Performance evaluation of a small-scale dryer for agricultural products

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Abstract: A cabinet dryer fabricated using locally available materials was evaluated in this study. The drier comprises a heating chamber, heat exchanger, drying trays, 3-phase blower, three heating elements of 1800 W each, and a control box consisting of temperature control, contactor, thermocouple, and circuit breaker. The dryer was evaluated based on power consumed, moisture removal, drying rate, and drying efficiency. The result showed that the energy consumed when drying plantain chips, moringa leaves, okra, and locust beans were 346.55, 55.92, 110.63, and 49.64 kJ, respectively. The energy consumed increased with an increase in the moisture removed and drying time. Similarly, the drying rate for plantain chips, moringa leaves, okra, and locust beans was 34.80, 5.40, 10.80, and 6.00 g h^{-1}, respectively, which depended on the initial moisture content of the product and the air velocity. The drying efficiency ranged between 62.1% and 65.5%, and it reduced with an increase in the amount of moisture removed and the drying temperature. The drying system promises satisfactory performance for small-scale applications for the products with which the dryer was tested.

Keywords: small-scale dryer, crops, moisture content, drying rate, drying efficiency

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1 Introduction

Drying is one of the vital and widely reported methods of food preservation. Many artificial drying systems have been developed. Without adequate water, bacteria that cause food deterioration and decay cannot develop and reproduce. Many of the enzymes that enhance undesired changes in the chemical composition of the food cannot function without water (Ghimire, 2017; Liu et al., 2018). Khan et al. (2020) reported that the drying process was a heat and mass transfer phenomenon; moisture migrates from the inside of the product to the surface, where it evaporates through diffusion.

Although different studies have established the importance of an efficient and effective drying procedure and practices (Naseer et al., 2013; Arah et al., 2016; Kumar and Kalita, 2017), some developing countries still record substantial postharvest losses. The farmers in these developing countries usually have no access to high-tech dryers; hence they settle for traditional drying and storage methods. Traditional techniques of open-air sun drying of vegetables and other food crops are insufficient since the goods degrade quickly. Furthermore, traditional sun-drying methods expose products to contamination by dirt, debris,

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insects, rodents, and micro-organisms. There is, therefore, a need for small-scale food dryers to meet the needs of agrarian farmers.

Different multi-purpose dryers have been developed for agricultural products (Ilechie et al., 2011; Adetan et al., 2016; Prakash et al., 2018; Ndirangu et al., 2020), but some of these designs have insufficient evaluation reports. Developing dryers for food processing require conceptual design, analysis, and optimisation (Adesoji and Omotara, 2014). According to Gunathilake et al. (2018), the essential elements of a dryer include; the drying chamber, the hot air generator, and a ventilator. Different dryers use different drying technologies and energy sources (Kumar et al., 2015; Gunathilake et al., 2018). As a result of these dryers' high technical and financial requirements, most of these technologies are not adaptable to rural communities in developing countries. In addition, these communities need a multi-purpose dryer that is versatile and can efficiently dry different types of agricultural products.

Ikejiofor and Okonkwo (2010) developed an active multi-purpose solar dryer with adjustable airflow rates for agricultural products. The components include a solar collector, heat storage unit, drying chamber, air outlet unit, and a suction fan. The test results showed that a drying period of 8-11 h was obtained using the solar dryer and the suction fan together at a 27.29 m^3 s^{-1} suction rate. The dryer performed satisfactorily compared with a drying period of 42-50 h obtainable by sun drying. Another multi-purpose dryer was developed by Ilechie et al. (2011) for agricultural products. The multi-purpose dryer was made of steel angle iron and aluminum sheet, while the dryer's interior was painted black for maximum heat retention and improved drying rate. In the dryer, hot air was distributed at 18.7 ms^{-1} uniformly within the drying chamber. The presence of vents further enhanced the air distribution. Test results showed that the dryer had a drying efficiency of 75%. Olaniyan and Alabi (2014) also documented a prototype column dryer for paddy rice considering small-scale rice farmers and processors' size, durability, and techno-economic status. The drying chamber comprises a plenum chamber between two perforated vertical columns for uniform air distribution. Four electrical heating coils generated hot air in the heating chamber and a backward curved centrifugal fan. This hot air passes through the plenum into a paddy-filled grain column to reduce the moisture content from 22.4% to 13.4%, which is admissible for safe storage. Liu et al. (2018) reported a heat pump dryer's design and thermal analysis for food drying. This dryer comprised the main fan, auxiliary fan, compressor, electric heater, humidifier, evaporator condenser, expansion valve, airflow sensor, and the drying chamber. This system was used in drying 3 mm thick slices of garlic. Liu et al. (2018) reported a decrease in moisture content of the sliced garlic from 66.7% w.b to 10% w.b. Argo and Ubaidillah (2020) reported valuable energy loss in multi-purpose convective-type tray dryer was around 3.30–4.27 kJ s^{-1} during drying. The findings mean that attention should be paid to the energy use of dryers, creating room for energy optimisation. This dryer comprises a fan, a horizontal tube-type heat exchanger heated by two gas burners, and a temperature-controlled drying chamber. The drying chamber was reported to have four drying layers containing perforated trays, receiving hot air at 2.5 ms^{-1}. A maximum drying rate of 0.33 g water g^{-1} dry matter min^{-1} was reported (Argo et al., 2018).

Some of the small-scale food dryers developed for rural communities are usually poorly designed and not properly evaluated to understand the energy consumption of such dryers. According to Kumar et al. (2014), aside from the quality of the dried product, the energy efficiency of the drying process was an essential factor in food drying. Therefore, a dryer should be evaluated to determine the physical and chemical properties of the dried product and the thermal performance. Most research on small-scale dryers has limited reports on energy consumption, thermal efficiency, and drying rate. Therefore, this work aims to evaluate a small-scale dryer and determine its heating power, percentage of moisture removal, drying rate, and drying efficiency for different dried products.

2 Materials and Method

2.1 Materials selection

Table 1 shows the specification of the materials selected for the design. Materials selection was based on the heat and corrosion resistance, thermal conductivity, creep, fatigue, malleability, durability, density, cost, ease of operation, and maintenance.

2.2 Parts description of the dryer

The dryer consists of five functional units, which include: heating chamber, heat exchanger, blower (axial flow fan), drying chamber, and control board, with the components being connected by 80 mm diameter of circular pipes. The dryer's isometric, plan, and elevation views are shown in Figures 1a, b, and c. The combustion chamber was electrically powered by three electric elements (burner), each of 1.8 kW; a thermocouple was incorporated with the temperature control (0°C–400°C) to sensitize the heat dissipated into the combustion chamber as well as to regulate the temperature. A heat sensor (probe) was also incorporated in the combustion chamber, enerating heat energy. The blower, a 2500 rpm axial-flow fan, delivers hot air from the combustion chamber to the drying cabinet through the heat exchanger. The drying chamber was made up of four trays shelves where the products were spread for drying (Figure 1a).

As shown in Figures 1b and c, the interior of the drying cabinet measures 1000 mm long, 550 mm wide, and 1100 mm high with the external dimension of 1100 mm × 650 mm × 1300 mm, respectively. Four sets of trays of 960 mm by 550 mm (Figure 1c), spaced 300 mm apart, are provided. The drying chamber was lagged with 50 mm thick fiberglass. The heat generated in the heating chamber is blown through the heat exchanger and conveyed to the drying chamber. As the heated air absorbs and conveys moisture from the products on drying trays, heat and mass transfer occur by diffusion, and drying is achieved. Exhaust air exits through the chimney on top of the cabinet. The dryer is fitted with indicator lights, circuit breaker, contactor, and heat sensor.

Table 1 Materials selection and specification

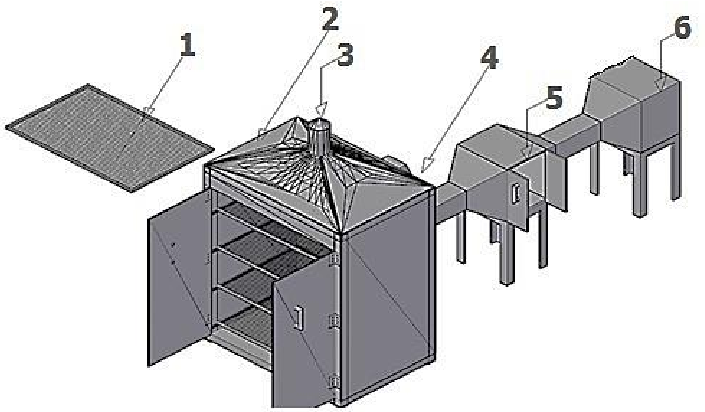
Materials	Specification	Quantity
Black steel sheet	1 mm thick	6 standard size
Perforated iron sheet	3 mm thick	1/2 standard length
Mild steel Sheet	2 mm thick	1 standard length
Blower (centrifugal fan with prime)	3.5 hp	1
Cutter bar	8 mm diameter	3 standard length
Lagging material	fiberglass	lump (3 bags)
Square pipe	25 mm x 25 mm mild steel	4 standard length
	50 mm x 50 mm mild steel	1 standard length
Angle iron	42 mm x 42 mm mild steel	1 standard length
	60 mm x 60 mm mild steel	2 standard length
Temperature control	0 - 400 C	1
Temperature probe		9
Digital thermometer	-50 - 750 C	1
Heating element	1.8 kW	3
Contactor	Three-phase connection	1
Heat resistance cable	3 mm diameter	4 yards
Copper wire	2.5 mm diameter	3 yards
Circuit breaker	Three-phase connection	1

2.3 Performance evaluation of the dryer

The dryer was evaluated at the Agricultural and Environmental Engineering Department, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria (7.5165° N, 4.5286° E). The dryer was tested at its default state without any load for 4 hours at 50°C and then allowed to run for 4 hours, and the temperature was determined at 30 mins intervals using the temperature probe and digital thermometer for the performance evaluation

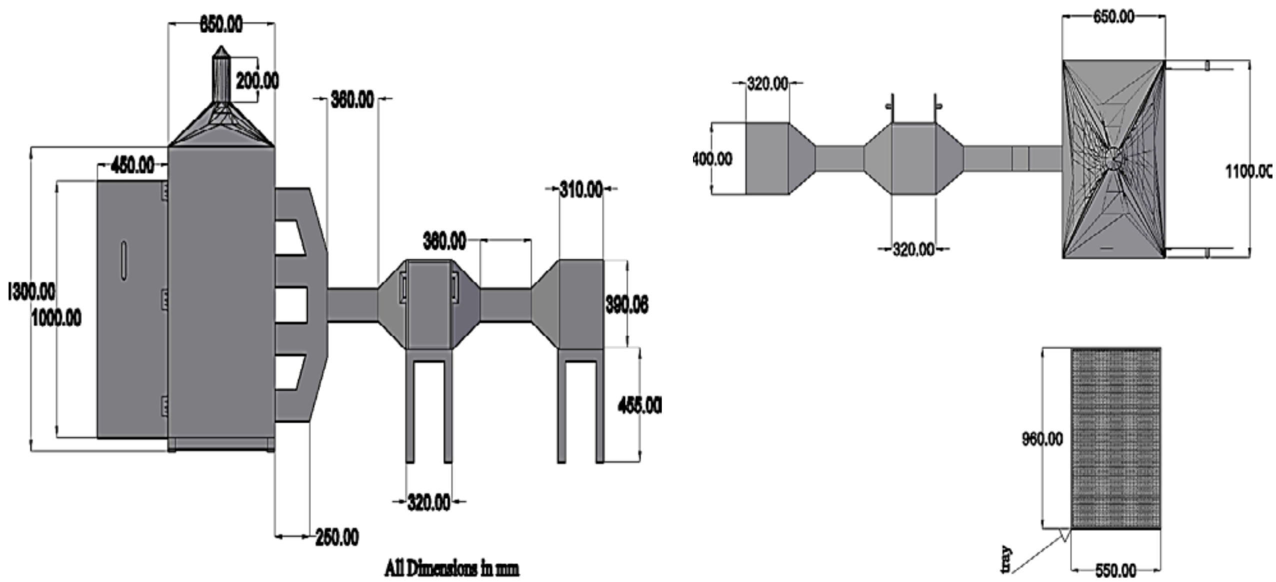
2.3.1 Testing with no load

The dryer was subjected to two test conditions: test without loading and with the loading of produce. The dryer was later loaded with the following agricultural materials: plantain chips, moringa leaves sliced okra pod and locust beans.



Code	Part Name
1	Tray
2	Cabinet
3	Chimney
4	Delivery Pipe
5	Heat Exchanger
6	Blower Unit

(a) isometric view



(b) end elevation

(c) plan view

Figure 1 The multi-purpose dryer

2.3.2 Testing with load

Samples tested on the dryer were moringa leaves, sliced okra pod, plantain chips, and locust beans obtained from Obafemi Awolowo University, Ile-Ife, Nigeria. The plantain was peeled and sliced into a thickness of 50 mm (Ashaolu et al., 2015), while okra was sliced to 10 mm (Afolabi and Agarry, 2014). The initial mass of the samples was measured and recorded before treatment and drying. These samples were arranged on each tray as follows: plantain chip, moringa leaves, sliced okra pod, and locust beans were placed on tray 1 (L1), tray 2 (L2), tray 3 (L3), and tray 4 (L4) respectively.

During the preliminary test, the dryer was preheated for 60 min under the no-load condition to ensure uniform temperature distribution within the drying chamber. A 35.06 g of moringa leaves, 71.31 g of sliced okra pod, 48.83 g of locust beans, and 479.78 g of plantain chips were initially weighed and dried for 4 hours temperature of the drying chamber being set at 70^{o}C throughout the drying process at different levels. Thus the experimental design is as shown in Table 2.

Drying different materials simultaneously on different trays was carried out since it is one of the extreme conditions the dryer will be subjected to during use. Also, this testing method will suggest whether the levels of the tray have a significant effect on the dried product, drying time, and efficiency of the dryer.

Table 2 Experimental design for evaluation of the dryer

Materials	Tray level	Initial mass (g)
Plantain chips (50 mm disc of thickness)	L1	479.78
Sliced okra pods (10 mm disc of thickness)	L2	35.06
Moringa leaves	L3	71.31
Locust beans	L4	48.83

2.3.3 Estimation of dryer performance

The performance of the dryer was estimated using three parameters:

Heating power: The heat consumed in removing water from the produce was estimated using the method reported by Mercer (2014). It considers drying as a two-stage process where the first one is raising the temperature of the wet material to the desired level, which the moisture will be removed. The formula is expressed as:

$$Q_s = M_w C_p \Delta T \quad (1)$$

$$\Delta T = T_d - T_a \quad (2)$$

Where; C_p is the specific heat capacity of water (kJ kg^{-1} ^oC), ΔT is temperature change (^oC), T_d is the temperature in the dryer (^oC), and T_a is the ambient temperature (^oC).

The second stage is evaporating the moisture from the produce. The quantity of heat required to evaporate water from the material is given by:

$$Q_l = M_w \times L \quad (3)$$

The latent heat of vaporization, L, was estimated using Equation 4.

$$L = h_g - h_f \quad (4)$$

Where: h_g is the enthalpy of water as a vapour (kJ kg^{-1}) and h_f is the enthalpy of water as a liquid (kJ kg^{-1}) at the drying temperature obtained from the steam table.

Therefore, the total heat requirement was determined using Equation 5.

$$Q = Q_s + Q_l \quad (5)$$

Drying Thermal Efficiency: According to Chenga et al. (2018), the temperature reduction in the drying air correlates to the valuable heat supplied to the food for drying. The heat that has to be supplied corresponds to the rise of the air temperature in the air heater. So this adiabatic air-drying efficiency was determined with Equation 6.

$$\mu = \frac{T_1 - T_d}{T_1 - T_a} \quad (6)$$

Where; T_1 is the temperature of the air entering the dryer from the heat exchanger (^oC) and T_a is the ambient air temperature, (^oC)

Drying Rate: In line with Matuam et al. (2015), the drying rate was estimated using Equation 7.

$$DR = \frac{M_i - M_f}{t} \quad (7)$$

Where; DR is the drying rate (g h^{-1}), M_i is the mass of product before drying (g), M_f is the mass of the sample after drying (g), and t is the drying time (minutes)

Percentage Moisture Loss: The percentage of total moisture content loss in the product was estimated using equation 8.

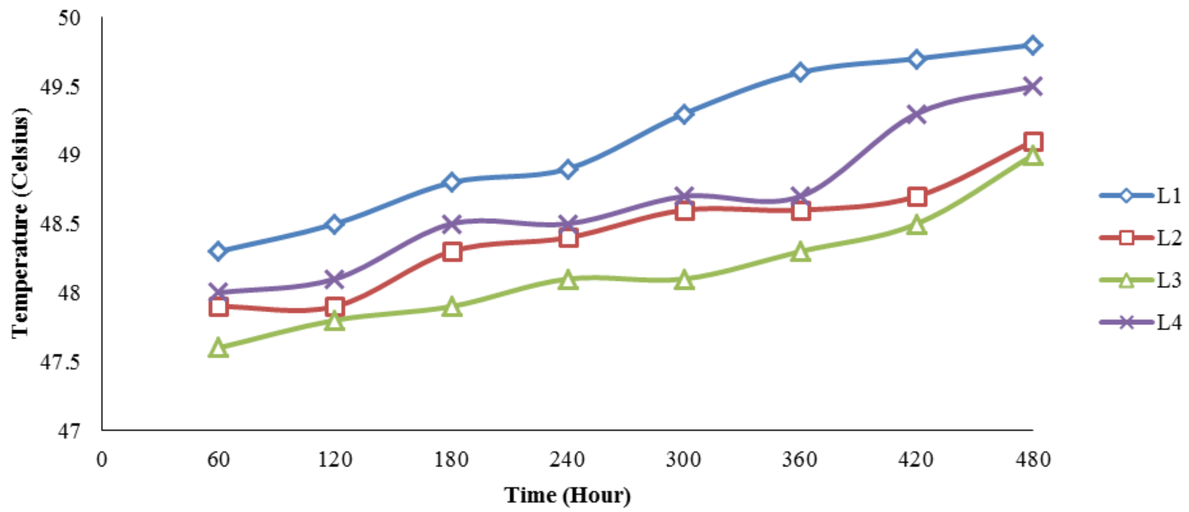
$$ML = \frac{\text{initial mass} - \text{final mass}}{\text{initial mass}} \text{ x } 100 \quad (8)$$

3 Results and discussion

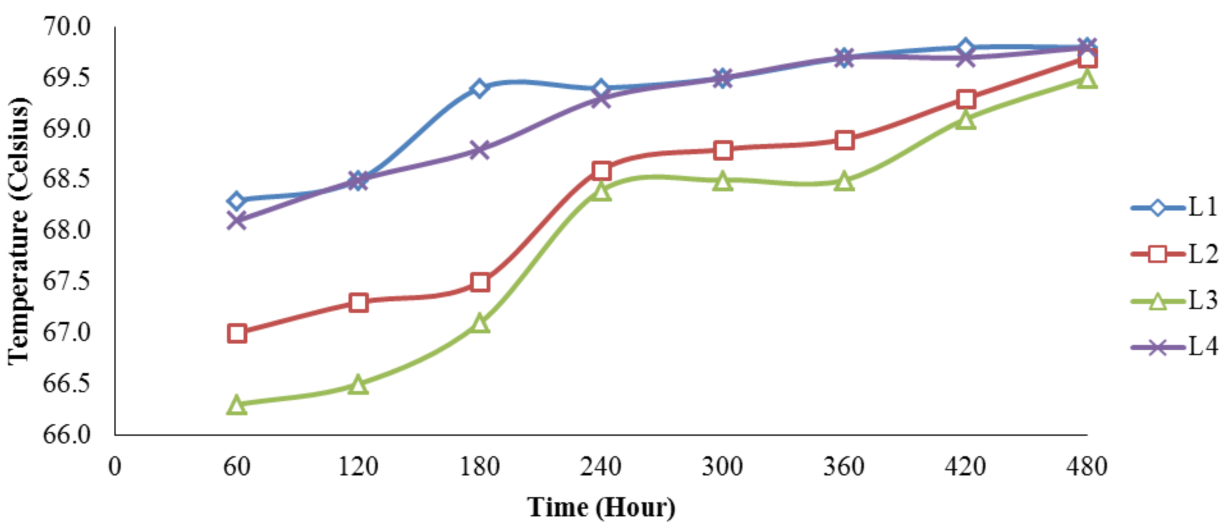
3.1 Temperature distribution

Figures 2a and b show the temperature distribution in the dryer when tested at no-load and load, respectively. The result shows that the temperature readings for the four trays/levels are very close to 50^oC, although the temperature rise occurred in two phases. The first phase spanned between 30 and 120 minutes. This phase had 0.5^oC - 0.6^oC rise in temperature, implying that the heat applied increased the internal energy of the tray materials. The temperature rises in the second phase spanned 120 – 240 minutes. It can be classified as quasi-static with a temperature rise of 0.5^oC -0.9^oC. This is because the system attempts to attain thermal equilibrium.

On the other hand, the situation was slightly different when the test materials were introduced into the dryer. Although a similar two-phase drying behaviour can be identified, the first phase (30-120 minutes) was observed to have a temperature rise of 1.2°C -2.4°C. The materials on each tray caused an initial deficit (thermal mass), which had to be heated up before the temperature rise could occur in the dryer. The second phase (120-240 minutes) has 0.5°C-1.2°C temperature rise, showing behaviour close to attaining thermal equilibrium and an adiabatic process, which is the characteristics of the food drying process (Correia et al., 2015; Liu et al., 2018; Friso, 2020; Barbosa-Cánovas and Juliano, 2020). In this forced convention air-drying system, setting heat and mass transfer initiates the removal of water by heat flow since the heated air moves across the product (Correia et al., 2015).



(a) no-load



(b) load

Figure 2 Temperature distribution in the dryer with no-load or load

Table 3 shows the analysis of the temperature at each level of the dryer. It was observed that there was no significant difference between the temperature on each tray compartment during the no-load and with the load test. The result implies a good and even heat distribution within the dryer, even though the initial temperature was different at each level. According to Lee et al. (2018), this good air distribution could be attributed to the adequate space between the air ducts in the dryer.

Table 3 Column t-test of drying temperature

Tray	Temperature (°C)	
	No Load	With Load
L1	49.11±0.57$_{a}$	69.30±0.58$_{a}$
L2	48.44±0.41$_{a,b}$	68.39±0.99$_{a,b}$
L3	48.16±0.44$_{b}$	67.99±1.20$_{b}$
L4	48.66±0.52$_{a,b}$	69.18±.63$_{a,b}$

Note: Values in the same column not sharing the same subscript are significantly different at $p< 0.05$ in the two-sided test of equality for column means.

3.2 Heating power

Table 4 shows the result of the thermal analysis of the dryer while drying plantain chips, moringa leaves, okra, and locust beans. The energy needed to raise water temperature from room temperature to the drying temperature (sensible heating power) was 22.77, 3.59, 7.04, and 3.25 kJ for plantain chips, moringa leaves, okra, and locust beans, respectively. In comparison, the energy required to evaporate the heated water in the products was estimated as 323.77, 52.32, 103.60, and 46.38 kJ for plantain chips, moringa leaves, okra, and locust beans, respectively. Similarly, the energy consumed when drying plantain chips, moringa leaves, okra, and locust beans is 346.55, 55.92, 110.63 and 49.64 kJ. The energy consumed was observed to increase with the amount of moisture removed and drying time in line with Nwakuba et al. (2016). According to Nwakuba et al. (2016), the drying air performs work to overcome the capillary forces holding the water within the products and the surface evaporation. Therefore, more energy and more time are consumed to remove more moisture from the products.

Table 4 Heat energy parameters for the small-scale dryer

Parameters	Product Dried			
	Plantain chips	Moringa leaves	Okra	Locust beans
Drying Temperature (°C)	69.30	68.39	67.99	69.18
Moisture removed (kg)	0.14	0.02	0.04	0.02
Ambient temperature (°C)	30.00	30.00	30.00	30.00
Specific heat capacity of water (kJ Kg^{-1} K)	4.18	4.18	4.18	4.18
Sensible heating power, $Q_{s,}$ (kJ)	22.77	3.59	7.04	3.25
Enthalpy of water vapour, h_g, (kJ kg^{-1})	2624.40	2622.70	2622.70	2624.40
Enthalpy of liquid water, h_f, (kJ kg^{-1})	288.87	284.68	284.68	288.87
Latent heat of vaporization, L, (kJ kg^{-1})	2335.53	2338.02	2338.02	2335.53
Latent heating power, $Q_{l,}$ (kJ)	323.77	52.32	103.60	46.38
Heating Power, Q, (kJ)	346.55	55.92	110.63	49.64

3.3 Drying efficiency

Figure 3 shows the drying efficiency of the dryer while the different agricultural products were dried. The dryer's drying efficiency ranged between 74.36% – 79.41% after 30 minutes, depending on the type of products dried, to around 63.16% – 67.57% after 4 hours. The thermal efficiency dropped with time after initially rising to the peak after 60- 120 minutes (depending on the type of produce dried) due to an increase in the amount of moisture removed and the drying temperature (Matuam et al., 2015). Furthermore, Table 5 shows the statistical analysis of the thermal efficiency of the dryer. It was observed that the dryer's efficiency varied significantly ($p<0.05$) with time and agricultural products. The change in dryer efficiency might be because agricultural goods contain variable amounts of moisture.

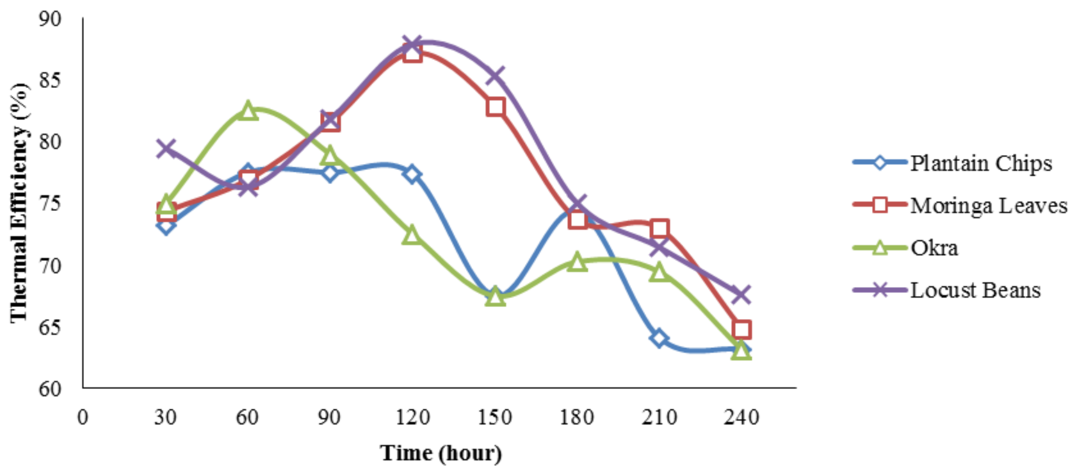


Figure 3 Thermal efficiency of the dryer

Table 5 ANOVA of thermal efficiency of the dryer

Source of Variation	SS	df	MS	F	P-value	F critical
Time	856.9908	7	122.4273	7.460846	0.000149*	2.487578
Agricultural products	234.348	3	78.11601	4.760472	0.010999*	3.072467
Error	344.5953	21	16.4093			
Total	1435.934	31				

*-significant factor ($p<0.05$), SS-sum of squares, df-degree of freedom, MS-mean square

3.4 Drying rate

The result obtained under the loading condition is presented in Table 6. The result shows that the mean of the percentage moisture loss, the mass of moisture removed, and the drying rate of the product are as follows: for plantain chips; 28.90%, 138.63 g, and 34.80 g h^{-1}, respectively; for the moringa leaves; 63.83%, 22.38 g, and 5.40 g h^{-1}, respectively; for the sliced okra pods; 62.14 %, 44.31 g, and 10.80 g h^{-1}, respectively and for the locust beans; 46.82%, 22.86 g, and 6.00 g h^{-1} respectively. These imply that the dryer is drying fast and could sufficiently, efficiently, and effectively dry plantain chips, moringa leaves, okra, and locust beans. Besides, the result also suggests that the dry will perform equally well on other farm products. The drying rate was observed to increase with the amount of moisture available in the product. The products will have more moisture available at higher moisture content for the constant drying rate (Zambrano et al., 2019). This high drying rate can also be attributed to the air velocity of the dryer (Kilic, 2020). A high drying rate is desirable to reduce the risk of overheating the products in the dryer (Violidakis et al., 2017).

Table 6 Mass of moisture removed from the products and effect of the drying temperature on the products

Parameters	Plantain chips	Moringa leaves	Okra	Locust beans
Initial mass (g)	479.78	35.06	71.31	48.83
Final mass (g)	341.15	12.68	27.00	25.97
Initial moisture content (%)	61.97	81.30	88.30	58.13
Final moisture content (%)	34.36	1.85	0.03	0.17
Mass of moisture removed (g)	138.63	22.38	44.31	22.86
Percentage moisture loss (%)	28.90	63.83	62.14	46.82
Drying rate (g h^{-1})	34.80	5.40	10.80	6.00

4 Conclusions

A cabinet dryer was fabricated and tested using various agricultural products such as okra, moringa leaves, locust beans, and plantain. The dryer was evaluated based on moisture removal, drying rate, thermal, and drying efficiency. The amount of thermal energy consumed during drying increased as the moisture removed and drying time increased. The drying rate of the dryer varied between 5.40 and 34.80 g h^{-1}, depending on the type of product dried. The thermal efficiency varied from 62%-65%, implying that electric drying is an effective method for drying farm produce, which allows for shorter drying periods as the temperature of the heating elements could be controlled.

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