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Designing and Experimenting a Greenhouse Dryer for Fruits, Vegetables and Spices

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Abstract
Curbing postharvest losses in fruits, vegetables and spices by drying has been a serious challenge due to limitations of open sun drying and high cost of mechanical dryers. In this study, a Greenhouse dryer (GHD) was designed, constructed and tested. Experiments were conducted using Completely Randomized Design (CRD) to evaluate the performance of the GHD with fresh plantain, tomato and turmeric in comparison with open sun drying (OSD) under the same weather condition. Data collected were subjected to Multivariate Analysis of Variance (MANOVA) using the Statistical Analysis System (SAS) 2011 version 9.4 at 5% significant levels. The initial moisture contents of the products were reduced from 60%, 96% and 82% respectively wet base to final moisture contents 9%, 10% and 10% in 31hrs, 58hrs and 31hrs respectively. The average drying rates and the efficiency of the GHD are 0.024kg/hr, 0.030 kg/hr and 0.013kg/hr and 87%. The temperature of the GHD per hourly basis was significantly highest 50°C and the relative humidity was significantly lowest 17%. The results showed that, the GHD performed satisfactory, improves drying conveniences and comfort and is beneficial to farmers in developing countries to curtail postharvest loss.
Keywords: Design, Construction, Greenhouse Dryer, Instrumentation, Agricultural commodities

1. Introduction

Food supply and its availability have been severely impacted as a result of postharvest losses. Preservation of fruits, vegetables and spices by drying techniques has been a serious challenge in developing countries. This was has a results of high moisture content, limitations of open sun drying, intermittent of sun, lack of access to electricity and high cost of mechanical dryers. The importance of clean and sustainable energy (solar) in ensuring food security cannot be over emphasized. In tropical regions, solar energy a renewable energy source has great potential for a wide range of applications, including drying.

Greenhouse dryer technology functioned admirably in developing Nations with limited access to electricity and high fossil fuel expenditures, it creates an optimal environment for drying agricultural commodities regardless of weather conditions. The method combines the function of a solar collector with the greenhouse effect to raise the air temperature and lower the relative humidity in the dryer. A control greenhouse dryer improved air flow distribution resulting to homogeneous moisture content of crops on separate trays, save drying time, space and energy. It provides a viable alternative for preserving food in a clean, hygienic and improves product quality.

According to (Olaniyan et al., 2014) different types of dryers have been used for preservation of agricultural commodities. However, many farmers and food processors in most developing nations face huge hurdles because electricity and other non-renewable energy sources are unavailable, unreliable or prohibitively expensive. Another disadvantage of some of these dryers was that, they are designed without any type of backup heating system which make them useful only during sunshine and secondly, the moisture contents of drying produces varies due to insufficient airflow distribution.

Some hybrid dryers have been developed and tested independently of the sunshine, using alternative heating sources. (Arun et al., 2014a) built a natural convection sun tunnel greenhouse dryer with a biomass backup heater. Coconut fronts, coconut husk, and coconut shells were used as fuel in the biomass heater. From initial moisture content of 53.84% (w.b.) to a final moisture content of 7.003% (w.b.) coconuts were dried in 44 hours, whereas the dryer without a backup heater took 56 and 148 hours, respectively. (Rupnar et al., 2020) developed a solar-biogas hybrid GHD for drying onion with the capacity of 8 kg/batch, and its performance was evaluated. Solar energy was considered as the primary energy source while biogas was projected to be the secondary heat source to provide a steady operation. The hybrid mode of operation was only used when the sunlight was not sufficient to keep the indoor air temperature at 60^0C.When the system operates in the hybrid drying mode, the drying time for onion slices to reach 9.88% (w.b.) from 80.06 % (w.b.) was reported as 12 hours in the testing.

Janjai (2012 developed and tested a solar greenhouse dryer made up of a concrete floor and parabolic roof structure wrapped with polycarbonate sheet. It has a loading capacity of 1,000kg of fruits or vegetables, 100kw LPG gas burner was installed to provide hot air and nine 15 WDC fans powered by three 50 W PV modules were employed to ventilate the dryer. Three batches of osmotically dehydrated tomato and other fruits and vegetables such as Bananas, coffee, chili, were dried with it. The drying air temperature in the dryer ranged from 35°C to 65°C, according to the results. The drying time for osmotically dehydrated tomatoes was 2-3 days less than for open sun drying, and the dried goods were of good quality. However, a less expensive auxiliary energy source than LPG gas could lower the dryer's operating costs. (Azaizia et al., 2020) created a unique mixed-mode solar greenhouse dryer with and without paraffin wax as the PCM, of red pepper. At night period, the inner air temperature of the dryer with PCM is 7.5^0C higher than other dryers, and the relative humidity is 18.6% lower than the ambient. For dryer with PCM, without PCM, and in the open sun, the moisture content was reduced to 95% after 30 hours, 55 hours, and 75 hours, respectively. They came to the conclusion that storing thermal energy in PCMs in solar greenhouse dryer s is a viable way to improve drying efficiency.

The application of this project's work as a technique of food preservation would aid in the resolution of the aforementioned issues as well as contribute to a country's economic growth. Therefore, the objectives of the study were to design, construct and testing of a Greenhouse dryer for fruits, vegetables and spices.

2 Materials and Method

2.1 Overall Structure and Working Principles of the GHD

2.1.1 Overall Structure of the GHD

The Greenhouse dryer as shown in Figures 1 was made up of two parts: the main drying chamber of 3 meters long by 2.4 meters width by 2.7 meters high and an instrumentation unit. For best solar exposure, it was orientated in an East-West longitudinal and North-South width. It has a 0.3meter raised platform concrete floor surface to prevent flooding and serve as insulation to prevent heat energy sinking. To maximize the rate of heat absorption, the concrete floor was covered with black tiles. The supporting frame columns and roofs were made of a well-seasoned 2by3inches hard wood and were firmly tightened at equal intervals on the 4mm thick galvanized angle irons. The drying trays frame support of 2mm square mild steel with four drying racks were hung with bolts and nuts on the dryer's columns. To ensure an uninterrupted passage of air within the trays, the drying trays were made of square stainless steel wire mesh. A 3mm thick clear corrugated polycarbonate sheet were used as cover and sealed to prevent humid air and rain from entering other than those introduced through the inlet vents.

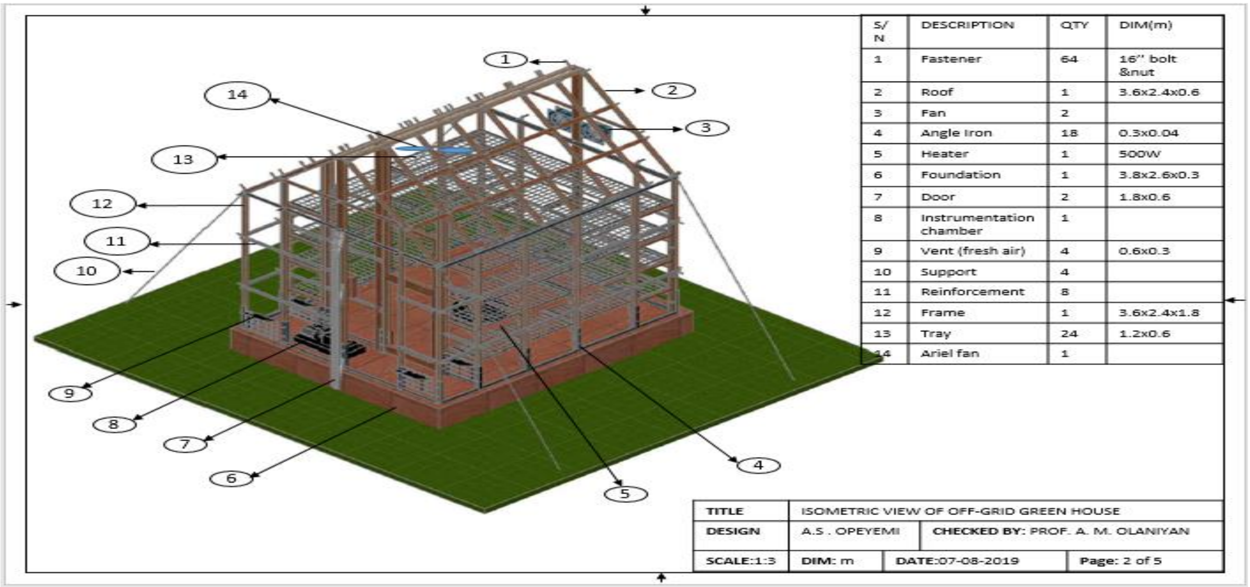

***Figure 1**: Overall Structure of the GHD*

2.1.2 Working Principle of the GHD

Figure 2 shows the schematic diagram of heat and mass transfer in the GHD, the short waves from the sun falls directly on the polycarbonates covers and penetrated in causing greenhouse effects that evaporate moisture from the drying crops. The polycarbonates act as a barrier preventing trapped energy from escaping and unwanted ambient air circulation. Fresh air is drawn into the dryer by natural convention means through the vents and is heated then partially cooled as it picks moisture from the products, damp air rises and discharged by fans positioned at the rear top of the GHD. Because the sun is intermittent in nature, a 2 kVA inverter, deep cycle batteries, solar panels were utilized to power a 500w electric heating lamp the supplemental heat energy source, DC fans, and the instrumentation unit. Depending on the detected temperature and humidity in the GHD, different stages of the actuators were entered by the instrumentation unit, either to turn NO the heater /fans or OFF it.

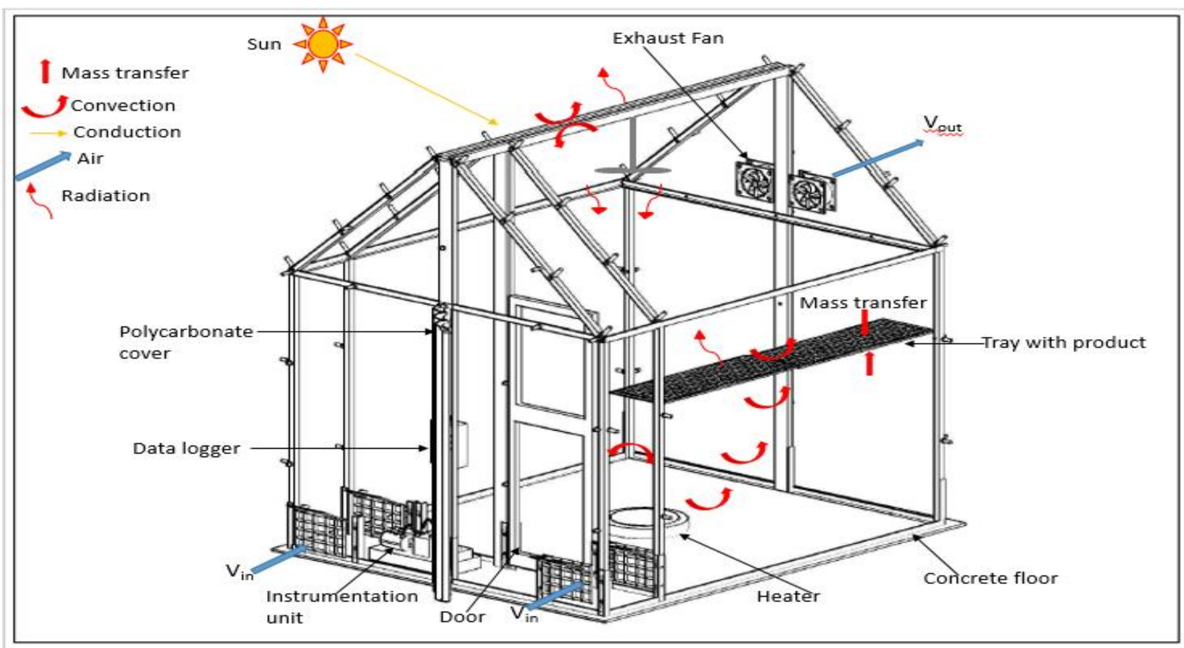

***Figure 2**: Schematic diagram showing heat and mass transfers in the Greenhouse dryer*

2.2 Design Considerations

While designing the Greenhouse dryer the following determinant factors and assumptions were taken into consideration. The geographical and meteorological data of the location, conservation and storage of daily solar radiation, sanitary factors such as the use of noncorrosive and nontoxic materials, ease of taking measurements and control of inside environment air parameters, ease of operation and storability of dried products were critical designed computational considerations and materials selection. Heat and mass transfer, airflow velocity, drying air temperature, and relative humidity, crop type, bulk density, layer thickness, product sizes and shapes were all taken into account in determine the drying rate and the final q]uality of the product. Stability, reliability, durability, maintainability and the techno-economic condition of farmers and food processors were among other structural analysis considered. The following design parameters were used in the calculation: the amount of moisture to be removed from the products, amount of heat energy required by the drying air to remove the moisture, quantity of air required to remove the moisture, batteries bank capacity and photovoltaic module sizing.

2.3 Design Calculations

2.3.1 Amount of Moisture Removed

The mass of water to be removed (M_{ev}) from the wet product was calculated by equation given by (Hussein et al., 2017)

$$M_{ev} = m_p[\frac{M_i - M_f}{100 - M_f}] \quad (1)$$

Where; m_p is the initial mass of the wet product to be dried (kg); M_i is the initial moisture content (% wet basis) and M_f is the equilibrium or final moisture content (% wet basis).

2.3.2 Quantity of heat required by drying Air to remove the moisture

The quantity of heat required by drying Air to remove the moisture was calculated by equation given by (Hussein et al., 2017)

$$Q_e = M_{ev}\,\lambda + m_p\,C_{pc}\,(T_f - T_i) \quad (2)$$

Where; ($T_f - T_i$) is the difference between initial and final temperatures of the drying air respectively (°C); C_{pc} is the specific heat capacity of crop at constant pressure (KJ/kgK) and λ is the latent heat of vapourization.

2.3.3 Heater Power

$$\text{Power} = \frac{Q_e}{td} \quad (3)$$

Where; Q_e is quantity of heat required () and td is the total drying time per day (hours)

2.3.4 Mass Flow Rate of Air

The mass flow rate m_a (kg/s) of air needed to effect the drying was given by (Tonui et al., 2014).

$$m_a = V_A \times \rho_a \quad (4)$$

Where; V_A is the volumetric airflow rate in (m^3/s) and ρ_a is the density of drying air at 50°C = (1.2 kg/m^3).

2.3.5 Quantity of Air Needed to Effect Drying

The total volume of air V_a (m^3) required for removing the moisture was given by (Tonui et al., 2014). From the gas laws equation

$$V_a = \frac{maRT}{P} \quad (5)$$

Where; P is the atmospheric pressure = 101.3 KPa; Va is the total volume of air required for removing the moisture (m^3); m_a is the mass of the air in (kg); T is the absolute temperature in (Kelvin) and R denote gas constant (kPa m^3/kg K)

2.3.6 Volumetric Flow Rate

The volume flow rate of drying air V_A (m^3/s) was evaluated by (Tonui et al., 2014) equation.

$$V_A = \frac{V_a}{\text{td}} \quad (6)$$

2.3.7 Fan Power

$$\text{Fan power} = \frac{Air\ flow\ (cfm) \times static\ pressure}{6320 \times fan\ efficiency\ \%} \quad (7)$$

OR

$$HP = (cfm \times 1.44) \quad (8)$$

2.3.8 Greenhouse Dryer Area

The Greenhouse dryer area was calculated by equation given by (Kamble et al., 2013).

$$A_d = \frac{QT}{\eta I} \quad (9)$$

Thus, the length of the dryer L_d is determined as

$$L_d = \frac{Ad}{Wd} \quad (10)$$

W_d is dryer width

2.3.9 Strength Analysis of the Frame

The column of the structure was analyzed using Euler's equation for buckling as shown in equation 11 given by (Khurmi and Gupta 2005)

$$W_{CL} = \frac{\pi^2 EI}{Lc^2} \quad (11)$$

Where; W_{CL} is crippling load (KN), E is young modulus of column's material (N/mm^2) L_C is length of the column (m) and I is moment of inertia (mm^4)

2.3.10 Determination of Photovoltaic Module Sizing

Total peak watt of PV was determined using equation given by (Hussein et al., 2017)

$$W_{pt} = \frac{Let}{Fgp} \quad (12)$$

Where; W_{pt} is total peak watt of panel, L_{et} is total electric load (Wh/day), F_{gp} is Panel generation factor

2.3.11 Determination of Battery Size

The size of the battery was determined using equation given by (Hussein et al., 2017)

$$B_S = \frac{Let}{S_v \times B_{ce}} \quad (13)$$

Where; B_S is size of battery (Ah), S_v is system voltage (V), B_{ce} is battery charging efficiency (%)

2.4 Performance Evaluation of the GHD

After construction of the prototype GHD and installation of all utilities as shown in Figure 3 and 4; it was tested using plantain, tomato and turmeric as described in the following sections.

(a) (b)

Figure 3: *Prototype of the GHD after Construction (a) Exterior view and (b) Interior view*

Figure 4: *2kVA Inverter, Batteries, Charger Controller and Microcontroller Data Logger*

2.4.1 Materials Collection and Sampling Technique

The fresh harvested fruit (plantain), vegetable (tomato) and spice (turmeric) used in this experiment were procured from Ikole market. The samples were properly sorted out based on firmness, maturity, size uniformity, colour and the diseased and injured one were removed.

2.4.2 Experimental Design

The experimental design used was Completely Randomized Design (CRD). Two factors exist in the experiment which are: Trays and Hours. There are four replicate (trays) and 157 levels (hours) in the experiment at non-load condition. While 31, 58 and 31 levels (hours) during the drying of plantain, tomato and turmeric respectively.

2.4.3 Experimental Procedures

The samples were thoroughly washed with clean water and sliced into an average thickness of 5mm. Each products were weighted and spread one at a time in a single layer on the trays inside the Greenhouse dryer as indicated in Figure 5: and on the outside tray as a control sample (open sun drying). The samples were dried until constant masses were achieved. The temperature, relative humidity, mass of each drying samples were measured and data logged at every five minutes by the instrumentation.

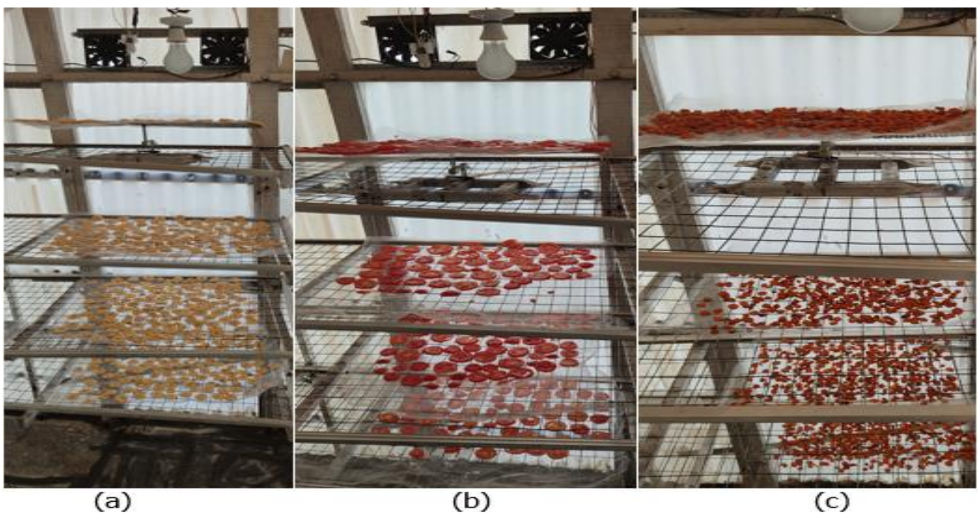

***Figure 5**: Prototype of the GHD during drying of (a) Plantain (b) Tomato and (c) Turmeric*

2.4.4 Performance Indicators

2.4.4.1 Drying Rate

According to (Tonui et al., 2014), the average drying rate was given as:

$$d_r = \frac{M_{ev}}{t_d} \quad (15)$$

Where; d_r is average drying rate (kg/hr) and M_{ev} is mass of water to be removed (kg)

2.4.4.2 Drying Efficiency

The drying efficiency was calculated using equation givan by (Hussein et.al, 2017).

For forced convection solar greenhouse dryers that use a fan;

$$\eta_{dryer} = \frac{M_{ev}\,\lambda}{I\,A_d + P_f} \quad (16)$$

I. The efficiency of hybrid dryers that utilize additional energy from a second source (e.g. heater coil, biomass, LPG, etc.)

$$\eta_{dryer} = \frac{M_{ev}\,\lambda}{I\,A_d + P_f + P_h} \quad (17)$$

Where; $M_{ev}$is amount of water evaporated from the food crop (kg); I is solar radiation (W/m^2)
A_d is dryer area (m^2); λ is latent heat of vaporization of water; P_f is energy consumption of fan; P_h is energy consumption of hater and t_d is drying time (hours).

2.4.5 Statistical Analysis of Data

The experiment was conducted for seven days at no load condition starting from March 3rd 2022 to March 9th 2022. Similarly, the load condition started from March 10th 2022 to March 16th 2022. The obtainable experimental data were retrieved from the secure digital card for analysis. Data collected were subjected to Multivariate Analysis of Variance (MANOVA) using Statistical Analysis System (SAS) 2011 version 9.4 at 5% significant levels. The means separation were done using Tukey's Honestly Significant Differences (HSD) and T-Test was used to get the levels of interaction between the means factors.

3. Results

3.1 Experimental Results of the Greenhouse Dryer under Non-Load Condition

Table 1 shows the comparison of mean temperature and mean relative humidity inside and outside the Greenhouse dryer (GHD) under no-load condition.

Table 1: T-Test Value of Temperature and Relative Humidity Inside and Outside the Greenhouse Dryer under Non-Load Condition

Parameters	Inside	Ambient	Difference	T-value
Temperature	34	26	8	29.30***
Relative humidity	56	89	-33	-15.96***

3.1.1 Air Temperature and Relative Humidity Profiles Inside and Outside the Greenhouse Dryer under Non-Load Condition

Figures 6 and 7 show the hourly air temperature and relative humidity profiles inside and outside the GHD when the instrumentation was tested for seven days at non-load condition.

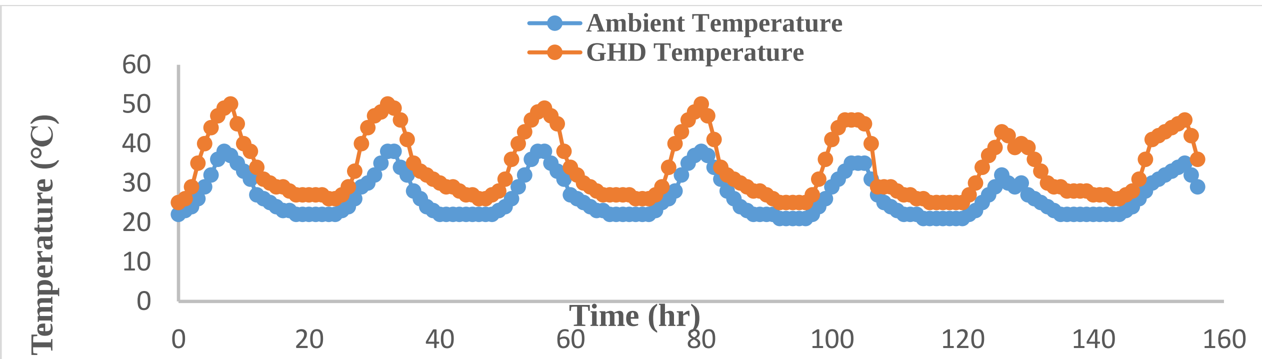

Figure 6: *Variation of Air Temperatures Profile inside and outside the Greenhouse Dryer under Non-Load Condition*

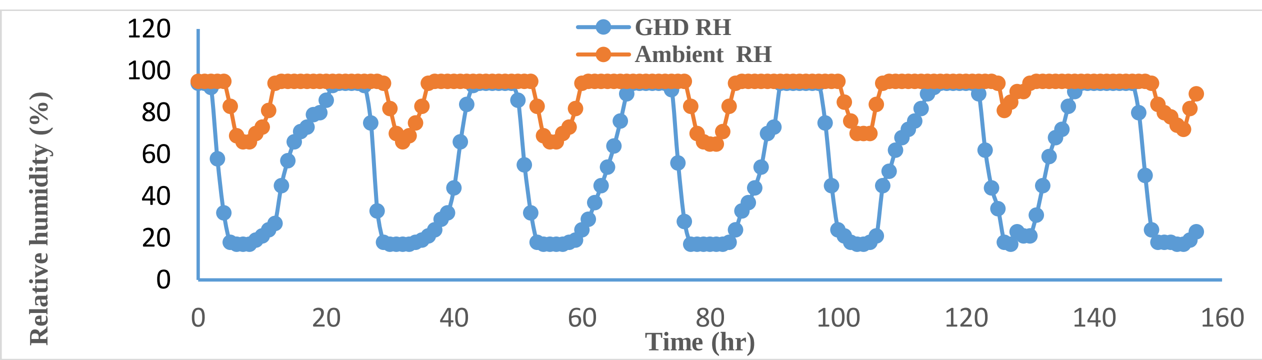

Figure 7: *Variation of Air Relative Humidity Profiles inside and outside the Greenhouse Dryer under Non-Load Condition*

3.2 Experimental Results of the Greenhouse Dryer under Load Conditions

Tables 2-4 show the comparison results of means of air temperature, relative humidity, drying mass, moisture content, amount of water removed and drying rate inside the GHD and ambient during the drying of plantain, tomato and turmeric.

Table 2: T-Test Value of Parameters Inside and Ambient the Greenhouse Dryer during Drying of Plantain.

Parameters	Inside	Ambient	Different	T-value

Temperature	34	27	7	14.21***
Relative humidity	61	89	-28	-5.88***
Drying Mass	0.3	0.32	-0.02	-7.28***
Moisture content	28	32	-4	-7.62***
H_2O Remove	0.08	0.09	-0.01	-4.92***
Drying Rate	0.02	0.02	0	-0.65ns

Table 3: T-Test Value of Parameters Inside and Ambient the Greenhouse Dryer during Drying of Tomato.

Parameters	Inside	Ambient	Different	T-value
Temperature	32	26	6	14.66***
Relative humidity	65	90	-25	-7.93***
Drying Mass	0.23	0.28	-0.05	-14.92***
Moisture content	80	89	-9	-4.51***
H_2O Remove	0.21	0.25	-0.04	-13.43***
Drying Rate	0.03	0.03	0	-8.23***

Table 4: T-Test Value of Parameters Inside and Ambient the Greenhouse Dryer during Drying of Turmeric.

Parameters	Inside	Ambient	Different	T-value
Temperature	34	26	8	13.33***
Relative humidity	62	88	-26	-5.97***
Drying Mass	0.08	0.09	-0.01	-9.45***
Moisture content	42	55	-13	-6.96***
H_2O Remove	0.04	0.05	-0.01	-5.74***
Drying Rate	0.01	0.01	0	-0.98ns

4. Discussion

4.1 Experimental Discussions of the Greenhouse Dryer under Non-Load Condition

Table 1 shows the comparison of mean temperature and mean relative humidity inside and outside the Greenhouse dryer (GHD) under no-load condition. The mean inside temperature of the GHD (34℃) was found higher than mean outside temperature (26℃). These differences in the means, showed highly significantly difference of (29.30). In addition, the mean inside relative humidity (56%) was lower than (89%) obtained outside. Figures 6 and 7 show the hourly air temperature and relative humidity profiles inside and outside the GHD when the instrumentation was tested for seven days. In the morning hours, as the solar insolation gradually increased, the air temperature in the GHD also increased while the air relative humidity decreased simultaneously. With the microcontroller system, the air temperature measured inside the GHD peaked at 50℃ at the 9th, 33rd and 81st hours, all corresponding to 2.00 pm. Conversely, the relative humidity attained its lowest value of 17% at the same 2.00 pm each of the seven days of measurement. While the ambient air temperature and relative humidity obtained at 2.00 pm were 38℃ and 66% respectively.

4.2 Experimental Discussions of the Greenhouse Dryer under Load Condition

Tables 2-4 show the comparison results of means of air temperature, relative humidity, drying mass, moisture content, amount of water removed and drying rate inside the GHD and ambient during the drying of plantain, tomato and turmeric. The T-test results for plantain, tomato and turmeric showed that, the GHD mean temperatures 34℃, 32℃ and 34℃ respectively were found higher than the ambient 27℃, 26℃ and 26℃ likewise the relative humidity (RH) 61%, 65% and 62% respectively were found lower than the ambient 89%, 90% and 88% respectively. These differences in the means showed highly significantly different of the air temperature and relative humidity inside the GHD compared to the ambient. The initial moisture contents of the products were reduced from 60%, 96% and 82% wet base to final moisture contents 9%, 10% and 10% respectively in 31hrs, 58hrs and 31hrs respectively. The average drying rates and the efficiency of the GHD are 0.024kg/hr, 0.030 kg/hr and 0.013kg/hr and 87%.

These results are in accordance with the one obtained by (Adelaja and Babatope 2013) who got final moisture content of 15.75% for plantain and (Hussein et al., 2017) who obtained final moisture content of 10% (w.b) for tomato. In addition, the mean temperatures 34℃, relative humidity 61%, mass 0.30kg, moisture content 28%, amount of water removed 0.08 and drying rate 0.02kg/hrs respectively of the samples on the trays are statistically the same. This is due to the equal spacing intervals and even distribution of energy between the trays.

5. Conclusion

A monitoring and control Greenhouse dryer capable of operating continuously all through the drying period was designed, constructed and tested using plantain, tomato and turmeric. It was designed and constructed making use of locally available construction materials. With the use of the instrumentation system, air temperature measured inside the GHD peaked at 50℃ conversely, the relative humidity attained its lowest value of 17% compared to the ambient 38℃ and 66% respectively. The study showed that, the GHD and the use of the instrumentation system performed satisfactory, brings about improved drying convenience and comfort, as well as the ability to dry a variety of crops in every weather condition, more efficient saving in manpower requirement and suitable replacement for direct human supervision, making the system helpful to farmers and food processors in developing countries to curtail postharvest loss.

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