries. The dryer had three trays that were evenly spaced. Tests were carried over four days, the test material was fresh yam chips. The maximum tray temperature reached was 53ºC which was obtained from the combination of solar and biomass for drying. The drying rate was 0.0142, 00732 and 0.0032 kg h^{-1} for solar-biomass, solar, and biomass drying respectively. The results obtained proved that the combination of solar and biomass for drying will improve the drying efficiency of the agricultural dryer. Dhanushkodi et al. (2015) designed and constructed a biomass dryer for cashew nut processing. The dryer consisted of a biomass heater that functioned in the production of hot air into the drying chamber, which contained the products to be dried. There was also an inclusion of a blower to blow hot air into the drying chamber, thereby making the drying a forced convection system. The system efficiency was evaluated, and it was found that the efficiency of the dryer was 9.5%. The temperature range for the drying chamber of the dryer was 70ºC to 75ºC. It was also recorded that it took 7 hours to reduce the moisture content of a cashew nut from 9% to 4%, while it took fifteen hours to achieve the same result using open sun drying. It was concluded that the use of biomass for drying agricultural products was faster and more efficient than open sun drying.

Raj et al. (2018) worked on the performance of a biomass dryer based on exergy analysis, the study analyzed the performance of the simple biomass dryer which makes use of briquette and wood to generate heat to dry cashew nut. The biomass dryer was able to generate an adequate and continuous flow of hot air between the temperature range of 70ºC and 75ºC with a combustion efficiency and energy efficiency of 36% and 19% respectively. Priya and Santhanakrishnan (2018) developed a solar biomass integrated crop dryer. Their research explained how a simple biomass burner integrated into a mixed-mode natural convection solar dryer can be used to dry fruits, vegetables and medical plants. It was concluded that the inclusion of the thermal backup made the drying of the products faster and also improved the quality of the products when compared to open sun drying. It was recorded that the average rate of drying for the dryer was 0.8 kg day^{-1} for every 10 kg of crops while the rate of drying was 0.3125 kg day^{-1} for open sun drying.

Anand et al. (2018) worked on the utilization of solar energy and biomass to generate the required amount of heat to remove moisture in perishable crops inside a drying chamber with an atmosphere controlled by a simulation. A mixed-mode solar biomass dryer was designed. The dryer made use of an intelligent system through a microcontroller, the humidity and the temperature inside the drying chamber were monitored by the microcontroller. The controlled atmosphere helped to maintain the desired temperature and humidity in the drying chamber. Onions, leafy vegetables, and garlic were the agricultural product used in the research. In the course of this research, a multi agricultural biomass dryer was designed and experimented. The design has multiple forced convective hot air entry and single air exit, it incorporates a three pass heat exchanger. This design improves the effectiveness of the heat exchanger, efficiency of the drying chamber and efficiency of combustion of the biomass burner and uniform temperature in the drying chamber which lead to great reduction in the drying time of tomatoes, okra and bitter leaf in a hygiene environment.

2 Design of drying chamber and biomass burner

2.1 Design of drying chamber

The drying chamber has two major components which are the drying cabinet and drying trays. The temperature across the products in the tray should be uniform and temperature differential limited to10ºC. The volume of the drying Chamber is expressed as Equation 1:

$$V_c = L_c \times W_c \times H_c \tag{1}$$

Where L_c equals length, m; W_c equals width, m; H_c equals height of the drying chamber, m. The dimensions of the drying chamber are based on the dimension of the drying tray, which is a function of the quantity of product to be dried. The amount of moisture to be evaporated from a sliced sample product can be estimated (Ehiem et al., 2009) as Equation 2:

$$M_W = M_{dry}\left(\frac{Q_1-Q_2}{1-Q_2}\right) \tag{2}$$

Where M_W equal mass of moisture evaporated, kg; M_{dry} equal amount of crop sample to be dried, kg; Q_1 equals initial moisture content of crop sample,%; Q_2 equals final moisture content desired for the crop sample,%.

The quantity of heat required for the evaporation of moisture from the crop sample can be approximated as Equation 3:

$$Q_W = M_W \times H_L \tag{3}$$

Where H_L equals latent heat of vaporization, kJ kg^{-1}. The latent heat of vaporization can be estimated as Equation 4 (Eke, 2014), or Equation 5 (Youcef-Ali et al., 2001):

$$H_L = 2{,}502{,}585.259 - 2{,}385.76424\,(T_D - 273.16) \tag{4}$$

$$H_L = 4.186\,(597 - 0.56T_\infty) \tag{5}$$

Where T_D equals drying temperature, K; T_∞ equals ambient temperature, K. The desired drying temperature is taken to be 65°C, while the temperature of the product is taken to be the ambient temperature. The quantity of air required for drying is obtained using the energy balance Equation 6 (Nwakuba et al., 2017 and Nwajinka and Onuegbu, 2014):

$$M_W H_L = m_a C_a (T_2 - T_\infty) \tag{6}$$

The specific heat capacity of the crop sample can be estimated using the expression of Heldman and Singh, (1980) as Equation 7:

$$C_a = 1.675 + 0.025(Q_1) \tag{7}$$

Where C_a equals specific heat capacity of crop sample, J kg^{-1} K^{-1}; m_a equals mass of drying air, kg; T_2 equals final temperature of the drying air before passing through the drying tray, K. The volume of air can then readily be expressed as Equation 8:

$$V_a = \frac{M_W H_L}{\rho_a C_a (T_2 - T_\infty)} \tag{8}$$

Where ρ_a is the density of air, kg m^{-3}. The amount of energy required to heat the volume of air that will be sufficient to remove the required quantity of water contained in a crop sample can be obtained by the equations given by Ehiem et al. (2009) as Equation 9:

$$Q_D = M_{dry} C_a (T_2 - T_\infty) + H_L M_W \tag{9}$$

According to Dhanushkodi et al. (2015), the efficiency of the drying chamber is as Equation 10:

$$\eta_D = \frac{(T_2 - T_3)}{(T_2 - T_\infty)} \tag{10}$$

Where T_3 equals temperature of air exiting the drying chamber, K.

2.2 Design of biomass chamber

The combustion chamber is rectangular and perforated to ensure that there is sufficient air for combustion. The combustion chamber can accommodate about 3 kg of biomass (Charcoal) which will be sufficient for providing the heat required for drying for about 2-3 hours (Madhlopa and Ngwalo, 2007). According to Zubairu and Gana (2014), the bulk density of charcoal is 180 – 220 kg m^{-3}. The volume of the space occupied by charcoal is calculated using the expression:

$$V_{ch} = \frac{M_{ch}}{\rho_{ch}} \tag{11}$$

Where M_{ch} equals mass of charcoal, kg; ρ_{ch} equals bulk density of charcoal, kg m^{-3}. There is a grate 0.068 m from the base of the combustion chamber so that ash produced falls into the ash tray. The ash tray is also removable and is directly below the grate, at a height of 0.01 m above the base of the combustion chamber. A 10 mm plate is placed on top the combustion chamber which acts as a thermal mass for the purpose of heating air entering the heat exchanger through force convection. The volume of the biomass chamber can be calculated using Equation 12:

$$V_B = L_B \times W_B \times H_B \tag{12}$$

Where L_B equal length of biomass chamber, m; W_B equals width of biomass chamber, m; H_B equals height of the biomass chamber, m.

The heat produced due to combustion of biomass is as Equation 13 (Okoroigwe et al., 2013):

$$Q_B = \eta_B M_{ch} C_V \tag{13}$$

Where η_B equals efficiency of the combustion chamber; C_V equals heating value of the biomass, kJ kg^{-1}. And the combustion efficiency according to Dhanushkodi et al. (2015) is expressed as Equation 14:

$$\eta_B = \frac{M_F \times C_p (T_O - T_\infty)}{(FC \times C_V) + E} \tag{14}$$

Where M_F equal mass of flue gas, kg s^{-1}; C_p equal specific capacity of air, kJ kg^{-1} K^{-1}; T_O equals outlet air temperature from heat exchanger, K; FC equal fuel consumption, kg s^{-1}; E equal energy consumption of the blower, kW.

The total mass of air assuming 20% excess air needed for combustion is given as Equation 15:

$$m_a = \frac{\{(^{32}/_{12} \times A) + (8 \times B) + (1 \times C) + (^{40}/_{31} \times D)\}}{0.23} \times 1.2 \quad (15)$$

Where A, B, C and D are the mass percentage of Carbon, Hydrogen, Sulphur and Phosphorus present in the biomass,%. The mass transfer rate in the drying chamber is obtained as Equation 16 (Ehiem et al., 2009):

$$M_{tr} = M_c A_t (H_{r1} - H_{r2}) \times q_{air} \quad (16)$$

Where M_c equals mass transfer coefficient of free water surface, kg m^{-2} s^{-1}; its numerical value is 0.083 kg m^{-2} s^{-1} (Ehiem et al., 2009), A_t equals total area of the three trays, m^2; q_{air} equals air flow rate, m^3 s^{-1}; H_{r1} equals initial humidity ratio, kg kg^{-1} dry air; H_{r2} equals final humidity ratio, kg kg^{-1} dry air. According to Ajisegiri et al. (2006), the difference between initial and final humidity ratio is given as Equation 17:

$$H_{r1} - H_{r2} = \frac{M_w}{M_a} \quad (17)$$

The moisture content of the air entering the and exiting the drying chamber is obtained as Equation 18 (Gatley, 2013):

$$\omega = \frac{0.622 P_v}{P_{atm} - P_v} \quad (18)$$

Where P_v is the partial pressure of water vapour, Pa; P_{atm} is the atmospheric pressure in Pa. Equation 19 is used to compute the partial pressure of water (Gatley, 2013):

$$P_v = P_w - \frac{(P_{atm} - P_w)(t_{db} - t_{wb})}{1547 - 1.44 t_{wb}} \quad (19)$$

Where P_w is the saturation pressure corresponding to wet bulb temperature, Pa; t_{db} is the dry bulb temperature, ºC; t_{wb} is the wet bulb temperature, ºC.

The relative humidity at the inlet and exit of the drying chamber is then computed using Equation 20 (Gatley, 2013):

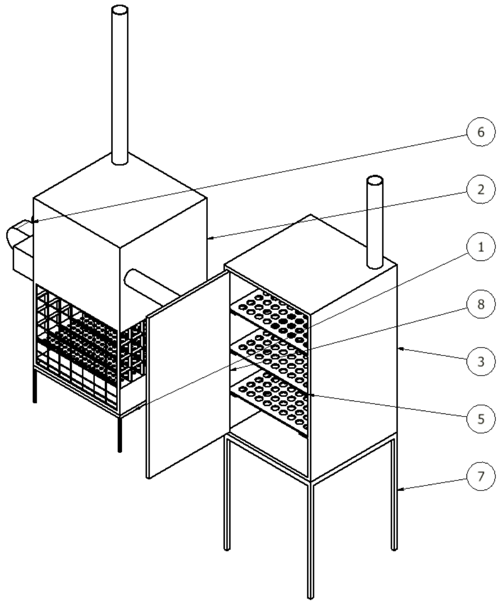
$$\Phi = \frac{P_v}{P_{vs}} \quad (20)$$

Where P_{vs} is the saturated water vapour corresponding to the dry bulb temperature, Pa.

The effectiveness of the heat exchanger is computed using Equation 21:

$$E_{eff} = \frac{T_2 - T_\infty}{T_{cs} - T_\infty} \quad (21)$$

Where T_{cs} is the combustion temperature in K.



Components of the Biomass Dryer

ITEM	QTY	COMPONENTS
1	1	combustion Chamber Stand
2	1	Combustion chamber
3	1	Drying Chamber
4	1	Hot air chamber
5	3	Drying Tray
6	3	Centrifugal Fan
7	1	Drying Chamber
8	1	Drying Chamber Door

Figure 1 Modelled multi agricultural dryer

Figure 2 showing (a) Experimental setup (b) Digital weighing scale (c) Anenometer (d) Digital psychrometer (e) Digital solar meter (f) Solar panels

3 Research method

The drying and biomass combustion chamber inbuilt exchanger were designed using AUTOCAD as shown in Figure 1, after which the fabrication and assembly was carried out.

The performance models were created and the components sized for the purpose of experimentation with tomatoes, okra and bitter leaf. The experimental setup consists of the two 180 W solar panels, two 100 AH, batteries, 30 A charge controller WH-B20 digital weighing scale, GM 8908 digital anemometer, 8706 digital psychrometer. TM-206 solar power meter and MTM-380SD 3 channel temperature data logger and blower as shown in Figure 2.

4 Results and discussion

4.1 Drying of tomatoes

Figure 3 shows experimental plot of air temperature variation on each tray and exit pipe against time. The plots followed a dynamic pattern and shows an increase in temperature with time due to the continuous combustion taking place in the biomass. The maximum air temperature from the bottom tray to the topmost tray and air exit temperature from the drying chamber are 95.7ºC, 90ºC, 92.8ºC, 81.7ºC respectively with an average temperature differential of 5.4ºC. Compared with the differential temperature limit of 10ºC, it can reasonably be concluded that the design objective of ensuring uniform temperature distribution is mostly achieved.

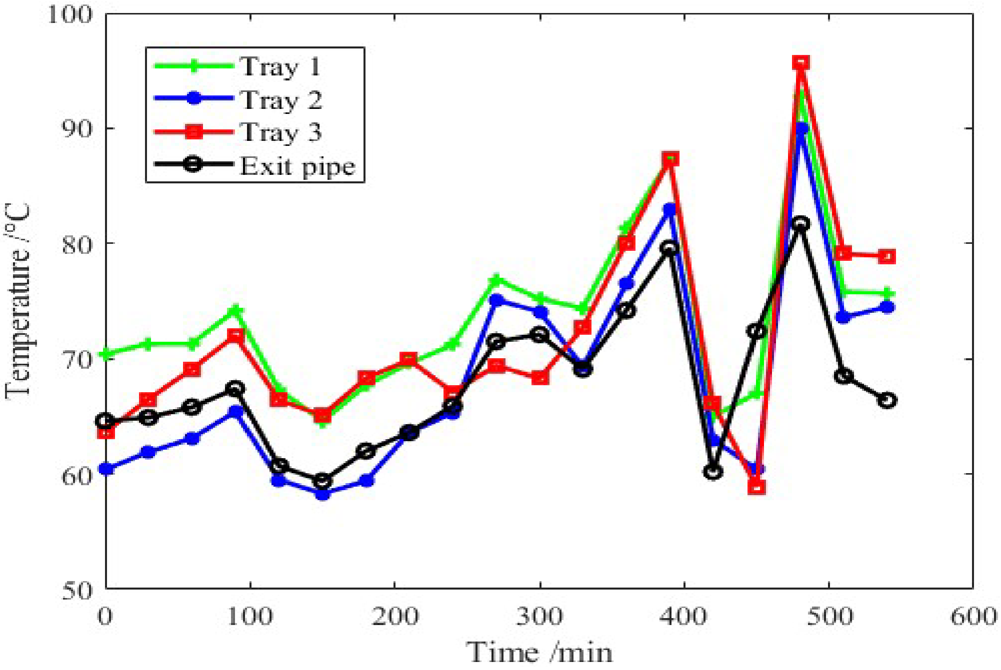


Figure 3 Air Temperature vs time

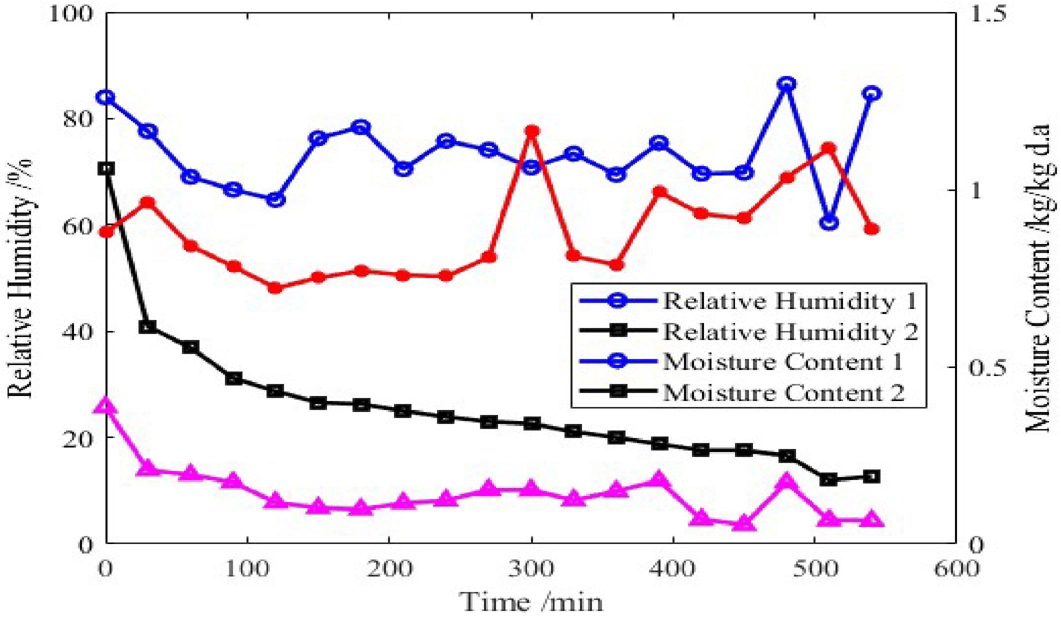


Figure 4 Relative humidity and moisture content vs time. Legend 1 and 2 represent inlet and outlet respectively

Figure 4 shows variations in inlet and exit air moisture content and relative humidity against time for tomatoes drying. The relative humidity and moisture content at inlet are dynamic in nature as expected but decreases steadily with time in the course of the experiment, as also observed by Tibebu et al. (2016) and Khan et al. (2018).

The initial and final moisture contents for tomatoes are 95% and 5% respectively (Tiwari, 2012; Nwakuba et al, 2017; Gumus and Banigo, 2015). The initial mass of the tomato crop samples before drying was 1.3629 kg, the final mass of the tomatoes crop sample after drying was 0.1138 kg after nine hours of operating the dryer. The experimental mass of water removed was 1.2478 kg and theoretical mass of water to be removed was computed to be 1.2912 kg with a percentage difference of 3.4%. The weight loss is due to rapid drop in moisture content as a result of increase in drying air temperature and decrease in relative humidity, a trend also reported by Demiray and Tulek (2012), Celma et al. (2012), Ehiem et al. (2009), and Khan et al. (2018), Figure 5 showed the dried tomatoes.

Figure 5 Dried tomatoes

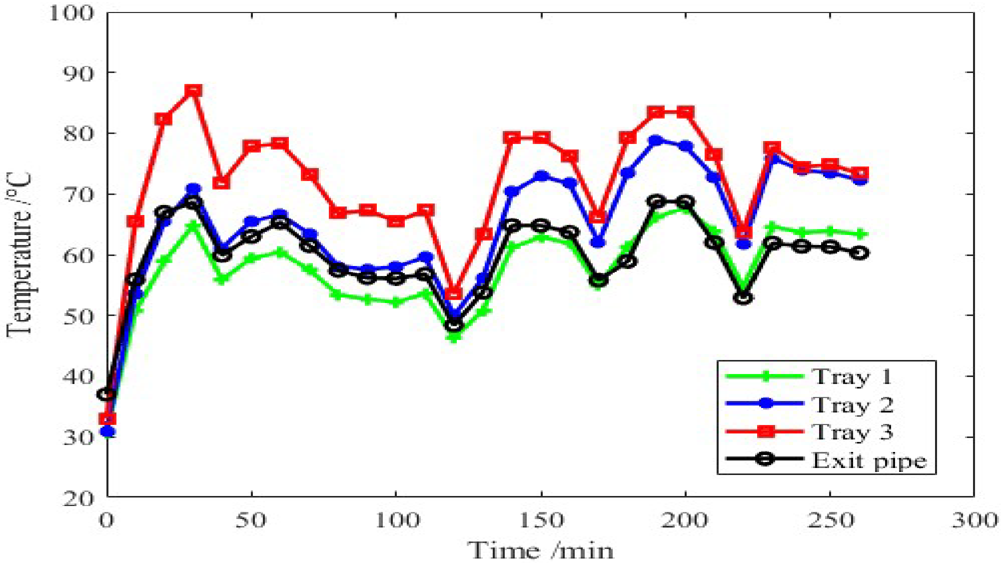


Figure 6 Temperature vs time

4.2 Drying of okra

Figure 6 shows experimental plot of air temperature variation on each tray and exit pipe against time during the course of drying Okra. The plots followed a dynamic pattern and shows an increase in temperature with time due to the continuous combustion taking place in the biomass. The maximum air temperature from the bottom tray to the topmost tray and air exit temperature from the drying chamber are 87.1°C, 78.9°C, 67.7°C, 68.8°C respectively with an average temperature differential of 7.28°C. Compared with the differential temperature limit of 10°C, it can reasonably be concluded that the design objective of ensuring uniform temperature distribution is mostly achieved.

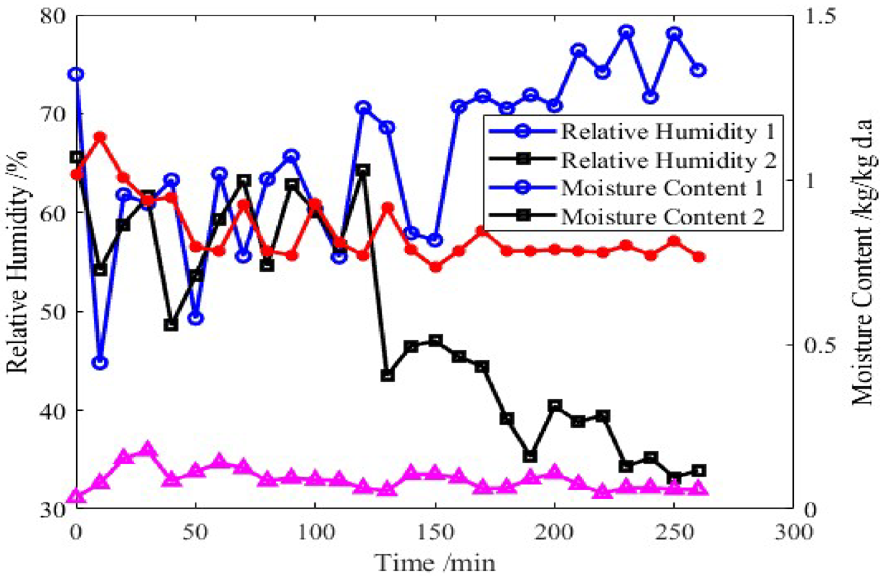


Figure 7 Relative humidity and moisture content vs time. Legend 1 and 2 represent inlet and outlet respectively

Figure 8 Dried okra

Figure 7 shows variations in inlet and exit air moisture content and relative humidity against time for okra drying. The relative humidity and moisture content at inlet are dynamic in nature as expected but decreases steadily with time in the course of the experiment.

The initial and final moisture for okra are 88.7% and 15% (Tiwari, 2012; Nwakuba et al, 2017; Gumus and Banigo, 2015). The initial mass of the okra crop samples before drying was 1.2006 kg, the final mass of the okra crop sample after drying was 0.2628 kg after four hours and ten minutes of operating the dryer. The experimental mass of water removed was 0.9378 kg and theoretical mass of water to be removed was computed to be 1.0499 kg with a percentage difference of 10.7%, a bit high and it can be improved by extending the drying time. Again, the weight loss is due to rapid drop in moisture content as a result of increase in drying air temperature and decrease in relative humidity, Figure 8 showed the dried okra。

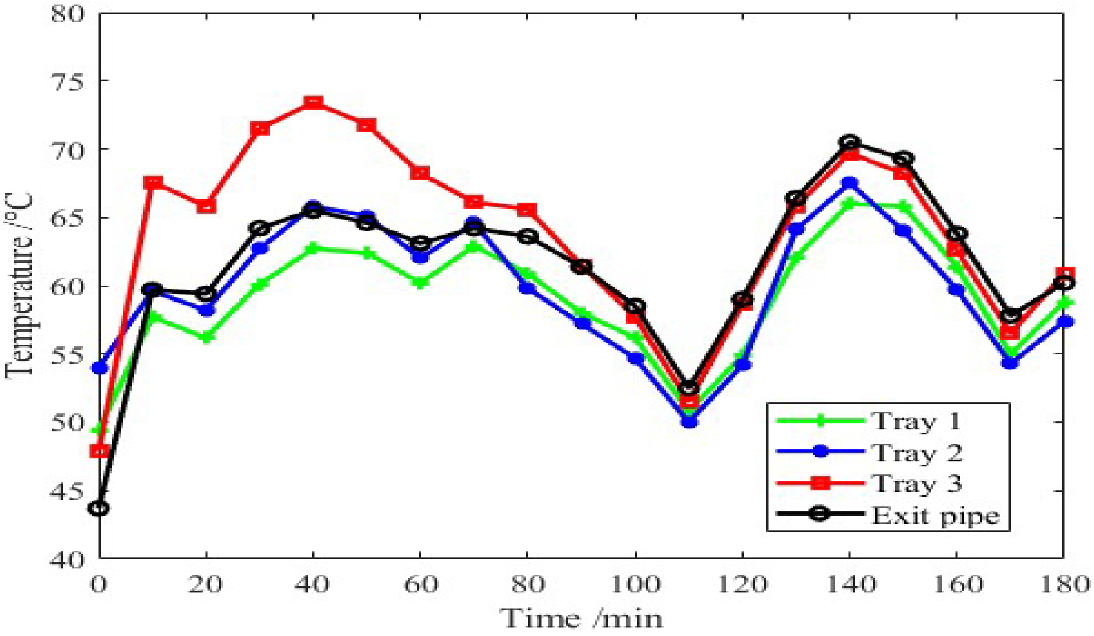


Figure 9 Temperature vs time

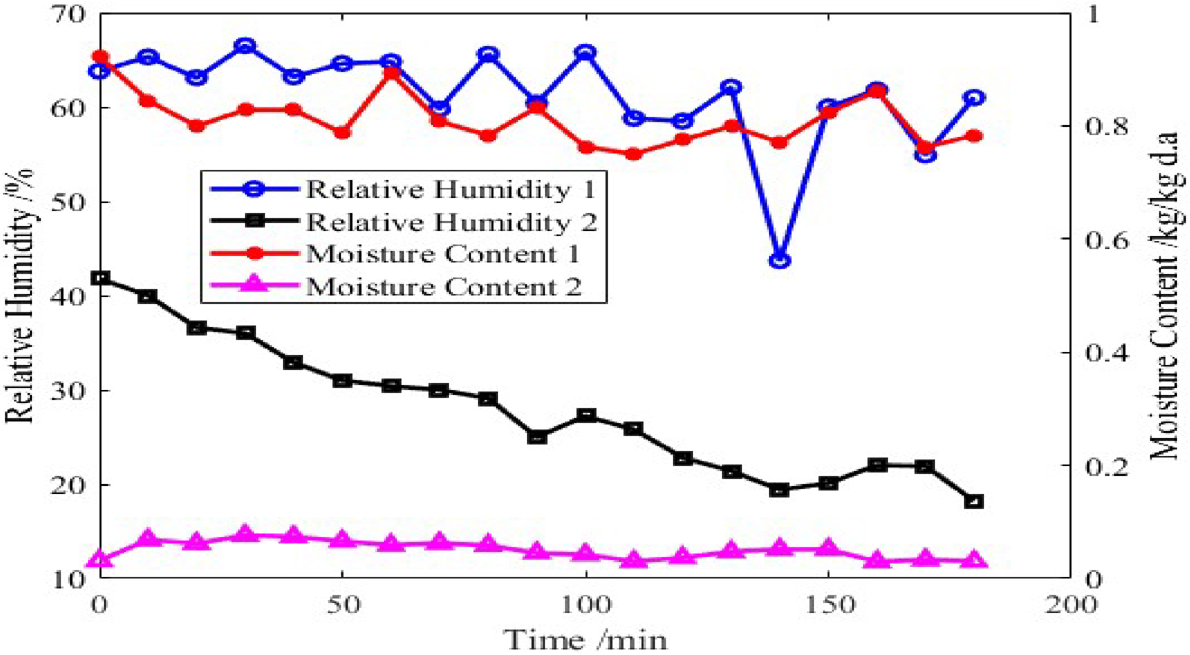


Figure 10 Relative humidity and moisture content vs time. Legend 1 and 2 represent inlet and outlet respectively

4.3 Drying of bitter leaf

Figure 9 shows experimental plot of air temperature variation on each tray and exit pipe against time during the course of drying bitter leaf. The plots followed a dynamic pattern and shows an increase in temperature with time due to the continuous combustion taking place in the biomass. The maximum air temperature from the bottom tray to the topmost tray and air exit temperature from the drying chamber are 73.4ºC, 67.5ºC, 65.8ºC, 70.5ºC respectively with an average temperature differential of 4.64ºC. Compared with the differential temperature limit of 10ºC, it can reasonably be concluded that the design objective of ensuring uniform temperature distribution is mostly achieved.

Figure 11 Dried bitter leaf

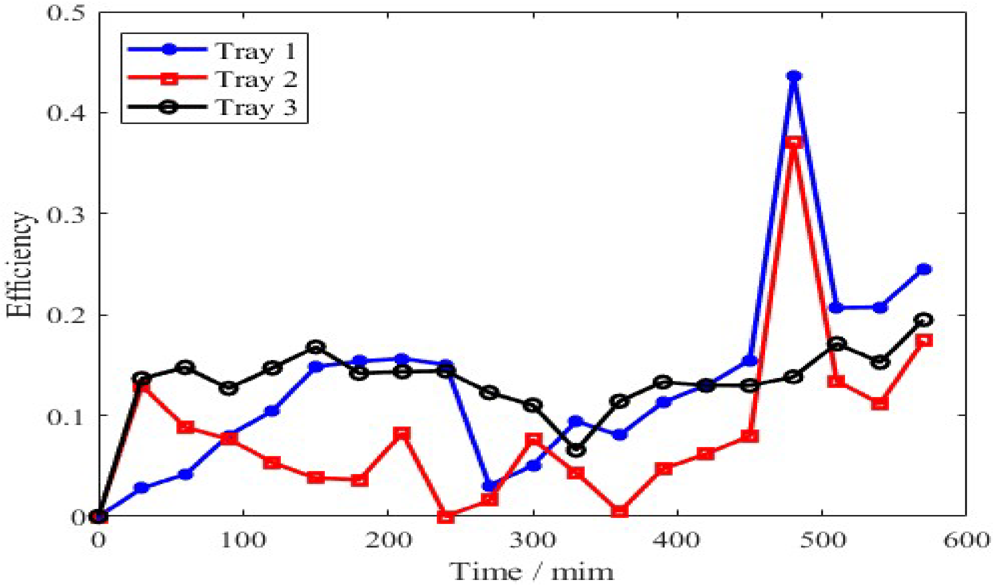


Figure 12 Drying chamber efficiency

Figure 10 shows variations in inlet and exit air moisture content and relative humidity against time for bitter leaf drying. The relative humidity and moisture content at inlet are dynamic in nature as expected but decreases steadily with time in the course of the experiment. The initial and final moisture contents for bitter leaf are 85.63% and 0.9% (Tiwari, 2012; Nwakuba et al, 2017; Gumus and Banigo, 2015). The initial mass of the bitter leaf samples before drying was 0.3004 kg, the final mass of the tomato crop sample after drying was 0.0663 kg. The total mass of water removed was 0.2341 kg. The experimental mass of water removed was 0.2341 kg and theoretical mass of water to be removed was computed to be 0.2568 kg with a percentage difference of 8.8%. The weight loss is due to rapid drop in moisture content as a result of increase in drying air temperature and decrease in relative humidity, Figure 11 showed the dried bitter leaf.

4.4 Drying chamber and combustion efficiency

Figure 12 shows the plots drying chamber efficiency with time which can be seen to dynamic in nature and varies per tray. The wavy nature and variation within each tray could be attributed to uneven distribution of the air across the drying chamber, the maximum recorded efficiency is 45%. Figure 13 is a graphical representation of the effectiveness of the heat exchanger against operating time of the dryer. Clearly the effectiveness varies within the trays and also dynamic in nature due to the combustion intensity of the biomass. The relatively low value of the heat exchanger effectiveness of 0.07 could be attributed to combustion energy loss and the finite nature of differentials between the combustion temperature and drying air temperature.

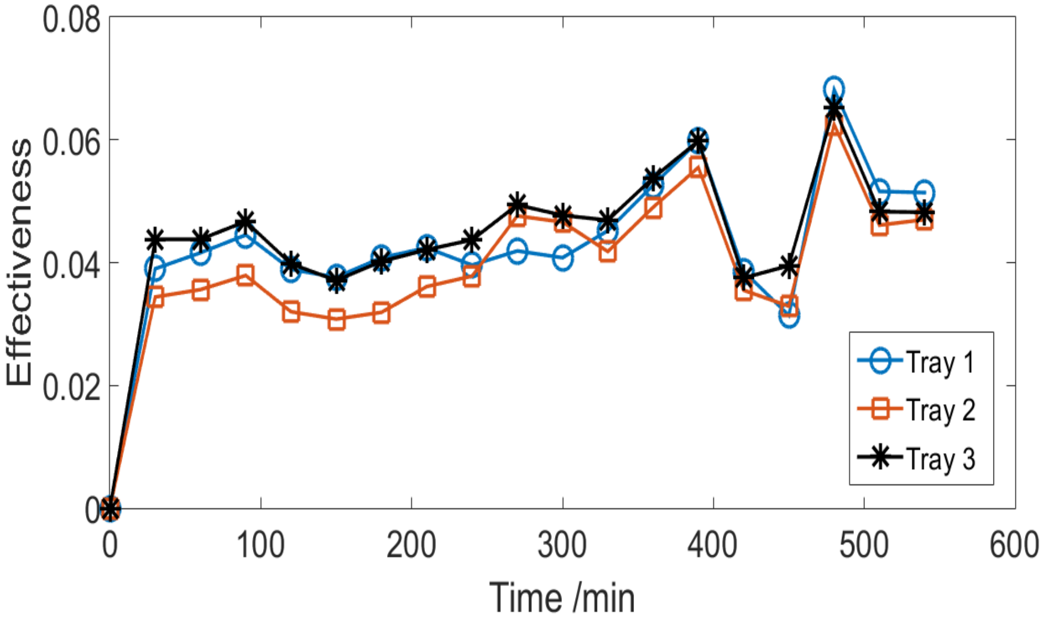


Figure 13 Heat exchanger effectiveness

5 Conclusion

The design, fabrication and experimental testing of a multi agriculture dryer using solar energy and biomass was successfully carried out. Parameters such as relative humidity, moisture content, weight loss, and temperature were measured and recorded with time. The dryer was used to dry tomato, bitter leaf, and okra. The maximum temperature obtained in the drying chamber when drying tomato, bitter leaf, and okra was 95.7ºC, 73.4ºC, 87.1ºC, respectively, while the drying rate was 0.1248, 0.0780, 0.1876 kg h^{-1} respectively. The dryer had an efficiency of 45% and effectiveness of the heat exchanger is 0.07 at an average combustion temperature of 1300ºC. The uniqueness of the machine is that it reduces the drying time and products are free from environment contaminations.

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Nomenclature

Parameters	Meaning
A	Mass fraction of Carbon in biomass (%)
B	Mass fraction of Hydrogen in biomass (%)
C	Mass fraction of Sulphur in biomass (%)
D	Mass fraction of Phosphorus in biomass (%)
A_t	Total area of the three drying trays (m^2)
C_a	Specific Heat Capacity of Crop Sample (J kg^{-1} K^{-1})
C_p	Specific Heat Capacity of Air (kJ kg^{-1} K^{-1})
C_V	Heating value of the biomass (J kg^{-1})
E	Energy Consumption of the Blower (kWh)
FC	Fuel Consumption (kg)
H_B	Height of the Biomass Chamber (m)
H_c	Height of the Drying Chamber (m)
H_L	Latent Heat of Vaporization (J kg^{-1})
H_{r1}	Initial humidity ratio (kg kg^{-1} dry air)
H_{r2}	Final humidity ratio (kg kg^{-1} dry air)
L_B	Length of the Biomass Chamber (m)
L_c	Length of the Drying Chamber (m)
m_a	Mass of air (kg)
M_c	Mass transfer coefficient of free water surface (kg $m^{-2}s^{-1}$)
M_{ch}	Mass of Charcoal (kg)
M_{dry}	Amount of Sample to be Dried (kg)
M_F	Mass of Flue Gas (kg h^{-1})
M_{tr}	Mass transfer rate (kg)
M_w	Amount of Moisture to be Removed (kg)
P_{atm}	Atmospheric pressure (Pa)
P_w	Partial pressure of water pressure corresponding to wet bulb temperature (Pa)
P_v	Partial pressure of water pressure (Pa)
P_{vs}	Partial pressure of water pressure corresponding to dry bulb temperature (Pa)
Q_1	Initial Moisture Content of Sample Crop, (%)
Q_2	Final Moisture Content Desired for the dry Sample Crop (%)
q_{air}	Air flow rate (m^3 s^{-1})
T_o	Outlet Air temperature from heat exchanger (K)
T_{co}	Temperature inside the combustion chamber (K)
T_{cs}	Combustion temperature (K)
T_D	Drying Temperature (K)
T_2	Final temperature of the drying air before passing through the drying tray (K)
T_3	Temperature of air exiting the drying chamber (K)
T_∞	Ambient temperature (K)
t_{db}	Dry bulb temperature (°C)
t_{wb}	Wet bulb temperature (°C)
V_a	Volume of air (m^3)
W_B	Width of the Biomass Chamber (m)
W_c	Width of the Drying Chamber (m)
ρ_a	Density of Air (kg m^{-3})
ρ_{ch}	Density of Charcoal (kg m^{-3})
ω	Moisture content (kg kg^{-1} air)
Φ	Relative humidity (%)