A study of a forced convective biomass dryer for plantain chips

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Abstract: Post-harvest processing of plantain to improve the market value is an important aspect of product supply chain. This study investigated a forced convective biomass dryer for plantain processing. Numerical simulation and experimental analysis were used to evaluate the performance of the biomass dryer and to optimize the drying process of plantain chips. The heat flow patterns within the drying chamber at air velocity of 1.5, 2.5 and 3.5 ms^{-1} was predicted numerically and validated experimentally. A fresh plantain of 5kg at initial moisture content of 60% dried to moisture content of 13% (dry base) was used to examine the drying rate of the biomass dryer. The mean drying rate was 0.0140 kgh^{-1} while the open sun drying rate was 0.0035 kgh^{-1}, indicating that the forced convective biomass dryer has considerable advantage over the traditional sun drying method in terms of drying rate, hygiene and produce quality. This study provides generic data towards enhancing the post-harvest processing of agricultural product using biomass fuel.

Keywords: post-harvest processing; biomass dryer; moisture content; and drying chamber.

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1 Introduction

Plantain (*Musa paradisiaca*) is a horticultural crop that has the potential of strengthening national food security and decreasing rural poverty (Adejoro et al., 2010). Available trade records and associated indices showed that Nigeria is one of the largest producers of plantain in the world (FAO, 2013). A study conducted on impact of technology adoption by plantain farmers in Nigeria shows that educating the plantain farmers will greatly enhance production of plantain in Nigeria (Afodu et al., 2021). With these available strategic plans in plantain production in Nigeria, there is an urgent need for the development of indigenous plantain processing techniques.

In terms of marketing and consumption of plantain, there is huge market demand for plantain products because of its nutritional and medicinal values (Olutomilola and Omoaka, 2018; Oluwajuyitan and Ijarotimi, 2019). A major challenge facing plantain farmers is its perishable nature that motivates high loss during its postharvest period. A situation that usually forces farmers to process plantain to plantain chips or flour to extend its shelf life (Oyejide et al., 2018).

Early researchers on plantain processing have observed that more than 40% of the harvested fruit is wasted which gives an estimated economic loss of about 11% (Olorunda and Aworth, 1996), (Akalumbe et al., 1996)). Traditional drying is laborious, unhygienic and slow (Aderinto, 2013), and (Yarkwan

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and Uvir, 2015), and the drying process is diffusion – control that is dependent on temperature (Satimehin et al., 2010).

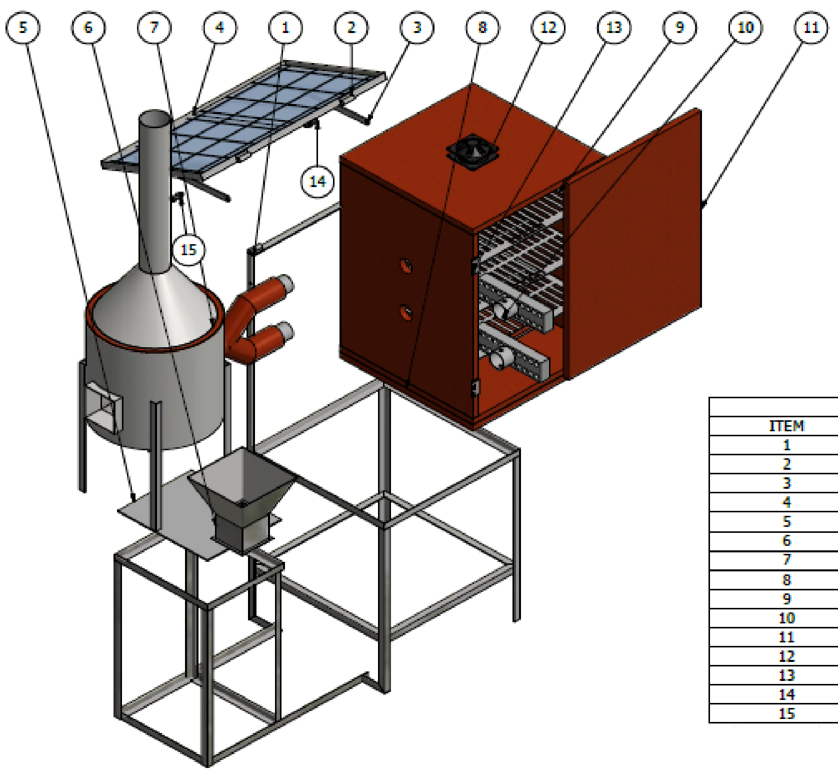
An improved plantain processing machine was designed and fabricated using available materials in Nigeria (Oyejide et al., 2018). The machine produced 4.29 kg of flour from 32 kg of plantain given about 19.25 kg of water. The percentage composition of water in the pulverized plantain pulp was 65.54%.

The research suggested the presence of large amount of moisture in plantain and the need for significance amount of energy for drying of the chips to the required moisture content.

A conceptual design and finite element analysis of a machine for grinding plantain in a plant that process unripe plantain into flour was investigated by Olutomilola et al.(2020). The functionality and structural stability were evaluated using solid works (Computer Aided Design) application software. There were results showing promising future industrial powdering of plantain into flour.

A very important drying parameter is the thickness of the plantain chips for a particular temperature kept in a steady flow of hot air stream. Earlier works by Satimehin et al.(2010), Famurewa and Adejumo (2015) and Yarkwan and Uvir (2015) have shown that plantain drying is diffusion-control process having drying rate increase with the increase in temperature.

In the present study, a biomass dryer that supplies hot air at a predetermined velocity is developed. The required heat is supplied from steady combustion of solid biomass in a burner located under a cyclone. The air motion is prompted by a suction fan that is powered by a solar power generating set. The complete system is shown as an exploded view of experimental dryer in Figures 1 and 2.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Main Frame
2	1	New Solar Panel Support
3	2	Braze
4	2	Solar Panel
5	1	Stove_Support
6	1	Stove
7	1	Multi_Body_heating_Chambe
8	1	Dryn Chamber
9	3	Tray (Stainless Steel)
10	2	Heat Distributn Plate
11	1	Door
12	1	rack fan
13	4	Hinge
14	2	ISO 4162 - M10 x 40 (Bolt)
15	2	ISO 7043 - M10 (Nut)

Figure 1 Experimental dryer

2 Materials and method

The dryer was designed and fabricated from materials locally source in Nigeria. There are three important components: air blowing system (solar panel, a fan and air passage); heat generating system (burner, burner chamber, and chimney); and drying chamber (drying trays in layers, main cabinet that covers the entire chamber). Drying process is affected by the interaction of hot air with different layer of plantain chips in the cabinet.

The speed of hot air is varied within the speed ranges between 1.5 ms^{-1} and 2.5 ms^{-1}. The temperature of air is made steady by gradual supply of biomass to the burner. However, the speed of blower fan is regulated to achieve the desired temperature of hot air directed to the drying cabinet.

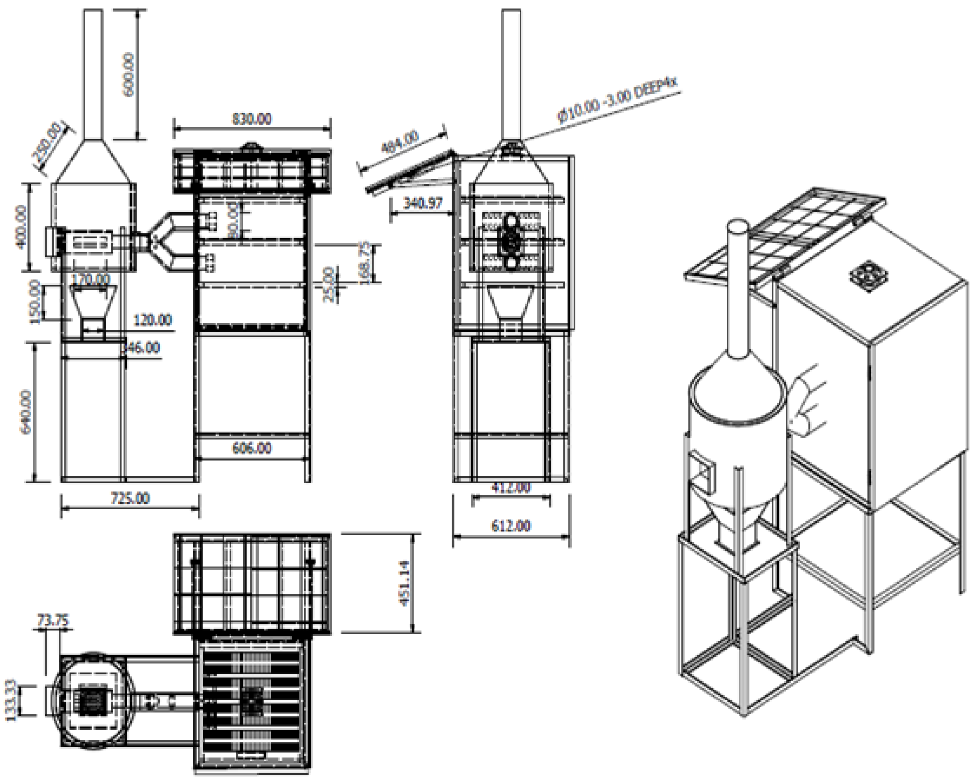


Figure 2 Experimental dryer

2.1 Design calculation

2.1.1 Dryer capacity

According to (Liberty and Dzivama, 2013), the average mass of a chip of a particular food product is 0.020 kg and it has a diameter of 3.5 mm. Assuming a tray will accommodate 90 chips, then,

Dryer capacity (kg) = the average mass of a chip (kg) × No of chips= 0.020 × 90 = 1.8 kg

Since there are three trays, a total of 5.4 kg will be obtained and this can be approximated to 5 kg.

2.1.2 Mass of moisture to be removed

The mass of plantain is 5 kg.

In this research, the maximum moisture content of the plantain used was 60 % (dry base) (Obiageli et al., 2016). (Holdsworth, 1983) reported that the level of moisture required to prevent bacterial growth in an unripe plantain is below 15 % and to prevent mould growth is below 13 % on a dry weight basis.

Moisture content of plantain = 60 %

Final moisture content of dried plantain = 13 %

The amount of moisture to be removed from a given quantity of plantain to bring the moisture content to a storage level (M_w) according to (Liberty, J. T., and Dzivama, 2013) is from the relationship below:

$$M_w = \frac{M_i(M_o - M_f)}{(100 - M_f)} \quad (2)$$

where M_w is the mass of moisture (dry base) to be removed (kg), M_i is the mass of plantain before drying (kg), M_o is the percentage moisture content before drying (%) and M_f is the percentage moisture content after drying (%).

The mass of moisture to be removed from three trays accommodated at once by the drying cabinet is obtained as follows:

M_w = 5 (60-13) / (100-13) = 2.70 kg.

The quantity of heat needed to evaporate the water from the trays of plantain chips is given by:

$$Q = M_w \times h_{fg} \tag{3}$$

where M_w is mass of water (kg) and h_{fg} is latent heat of water (kJ.kg^{-1}).

From the above equation, the amount of heat required to remove 2.70 kg of water is given by:

Q = 2.70 × 2264.705 kJ.kg^{-1} = 6114.70 kJ.kg^{-1}

2.1.3 Average drying rate, DR

DR is given by Adeaga et al.(2014):

$$\mathrm{D_R} = \frac{\mathrm{M_R}}{\Delta \mathrm{t}} \tag{4}$$

where D_R is the average drying rate, which is the daily hours used for the drying process. 't' is the total drying time required to remove water (hr), MR mass of water that is removed from the wet produce (kg).

2.1.4 Fan size

The fan size is selected based on the calculated volumetric flow rate of the drying air. The volumetric flow rate (M_V) is obtained from Equation (5) (Hanif et al., 2014).

$$M_V = M_A \times V_S \tag{5}$$

where M_A and V_S are the mass and specific volume of the drying air. The specific volume is read from the chart.

2.1.5 Drying efficiency

The efficiency of the dryer, η according to (Liberty & Dzivama, 2013), is given by

$$\eta = \frac{M_{c1} - M_{c2}}{M_{c1}} \times 100\% \tag{6}$$

where M_{c1} is initial mass of the (kg), M_{c2} is the final mass of the substance (kg).

Table 1 Design Specification, Assumption and Pertinent Design Parameters

S/N	Parameters	Symbols	Formula	Value
1	Initial moisture content	m_o	-	60% (w.b)
2	Final moisture content	m_f	-	13% (w.b)
3	Mass of plantain/batch	m_i	-	5kg
4	Average ambient temperature	T_a	-	27 ^{o}C
5	Ambient relative humidity	RH_a	-	75%
6	Max. drying air temperature	T_b	-	60 ^{o}C
7	Mass of water to be evaporated	M_ω	Equation 2	2.70 kg
8	Heat required to remove water	Q	Equation 3	6114.71 kJ
9	Heat of vaporization	h_{fg}	Equation 5	2264.70 kJ.kg^{-1}

2.2 Numerical simulation

Simulation of the convective flow within the drying cabinet was conducted in ANSYS' 14 software. The complete set of mathematical equations for the flow is based on the conservation laws of motion which are conservation of mass, conservation of momentum and energy equation that introduces temperature.

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}.(\rho U) = 0 \tag{7}$$

$$\frac{\partial(\rho U)}{\partial t} + \vec{\nabla}.(\rho U * U) = -\vec{\nabla} p^1 + \vec{\nabla}.\left(\mu_{\text{eff}}(\vec{\nabla}\mathrm{U})\right) + \mathrm{F} \tag{8}$$

$$\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + \vec{\nabla}.(\rho U h_{tot}) = \vec{\nabla}.\left(k(\vec{\nabla} T)\right) + S_E \tag{9}$$

where ρ is the density of air, U is the velocity, p is the pressure, μ_{eff} is the effective viscosity, h_{tot} is the total enthalpy and F is the body force.

The expression for effective viscosity, modified pressure and total specific enthalpy in equations 8 and 9 are given in Equations 10, 11 and 12 respectively.

$$\mu_{eff} = ff\mu_t \qquad (10)$$

$$p^1 = p + \frac{2}{3}\rho k \qquad (11)$$

$$h_{tot} = h + \frac{1}{2}U^2 \qquad (12)$$

$where\ S_\epsilon$ is the energy equation source term. This term was computed in ANSYS.

The CFD simulation predicts the flow behavior of the hot air in the drying chamber in other to know the position at which each tray will be placed in the drying chamber. Figure 3 shows the meshing of the flow domain for the simulation.

Figure 3 Meshing of the drying chamber

2.3 Experimental set up and drying procedure

Experimental investigation was carried out in Ile-Ife (Latitude 7^o 28^I, longitude 4^o 34^I) between March and June 2017. It was designed for studying the drying characteristics of the plantain chips at different fan speed levels (1.5, 2.5, and 3.5 ms^{-1}) and to compare it with open sun method. The general description of devices used during experimental test is given in Table 1. Plantain was procured from the local market at Ile-Ife, Osun state Nigeria.

Air temperature, relative humidity, moisture content, drying rate and change in weight of the plantain chips sample were monitored throughout the drying period between 9:00 am and 5:00 pm each day at 30 minutes intervals. The plantain chip samples were taken out of the dryer at the end of the drying process each day and spread on a table at room temperature because of high humidity observed in the dryer at night which can lead to moisture reabsorption but no appreciable moisture was lose to the atmposphere. The drying process of each of the experimental run was ended when the change in weight was no longer significant.

Table 2 Characteristics of Instrument used during the experiment

Instrument	Technical Properties
Thermocouple	k type TP-01, range -500C -3500C, accuracy ±0.4%
Data logger	S220-T8, battery 3.6V, LCD display, resolution 0.1oC, accuracy ±0.2%FS
Multi-meter (Anemometer Hydrometer)	LM-8010, range (air vel.) 0.4 - 30ms-1, range (humidity) 10% - 95%, accuracy (air vel.) ±3% FS, accuracy (humidity) ±4% RH, battery 9V
Weighing balance	LCD, 0 - 1000g, accuracy 0.1g, power AC 100V-240V

2.4 Performance of the biomass dryer

The drying efficiency of the dryer describes how effectively the input energy to the drying system is used in the product drying. The overall thermal efficiency of the heater $\boldsymbol{\eta_{bmas}}$ can be defined as the ratio of useful heat transferred to the drying air to the energy potential of fuel (Bena, 2002). This efficiency is a product of the combustion efficiency and the efficiency of heat transfer to the air. In this project an overall efficiency of the heater, was calculated using Equation 13.

$$\boldsymbol{\eta_{bmas}} = \frac{\textbf{heat transferred to air entering the drying chamber}}{\textbf{calorific value of biomass used}} \qquad (13)$$

The initial moisture content of the plantain sample was measured using the standard (AOAC – 2000) which is air oven method. The loss in mass of the samples was recorded using electronic digital balance. The recorded losses in mass were converted into corresponding moisture contents on wet basis using Equation 14.

$$\boldsymbol{W_{twb} = 1 - \left[\frac{(1-M_{owb}) \times W_o}{W_t}\right]} \qquad (14)$$

The drying rate is a fundamental parameter in the evaluation of drying process and was calculated using Equation 15.

$$\boldsymbol{DR} = \frac{\Delta M}{\Delta t} \qquad (15)$$

3 Results and discussion

The results obtained from numerical and experimental analysis are compared for temperature variation with distance from the inlet along the plate length. The graphs of temperature against distance along the plate length are shown for suction fan speed 1.5ms^{-1} in Figure 4. A similar trend is followed by the two curves except that higher temperatures were recorded in the numerical data. The difference can be attributed to heat loss in the experimental analysis probably due to poor insulation of the hot air passage.

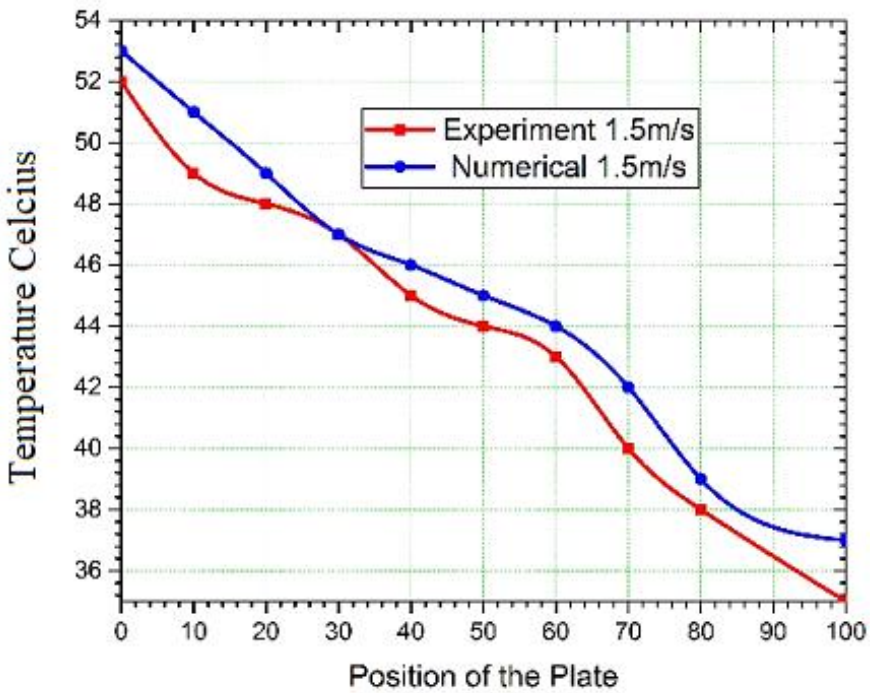


Figure 4 Validation of results

3.1 Numerical optimization of the dryer

Forced heat convection refers to the heat transferred by the movement of fluid under the influence of an external force. Computational Fluid Dynamics (CFD) simulation was conducted for dryer model based on the assumption that air flow is supplied into the inlet of the chamber. The hot air was convected with the help of a suction fan that is located at the outlet section of the drying chamber and run with speed varied between 1.5 and 3.5 ms^{-1}. The maximum temperature of hot air is 333 K.

3.2 Temperature contours in the drying chamber without distribution plate

The initial simulation was run without distribution plate at the inlet pipe of the drying chamber. The flow over each tray was monitor to determine how the temperature was distributed on each tray and to know the tray with maximum temperature. The forced convective model at fan speed 1.5, 2.5 and 3.5 ms^{-1} without distribution plate is shown in Figure 5. The absence of distribution plate allows incoming hot air to loose significant amount of heat before it is distributed among the drying trays. Heat could not be concentrated on various trays but instead spread within the enclosure with little interaction with the surface of the trays. The temperature distribution of the forced convection model dryer at suction fan speed of 1.5 ms^{-1} was observed to have non-uniform distribution of temperature field on top tray follows by the middle tray and the bottom tray.

At suction fan speed of 3.5ms^{-1}, most of the heat has been sucked out from the drying chamber because there is increase in the speed of the suction fan. This phenomenon indicates that the heat needed to dry the product has been sucked out from the drying chamber. And the drying process of the product takes place at a very low rate because the hot air that is needed to dry the plantain chips has been sucked out.

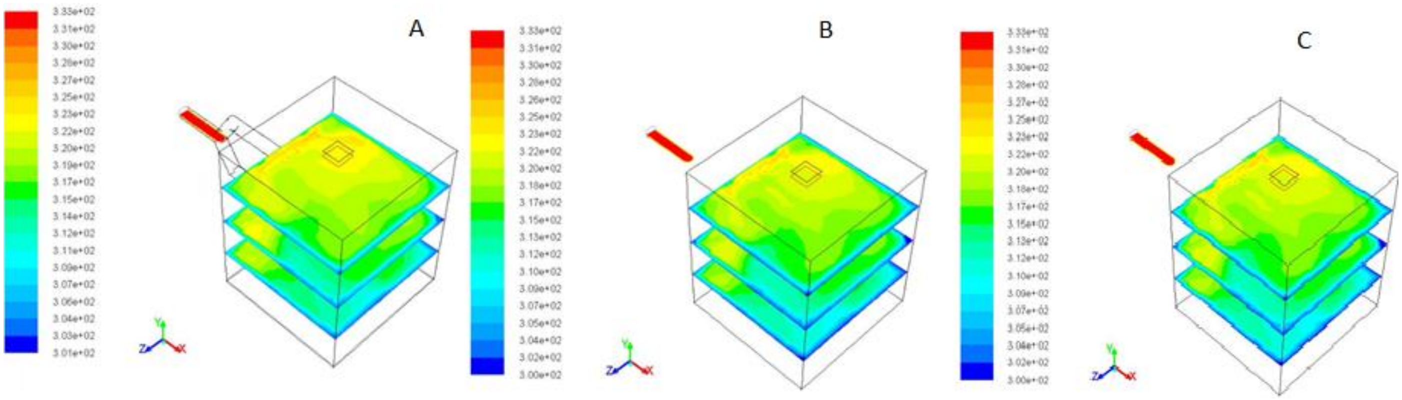


Figure 5 Temperature contours at A-1.5 ms^{-1}, B-2.5 ms^{-1} and C-3.5 ms^{-1}

The suction fan is expected to distribute the hot air on various trays and also sucks out moisture from the drying chips. The incoming hot air will lose heat as latent heat of vaporization and sensible heats. Moisture will absorb its latent heat from the hot air and escape with air through the suction port of the fan.

3.3 Temperature contours in the drying chamber with distribution plate

The simulation was run with distribution plate mounted at the inlet pipe of the drying chamber. The flow on each tray was monitored in order to see how the temperature was distributed on each tray to know the tray with the highest temperature. Below are the temperature profiles of the forced convective model with distribution plate at the inlet pipe of the drying chamber.

The heat distribution in the drying chamber is shown by the temperature contours in Figure 6. The effect of the presence of the flow distribution plate is very significant as observed in the temperature contour shown in Figures 6 (A, B & C.). The heat is distributed uniformly on the three drying trays. The adverse effect of high speed of the suction fan is very minimal indicating little loss of heat during the drying process within the chamber. The heat provided for drying does not concentrate along the proximity of the wall but it spreads out from the inlet as the drying process progresses. The above observation shows that the distribution plate enhances convection of heat from the inlet of the drying chamber to other part around the trays.

3.4 Experimental results

The drying rate of the sample was initially high and dropped drastically over time. The high removal of moisture that was observed after some time on the first day is attributed to the drying of surface water which is motivated by hot air movement. The influence of air flow begins to diminish on the plantain as soon as the outer moisture content of the products has significantly reduced. The remaining moisture in the chips requires longer time for the inner moisture content to move to the surface for complete drying.

Further increase in drying time does not increase the drying rate significantly and this conforms with previous study carried-out on drying of agricultural product by Micheal et al., (2012) and Okoroigwe et al., (2013). The dried samples obtained suggest prospect for better performance than open sun drying.

The moisture loss at different fan speeds (1.5, 2.5 and 3.5 ms^{-1}) on the three trays was compared with the open sun drying. It was observed that the moisture reduces drastically for top trays at all speeds used for the experiments. The middle trays also dried faster than the lower tray. There is a significant difference between the drying rate of the convective biomass dryer and the open sun dryer as shown in Figure 7. The good drying rate of the top tray can be attributed to abundant heat from the inlet and effective suction of the moisture due to its close proximity to the suction fan.

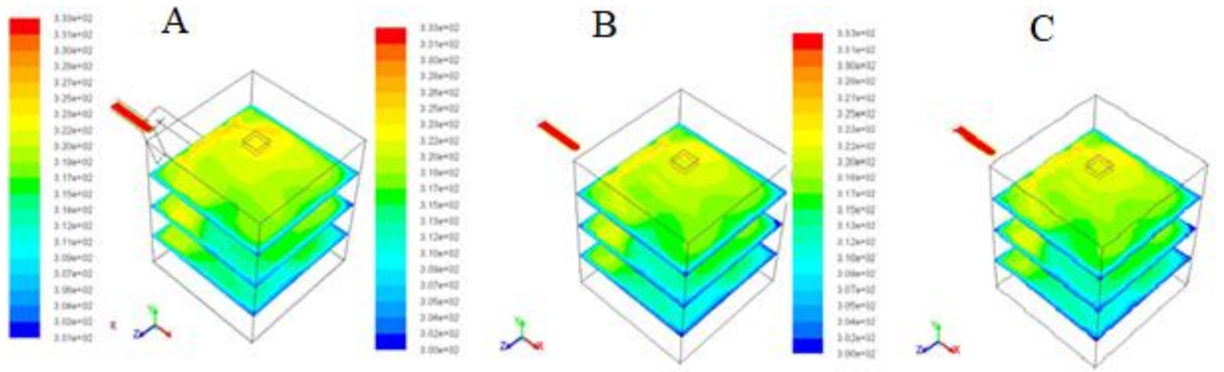


Figure 6 Temperature contours at 1.5 ms^{-1}, 2.5 ms^{-1} and 3.5 ms^{-1}

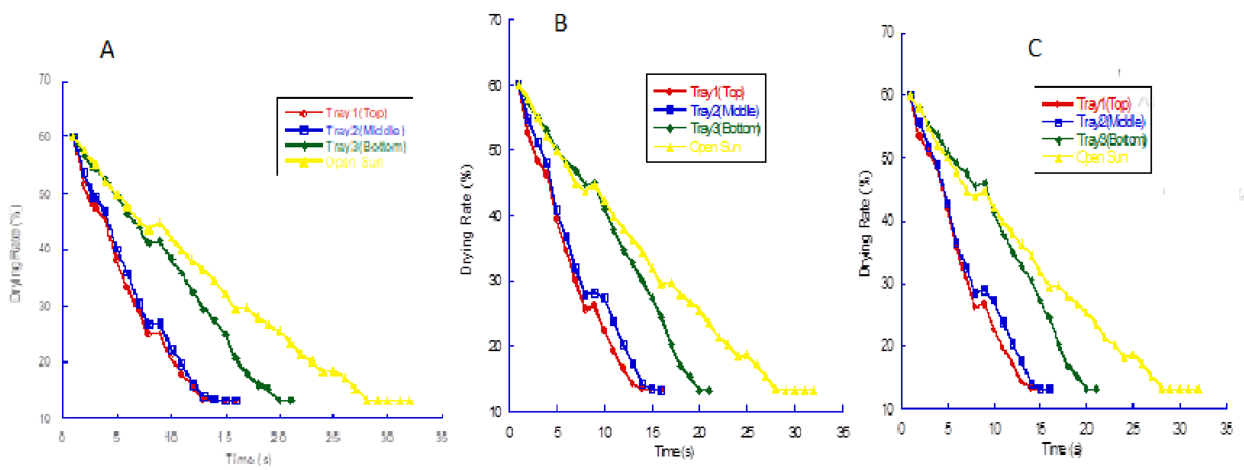


Figure 7 Drying rate at fan speed A-1.5 ms^{-1}, B-2.5 ms^{-1} and 3.5 ms^{-1} against open sun drying

At 1.5 ms^{-1} fan speed, the initial moisture content was 60% (350 g – dry base) while the final moisture content was 13.2% (78.1 g – dry base). The drying air temperature ranged between 30.2 ^{o}C and 46.5 ^{o}C. At 2.5 ms^{-1} fan speed, the initial moisture content was 60% (350.0 g – dry base) while the final moisture content was 14.2% (78.9 g – dry base). The drying air temperature ranged between 30.2 ^{o}C and 44.5 ^{o}C. At 3.5 ms^{-1}, the initial moisture content was 60.0% (350.0 g- dry base) while the final moisture content was 18.6% (96.3 g – dry base). The drying air temperature ranged between 30.5 ^{o}C and 40.5 ^{o}C. When these results were compared it was observed that fan speed at 1.5 ms^{-1} has a better effect on the drying rate.

The open sun drying method was carried out using plantain chips with the initial moisture content of 60 and the final moisture content of 14.5% (80.3 g by weight). The ambient temperature ranged between 25.1 ^{o}C and 26.0 ^{o}C. The high moisture content and low drying rate recorded was as a result of poor air movement around the plantain chips. The drying curve shows the rate at which moisture content reduces with time in the drying chamber at various fan speed compared to the open sun drying method. The drying rate plotted does not showed much significant difference, however, drying at low speed gives the best drying rate.

4 Conclusion

The biomass dryer developed is capable of producing average air temperature between 55°C and 60°C with maximum air suction speed of 3.5 ms^{-1}. It can dry plantain chips from an initial moisture content of 60% (wet basis) to the required level of 13% (wet basis) in 12 hours. The drying time for plantain chips using the biomass dryer reduces drastically compared to open sun drying.

The drying efficiency observed was 77.8%, the drying rate of the biomass dryer was 0.0140kgh^{-1} while the drying rate for open sun drying was 0.0035kg h^{-1}. The quality of product is sustained in this drier as flue gas coming from the biomass stove had been directed outside using heat exchanger and chimney whereas in open sun drying it gets deteriorated due to long exposure to atmospheric condition. The dryer has potential to generate employment opportunities and offers a means of minimizing postharvest loss associated with microbial infestation and reduces wastage.

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