Mindanao Journal of Science and Technology Vol. 20 (2) (2022) 50-70

Development and Preliminary Testing of Rotary Dryer for Plantain Flour Processing Plant

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Date received: January 5, 2021
Revision accepted: July 21, 2022

Abstract

Plantain postharvest losses are significant in Nigeria and efforts are focused on processing the crop into storable products to ensure its availability throughout the year. To obtain the desired flour quality and quantity, plantain must be dried for an hour at a temperature not exceeding 70 °C and then discharged without human intervention. There have been significant obstacles in plantain processing. Regular turning of plantain pulps during drying, and intimate contact between them and the hot-drying air should be ensured to retain plantain nutritional and esteem values in the flour produced. In this study, a rotary dryer was developed. The machine is capable of drying plantain within the aforementioned hour and temperature range and is suitable for use in a plantain flour processing plant. A preliminary test was conducted to assess the fabricated prototype's functional performance and plantain particulates were able to move through the dryer. Upon varying the air-inlet aperture of the dryer from 0 to 125,680 mm^2, the drying air velocity increased from 0 to 4.4 m/s. The air-inlet aperture was proportional to air velocity/volume, particulate deflection within the dryer, particulate loss from the dryer and the time taken by the heater to reach the desired drying temperature. It became evident that drying air velocity/volume, deflection and particulate loss can all be influenced regardless of the blower's speed, potentially affecting the dryer's capacity and efficiency.

***Keywords**:* flour processing plant, plantain, plantain-drying, rotary dryer

1. Introduction

Food security is under threat in Nigeria – the world's fifth leading plantain producer – due to significant postharvest food losses corroborated by 5% to more than 50% postharvest losses of plantain (Ayodeji, 2016; Olutomilola *et al.*, 2021a; 2021b). Plantain is an important crop for people's livelihoods and food security around the world, particularly in Nigeria (Olutomilola, 2021a), adjudged capable of feeding the entire world if adequate technology for agriculture and postharvest handling or processing of farm produce could be developed and deployed (Olutomilola, 2021b).

In Nigeria, this study is a significant part of the development of a plantain flour processing plant, which will address the growing market demand for plantain due to the increasing understanding of its nutritional and health benefits and industrial/commercial qualities (Olutomilola *et al.*, 2016, 2019, 2020). Plantain is affordable and its products (i.e., flour) was found to be effective for managing diabetes – a risk factor for coronavirus infectious disease 2019 (COVID-19) and one of the world's five leading causes of death and debilitating diseases – with no adverse side effects (Oluwajuyitan and Ijarotimi, 2019; Adeyeri *et al.*, 2020; Olutomilola, 2021a). The preceding claims emphasize the importance of developing a technology for processing the crop into storable and value-added products. This would increase job opportunities and improve food security in Nigeria and around the world (Olutomilola and Omoaka, 2018; Olutomilola, 2021a, 2021b). Efforts were made to develop machines for processing plantains into flour; some of which are incompatible with direct integration into plantain processing plants. In addition, due to delayed drying – a critical process in plantain processing – the machines developed thus far typically take too long to convert plantain into flour.

Processing plantain into flour of high quality and desired quantity in a processing plant requires drying at a maximum temperature of 70 °C for 1 h or less than 2 h and automatic discharge of materials after drying. These are major challenges in plantain processing and research gaps that require immediate attention. Drying is the process of thermally removing moisture from a wet material to produce a solid product. Drying is one way to preserve some perishable agricultural products like plantains. It helps increase their shelf-life to ensure year-round availability, thereby reducing postharvest losses (Agoreyo *et al.*, 2011; Islam *et al.*, 2012; Olutomilola *et al.*, 2020). Food products can be dried in a variety of ways including direct sun drying, solar drying, fluidized bed drying, cabinet drying, rotary drying, spray drying, drum drying, freeze-drying, air-oven drying, microwave/dielectric drying, spouted bed drying, impingement drying, pneumatic and flash drying, conveyor drying, infrared drying, superheated steam drying, intermittent drying, pulse combustion drying, the use of dehydrators and many others. Furthermore, not all of the aforementioned drying technologies are suitable for drying plantains, particularly in a factory that is designed to continuously process plantains into flour. Plantain is customarily peeled, sliced and sun-dried for a few days although the actual drying rate or period is determined by the season of the year, slice thickness and sun intensity (Ogazi, 1996; Tchango *et al.*, 1999). According to a report, the dryness degree is typically assessed by how the slices can be easily broken; whereas the sun-dried product's quality is determined by its color, which is typically poor, resulting to dark brown flour which consumers find unappealing (Ogazi, 1996).

A study showed that, apart from sun-drying, cabinet drying is the most used method for drying plantain pulps after they have been sliced (Olutomilola, 2019). Thus, some researchers have developed a variety of cabinet dryers with varying capacities. For drying sliced plantain pulps, Ogazi (1996) used a cabinet dryer, which required about 3 h to dry a single layer and 6 h to dry double layers at a temperature of no more than 70 °C. Aasa *et al*. (2012) fabricated a hot air dryer for yam flour chunks – a form of cabinet dryer consisting of heating elements, a blower, and heating and drying chambers. In its performance evaluation, an efficiency of 53% was recorded. A cabinet dryer is found to be unsuitable for plantain processing plants because it disallows the continuous flow of materials; it prevents evaporated water or moisture to escape from the drying chamber; and the heated air is not uniformly circulated in the drying chamber resulting in inconsistency in product drying. Operating the equipment is highly laborious because it requires manual loading and unloading of sliced plantain pulps, which can adversely affect production capacity and the quality of flour produced (Olutomilola, 2019). It has been discovered that none of the existing plantain drying technologies is suitable for drying particulate plantain in 1 h in a plant that continuously processes plantain into flour (Olutomilola, 2019). Hence, a rotary dryer for drying plantain pulps is required to avoid the problems outlined above that are linked to cabinet drying and other related processes.

Rotary drying is one of the drying technologies used in the postharvest processing of farm produce into storable products and drying of food crops. Materials are dried in a rotary dryer, which is made out of a cylindrical shell that rotates on bearings. To facilitate the conveyance of wet feedstock, the cylindrical shell is normally tilted a few degrees to the horizontal. Wet feed is fed into the dryer's upper end, where it moves through the dryer due to rotation, head effect and shell slope, while dried product is extracted from the bottom end (Krokida *et al*., 2015). According to Moyers and Baldwin (1997), the drying medium travels axially through the drum either cocurrently or countercurrently with the feedstock. When the material is not heat-sensitive and needs to be dried to a very low moisture content level, the countercurrent method is said to be preferred. With any given inlet-gas temperature, countercurrent movement of gas and particles has been proven to have better heat-transfer efficiency, whereas cocurrent mode is recommended for faster drying rates and heat-sensitive materials. Moyers and Baldwin (1997) and Krokida *et al*. (2015) highlighted that rotary dryers are typically classified into two groups based on modes of heat transfer: direct heat transfer, which occurs when heat is supplied to or withdrawn from a feedstock being dried via a direct exchange between it and the heating medium, and indirect heat transfer, which occurs when a metallic tube or wall is used to separate heat-supplying medium from the feedstock. Direct rotary dryer (Genskow, 2008), direct rotary kiln, indirect steam-tube dryer, indirect rotary calciner, and direct roto-louver are the five major types of rotary dryers (Krokida *et al*., 2015).

It should be emphasized, however, that using a rotary dryer to dry plantain pulps is not a typical practice. It is also worth noting that previous works in this study area never considered incorporating particulate separators into rotary dryers. This is a research gap that must be filled. With the previously provided information, there is a need to investigate or explore the potential of rotary dryers for drying particulate plantain pulps. As a result, the study's goal was to develop a countercurrent direct-heat rotary dryer, capable of drying plantains in an hour at a maximum temperature of 70 °C – something that none of the previous dryers developed by researchers could do (Olutomilola, 2019). This study also evaluated the dryer's functional performance to identify other components that should still be included in the dryer's full-scale design. The dryer's selection was based on its inherent advantages over other dryers. The development of this dryer will aid in drastically reducing plantain processing time.

2. Methodology

2.1 Rotary Dryer's Design Concept

The rotary dryer is a countercurrent direct-heat type that consisted of a formed-flange cylindrical shell (equipped with parallel lifting flights along its length), an industrial electric blower-heater, an air filter, a gear drive, an electric motor and four rollers (Figure 1). A rotary dryer was chosen because it ensures good contact between heated air and material, allows proper circulation of heated air, permits the material being dried to be turned without manual input and lets evaporated moisture escape from the drying chamber without the use of a moisture-removing device (unlike cabinet dryer). The countercurrent mode was chosen because it provides higher heat-transfer efficiency at any given inlet-gas temperature. In addition, a direct-heat rotary dryer was selected because it is generally the simplest and most economical in operation and construction compared with others.

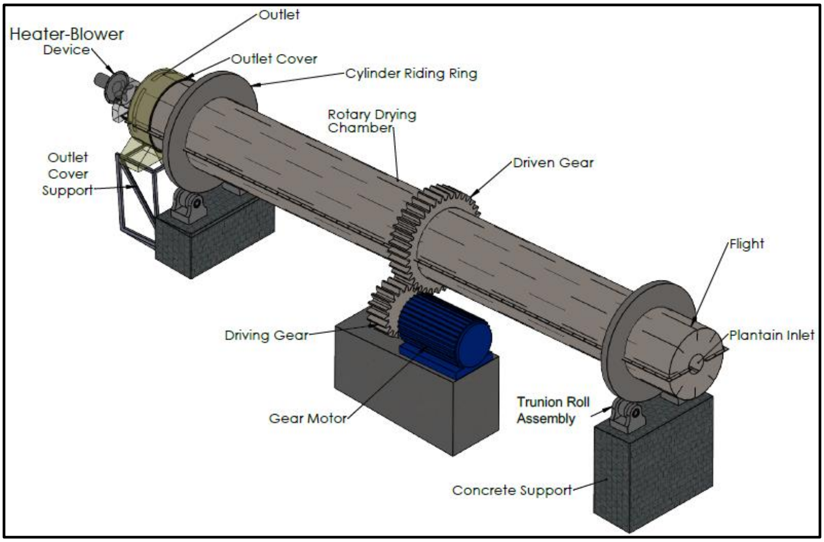

Figure 1. Isometric view of the rotary dryer assembly

In the dryer, a continuous feed of wet particulate plantain pulp was dried by coming into contact with heated air while being transported along with the interior of the rotating cylinder or shell. The rotating shell served as both a conveyance and a stirrer (Genskow, 2008; Van ’t Land, 2012). To facilitate the transportation of plantain pulp particulates from the feeding end to the delivery end, the cylindrical shell was slightly inclined at a 5° angle to the horizontal plane. The length and inner diameter of the cylindrical shell were chosen to be 9 and 0.9 m, respectively, to satisfy the length to diameter ratio of 10:1 as revealed by the studies of Moyers and Baldwin (1997), Krokida *et al*. (2015) and Devahastin and Mujumdar (2015). The cylindrical shell’s interior surface was also outfitted with peripheral lifting flights. As the shell rotates, the flights helped to lift and shower plantain particulates through a hot air stream supplied by an electric blower-heater allowing the particulates to make intimate contact with the hot air. The particulates' movement through the dryer was influenced by four mechanisms: lifting, cascade action, sliding and bouncing (Yliniemi, 1999; Krokida *et al*., 2015). The cylindrical shell was made of a 3-mm thick stainless steel sheet. An electric motor (at a low speed of 5 rpm) drives the shell via a gear drive.

The shell's external surface was equipped with two riding rings that were mounted on four support rollers to aid the smooth rotation of the shell. The riding rings and support rollers were made of mild steel. Figure 2 depicts what happens in the dryer. It should be noted that the design of the dryer was based on a 1-h operation. A prototype of the rotary dryer was fabricated (Figure 6). The bill of materials is shown in Table 1. The velocity of the drying air within the dryer was measured using a digital anemometer (LM-8100, Lutron, Taiwan).

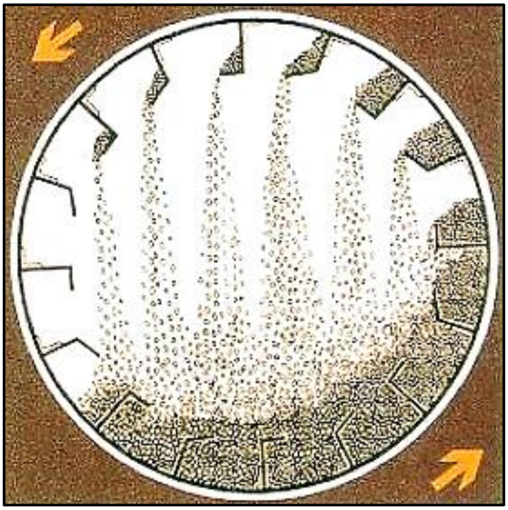

Figure 2. Illustration of what happens in the dryer

2.2 Design Specifications and Assumptions

The processing plant was expected to produce 1,000 kg of plantain flour per day while operating for 8 h (normal working hours) per day on a dry basis. According to Ogazi (1996), plantain pulp should be dried from 60% initial moisture content to 10% final moisture content and the inlet temperature of the hot drying air should be 70 °C. The exit temperature obtained from Equation 1 was 35 °C (Krokida *et al*., 2015; Moyers and Baldwin, 1997). The plantain's inlet and exit temperatures (wet and dry) were 27 and 60 °C, respectively (Kiin-Kabari and Njoku, 2016). The ambient air temperature and relative humidity were 27 °C and 68.1%, respectively. It should be noted that the dryer's design calculations were based on findings from Equipment Testing Procedures Committee (ETPC) (2005), Genskow *et al*. (2008), Van't Land (2012), Krokida *et al*. (2015) and Ademiluyi (2016).

$$T_{exit,air} = \left[\frac{T_{in,air} - T_w}{e^{N_t}}\right] + T_w \approx 35\ °C \quad (1)$$

where $T_{exit,air}$ is the exit or outlet temperature of the drying air; $T_{in,air}$ is the inlet temperature of drying air; T_w is the inlet wet-bulb temperature of the drying air (30 °C); and N_t is the number of transfer units (2) (Moyers and Baldwin, 1997; Krokida *et al*., 2015).

Table 1. Bill of materials for the fabricated rotary dryer

S/N	Component	Quantity	Materials used
1	Drying chamber (Ø400 × 4,000 mm)	1	Stainless steel
2	Driven and driving gears	2	Mild steel
3	Gear motor	1	Made in China
4	Outlet and inlet covers (Ø400 mm)	2	Stainless steel
5	Cylinder riding ring (Ø600 mm)	2	Mild steel
6	Fan and its housing (Ø400 x 1,000 mm)	1	Stainless steel
7	Fan mounting plate	1	Stainless steel
8	Fan belt drive assembly	1	Made in China
9	Flight	24	Stainless steel
10	Fan housing extension	1	Stainless steel
11	Supporting frame	3	Angle Mild steel
12	Roller block	4	Mild steel
13	Heater (1.8 kW)	3	Nichrome 80/20 wire
14	Drum flanges	4	Angle stainless steel

2.3 Heat and Mass Transfer in the Rotary Dryer

The heat from the hot air stream was transferred to the plantain pulp particulates as they fell through the air stream during drying. The heat from the dryer's hot walls was also transferred to the particulates. The supplied heat evaporated water from the particulates while also removing the corresponding vapor from the drying chamber. According to Krokida *et al*. (2015), the moisture and mass balances in the dryer were estimated as follows: production rate of plantain flour on a dry basis ($\dot{F}$ *=1,000 kg/day = 125 kg/h* or *0.034 kg/s*); the initial moisture content of plantain ($X_{p,i} = 0.6$); and the final moisture content of plantain ($X_{p,f} = 0.1$).

The total mass of wet plantain that was fed into the dryer was determined to be 200 kg/h or 0.06 kg/s using Equation 2 (Krokida *et al*., 2015).

$$\dot{M}_{wet} = \dot{F}\left(1 + X_{p,i}\right) \approx 0.06\ kg/s \tag{2}$$

The total mass of dry plantain particulates leaving the dryer was 137.5 kg/h or 0.04 kg/s calculated using Equation 3 (Krokida *et al*., 2015).

$$\dot{M}_{dry} = \dot{F}\left(1 + X_{p,f}\right) \approx 0.04\ kg/s \tag{3}$$

Utilizing Equation 4 (Krokida *et al*., 2015), the mass of water evaporating was 62.5 kg/h (0.02 kg/s).

$$\dot{M}_{water,\ E} = \dot{M}_{wet} - \dot{M}_{dry} \approx 0.02\ kg/s \tag{4}$$

2.3.1 Determination of Heat Transferred to Plantain in the Dryer

Using Equation 5, the total heat supplied to the plantain was 50.3 kJ/s (Krokida *et al*., 2015).

$$Q_o = (1 + \alpha)\left(\left[\left\{\dot{M}_{water,\ E}\left(\Delta H_{water} + C_{p,v}\left(T_{exit,air} - T_w\right) + C_{p,w}\left(T_w - T_{i,p}\right)\right)\right\} + F \left(T_{e,p} - T_{i,p}\right)\left\{C_{p,p} + (X_{p,f} \times C_{p,w})\right\}\right]\right) s \tag{5}$$

where ΔH_{water} is the latent heat of vaporization (2,350 kJ/kg); $C_{p,v}$, $C_{p,w}$ and $C_{p,p}$ are the specific heat capacities of vapor, water and plantain, respectively; $T_{i,p}$ and $T_{e,p}$ are the inlet (30 °C) and exit (70 °C) temperatures of the plantain (wet and dry); and α is a factor that represents the heat losses due to conduction between the outer surface of the dryer and the atmospheric air and due to radiation. According to Krokida *et al*. (2015), α has a maximum value of 0.1.

2.4 Determination of Air Mass Rate, Dryer Diameter and Dryer Length

Using Equation 6, the air mass flow rate $\dot{M}_{air}$ required to transfer sufficient heat for drying the plantain was determined to be 5,119.49 kg/h or 1.42 kg/s, while the diameter of the cylindrical shell was estimated at 0.9 m using

Equation 7 (Krokida *et al*., 2015). Because the inside and outside diameters of the rotary dryer shell were chosen to be 0.9 and 0.906 m, respectively, the length was estimated to be 9 m using Equation 8 (Moyers and Baldwin, 1997; Krokida *et al*., 2015).

According to Rajput (2013), the drying air volume flow rate and air velocity, calculated using Equations 9 and 10, were 1.3 m^3/s and 2.04 m/s, respectively. The volume of the dryer was 5.73 m^3 determined using Equation 11.

$$\dot{M}_{air} = \frac{Q_o}{C_{p,\,air}\left(T_{in,air} - T_{exit,air}\right)} \tag{6}$$

$$D_i = \sqrt{\frac{4\dot{M}_{air}}{3,600\pi j u_{p,air}}} \tag{7}$$

$$L_{dryer} = 10 \times D_i = 9\ m \tag{8}$$

$$\dot{V}_{air} = v_{air} \times A_{dryer} = \dot{M}_{air}/\rho_{air} \tag{9}$$

$$v_{air} = \dot{V}_{air}/A_{dryer} \tag{10}$$

$$Dryer\ volume\ (V_{dryer}) = A_{dryer} \times L_{dryer} \tag{11}$$

where $C_{p,\,air}$ is the specific heat capacity of air at constant pressure (1.01 kJ/kg °C or kJ/kg K); $u_{p,\,air}$ is the permissible air-mass velocity (2.63 kg/m^2 s); j is a constant (0.85); D_i is the cylinder's inner diameter; ρ_{air} is the air density (1.1 kg/m^3 at 70 °C); $\dot{V}_{air}$ is the air volume flow rate (m^3/s); v_{air} is the air velocity (m/s); L_{dryer} is the dryer's length; and A_{dryer} is the cross-sectional area of the dryer.

2.5 Determination of Plantain Residence Time and Heat Transferred into the Dryer

Residence time (R_t) is the average time spent by plantain particulates in the rotary dryer. This time is expected to correspond to the drying time required for plantain. Using Equation 12, R_t was 53.1 min (Genskow, 2008; Van't Land, 2012).

$$R_t = \left\{\left(0.23 \times L_{dryer}\right)/\left(S \times D_i \times N^{0.9}\right)\right\} + \left\{\left(1.97 \times B \times L_{dryer} \times G\right)/\left(\dot{F}\right)\right\} \tag{12}$$

$$B = 5 \times \bar{d}_p^{\,-0.5} = 5 \times 5000^{-0.5} = 0.071 \text{ and } S = \tan\varphi = \tan 5° = 0.0875 \quad (13)$$

$$G = \frac{\dot{M}_{air}}{A_{dryer}} \approx 8047 \ kg/h\ m^2 \ or\ 2.24\ kg/s\ m^2 \quad (14)$$

$$\dot{F} = \frac{\dot{M}_{dry}}{A_{dryer}} = 216\ kg/h\ m^2\ or\ 0.06\ kg/s\ m^2 \quad (15)$$

The velocity of the rotary dryer's shell was 0.24 m/s (Equation 16).

$$v_{dryer} = \pi D_o N/60 \quad (16)$$

where S is the shell's slope; φ is the angle of inclination of the cylindrical shell (5°); N is the rotational speed of the cylindrical shell (5 rpm) (Rajput, 2013); B is a constant depending on the material being handled; $\bar{d}_p$ is the particle size of the particulate plantain pulp (assumed to be 5,000 μm); G is the air-mass velocity (also known as air-mass flow rate per unit area of dryer cross-section) in kg/h m^2 or kg/s m^2; n is a constant; $\dot{F}$ is the dry plantain mass flow rate per unit area of dryer's cross-section in kg/h m^2 or kg/s m^2; and D_o is the outside diameter of the shell.

Using Equation 17, the total heat transferred into the dryer, which is the quantity of heat supplied by the heater, was calculated to be 67.233 kW (Moyers and Baldwin, 1997; Krokida *et al*., 2015; Van't Land, 2012).

$$Q_T = Ua \times V_{dryer} \times \Delta T_m = \frac{\bar{K} G^n}{D_i} \times V_{dryer} \times \Delta T_m \quad (17)$$

$$n = 0.67 \text{ and } \bar{K} = 5.25$$

$$\Delta T_m = \frac{T_{in,air} - T_{exit,air}}{ln\left[\frac{T_{in,air} - T_w}{T_{exit,air} - T_w}\right]} = \frac{T_{in,air} - T_{exit,air}}{N_t} = 17.5\ °C \quad (18)$$

where Q_T is the total heat transferred in the dryer; U is the total heat transfer coefficient; Ua is the volumetric heat-transfer coefficient; $\bar{K}$ is the proportionality constant (that is dependent on the feedstock properties, flight geometry, rotational speed and dryer's holdup); V_{dryer} is the dryer's volume m^3; a is the area of contact between the plantain particulates and the drying air per unit volume of the dryer; and ΔT_m is the mean temperature difference between the hot air and the plantain pulp (Moyers and Baldwin, 1997; Krokida *et al*., 2015).

Therefore, the rotary dryer required 67.233 kW to reduce the moisture content of the particulate plantain pulp from 60 to 10%. As a result, a heater-blower device rated at 67 kW was chosen for the rotary dryer.

Because sufficient heat (Q_{air}) was required to raise the temperature of drying air or airstream in the dryer from its atmospheric temperature ($T_{atm,air}$) to its inlet temperature ($T_{in,air}$), 222,339.5 kJ/h, calculated using Equation 19, was the quantity of heat required for this purpose. Hence, the thermal efficiency of the dryer ($\eta_{th,dryer}$) (Equation 20) was 74%.

$$Q_{air} = \dot{M}_{air} \times C_{p,\,air}\left(T_{in,air} - T_{atm,air}\right) \tag{19}$$

$$\eta_{th,dryer} = Q_o / (1 + \alpha) Q_{air} \tag{20}$$

2.6 Determination of Power required to Drive the Rotary Dryer

Because the volume of any rotary dryer that is normally filled with material during operation ranges from 10 to 15%, it was assumed that 15% of the inner shell volume would be filled with plantain pulp particulates (Moyers and Baldwin, 1997; Krokida *et al*., 2015). Hence, the total rotating load of the dryer (W_{TRL}) (Equation 21) was 957 kg.

$$W_{TRL} = w_p + W' \tag{21}$$

The weight of the particulate plantain pulps in the dryer was calculated using Equation 22, while the weight of the dryer in kilograms was given by Equations 23 and 24.

$$w_p = 0.15 V_{dryer} \times \rho_p \approx 344\ kg \tag{22}$$

$$W' = Volume\ of\ equipment\ material \times Density\ of\ equipment\ material \tag{23}$$

$$W' = \rho_m \left(\frac{2\pi D_i^2}{4} + \pi D_i L_{dryer} \right) dx = \left(\frac{\pi \left(D_o^2 - D_i^2 \right) L_{dryer}}{4} \right) \rho_m \approx 613\ kg \tag{24}$$

According to ETPC (2005) and Ademiluyi (2016), the power required (P_w) to drive the rotary shell and its content was estimated to be 0.5 kW using Equation 25, and the torque transmitted to the rotary dryer by gear motor was also obtained using Equation 26. Thus, 1.5 kW or 2 HP gear-motor was chosen for the rotary dryer.

$$P_w = \frac{N[(34.3D_i w_p) + (1.39D' W_{TRL}) + (0.73W_{TRL})]}{134040}$$

$$D' = D_i + 0.6 = 0.9 + 0.6 = 1.5\ m \qquad (25)$$

$$\therefore P_w \approx 0.5\ kW$$

$$T_{dryer} = 60P_w / 2\pi N = 2{,}864.42\ Nm \qquad (26)$$

where w_p is the weight of particulate plantain pulps in the dryer in kg; W' is the dryer's weight in kg; ρ_p is the density of the particulate plantain pulp (400 kg/m^3); ρ_m is the density of the material (stainless steel) selected for fabricating the cylindrical shell (8,000 kg/m^3); dx is the cylindrical shell thickness (3 mm or 0.003 m); D_o is the outside diameter of the cylinder in m; and D' is the outside diameter of cylinder riding ring in m.

2.7 Design of Lifting Flights

According to studies, the quantity of particulates in a rotary shell should be between 10 and 15% of the shell's volume (Moyers and Baldwin, 1997; Krokida *et al*., 2015). This loading has also been empirically proven to produce the best results. As a result, there must be a sufficient number of lifting flights to contain and distribute the particulates. Thus, eight lifting flights per circle or circumference of the dryer shell were chosen for this design (ETPC, 2005). Using Equation 27, the angular spacing between the lifting flights (θ_s) was 45° for proper lifting and showering of plantain pulp particulates through the hot air stream (Krokida *et al*., 2015).

Furthermore, lifting flights shapes have been reported to be determined by the properties of the drying feedstocks with lipless flat radial lifting flights recommended for sticky feedstocks, and 90° lipped radial lifting flights suggested for free-flowing feedstocks (Moyers and Baldwin, 1997; Krokida *et al*., 2015). The radial height of each lifting flight was estimated to be 140 mm using Equation 28 to ensure that the lifting flights carry and shower all of the holdups while minimizing any kiln action. To account for the changing properties of the plantain particulates during drying, the three flight designs, shown in Figure 3, were used along the dryer's length, with the first, middle, and last one-third of the dryer's length equipped with the lipless, 45° lipped, and 90° lipped flat radial lifting flights, respectively (Moyers and Baldwin, 1997; Dutta, 2009; Krokida *et al.*, 2015). The lifting flights were also offset at every 600-mm length. According to ETPC (2005) and Dutta (2009), the radial height of each lifting flight is given as,

$$\theta_s = 360°/n_f \tag{27}$$

$$H_R = D_i/6.6 \ \text{or} \ 0.15D_i \tag{28}$$

where n_f is the number of lifting flights in the shell per circumference; and H_R is the height of lifting flights.

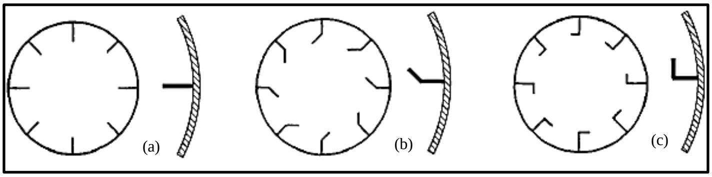

Figure 3. Selected lifting flight profiles – straight (a), 45° (b) and 90° (c) (Moyers and Baldwin, 1997; Krokida *et al*., 2015)

2.8 Design of Gear Drive

The rotary dryer was powered by a spur gear drive. The gear transmitted power from the 1.5-kW gear-motor to the rotary dryer. Because of its good wearing properties, excellent machinability and ease of producing complicated shapes from it via the casting method, cast iron was chosen for the design and manufacture of the drive's pinion and driven gear (Khurmi and Gupta, 2008).

2.9 Preliminary Test

The dryer's fabricated prototype was subjected to preliminary testing to assess its functional performance both at no load and under load. Figure 4 shows the process flowchart. Fresh unripe plantain fingers were purchased, weighed and peeled. The peeled plantain fingers (pulps) were weighed once more to determine the percentage lost to peels. After that, the pulps were made into particulate form for use in the rotary dryer. The dryer was then allowed to run until the temperature in its drying chamber reached 70 °C before the particulate pulps were introduced.

The corresponding values of air velocity were measured using an anemometer as the area of the air-inlet aperture was varied. The results were recorded and tabulated. The values of air-inlet aperture areas were then plotted against the corresponding air velocity values. The behavior of particulate pulps within the dryer and their flow through it were also studied. The residence time for each run was also noted. Moreover, the blower's speed, as well as the dryer's slope and speed, were held constant while the effect of the air-inlet aperture was evaluated on rising heater temperature, drying air volume flowrate or velocity, escape or loss of particulates with drying air from the dryer, residence time and particulate deflection in the dryer.

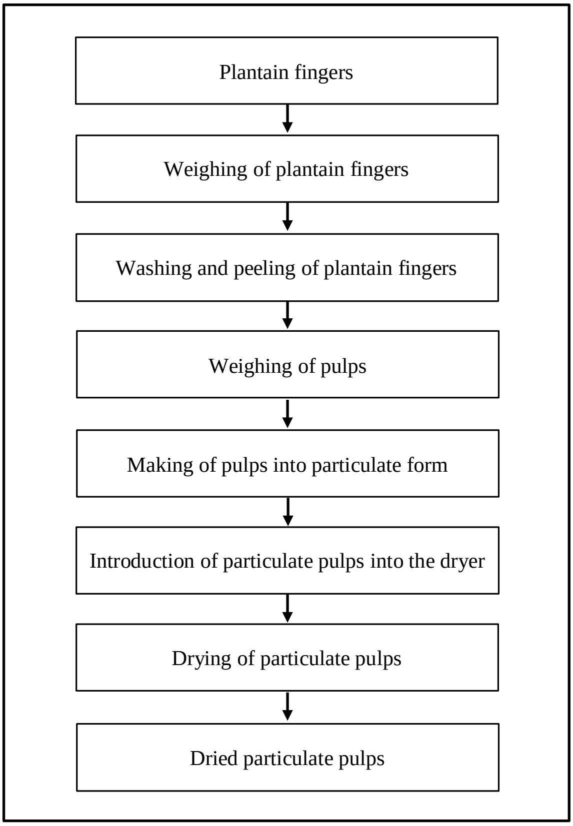

Figure 4. Process flow for drying particulate plantain pulps

Figure 5 shows the rotary dryer's heating unit, which included an air-inlet control plate. The control plate was designed to regulate the flow of air into the dryer, which in turn regulated the air velocity or volume flow rate. A four-in-one digital anemometer was then used to measure the velocity of the drying air.

Figure 5. Dryer heating unit showing air-inlet port

3. Results and Discussion

The fabricated prototype of the plantain rotary dryer is presented in Figure 6. During the dryer test, some particulates clumped together to form balls, while others clung to the interior wall of the rotary dryer. A portion of the particulates that adhered to the wall later detached, while another portion remained attached to the wall throughout the drying period. The particulates that formed balls exited the dryer undried in 15 min, which was significantly less than the expected residence time (60 min) calculated for the dryer's full scale. These drawbacks could be attributed to the fact that the rotary dryer was scaled down to a prototype, as well as the lack of separators for the plantain particulates prior to and during drying. This is a confirmation that the rotary dryer can serve its intended purpose if scaled up with the incorporation of particulate separators before and during the drying process. Meanwhile, the fastest movement of particulates from the feeding to the discharge end of the dryer (or the shortest residence time) was recorded when the blower/fan was turned off. This demonstrated that the blower's presence can influence residence time. Particulate plantain pulps were also observed to travel from the drying chamber's entry to its exit end, and they were received by the pulverizing unit as soon as they left the drying chamber.

Figure 6. The fabricated rotary dryer

When the blower was turned off, the heater reached 70 °C in 3.5 min. When the air-inlet port of the heating unit was fully closed during the dryer's preliminary test, the drying-air velocity was observed to be zero. When the heating unit's air-inlet control plate was completely removed, the drying-air velocity was 4.4 m/s resulting in a 125,680 mm^2 aperture area at the heating unit's air-inlet port. As shown in Table 2 and Figure 7, this was the maximum drying-air velocity obtained thus far within the dryer's chamber.

Table 2. Variation of air velocity with air-inlet aperture

S/N	Area of air-inlet aperture (mm^2)	Air velocity (m/s)
1	0.00	0
2	28,656.11	0.5
3	39,873.17	1.1
4	52,304.74	2.1
5	60,504.14	2.4
6	66,777.21	2.6
7	83,015.12	3.0
8	125,680.00	4.4

Also, when the air-inlet control plate was introduced and kept fully opened, resulting in an aperture area of 83,015.12 mm^2, the air velocity obtained within the dryer was 3 m/s (Table 2 and Figure 7). Different air velocity values (0.5, 1.1, 2.1, 2.4 and 2.6 m/s) were also achieved within the dryer's drying chamber when the aperture of the air-inlet port was adjusted to obtain 28,656.11, 39,873.17, 52,304.74, 60,504.14 and 66,777.21 mm^2 port areas, respectively. A larger air-inlet aperture resulted in a higher velocity of the drying air obtained within the dryer. As shown in Table 2, Figure 7 and Equation 29, the air-inlet aperture was directly proportional to air velocity or volume; particulate deflection within the dryer because particulate deflection increased as air velocity increased; and particulate loss from the dryer because more particulates escaped with the drying air as its velocity increased, but inversely proportional to the time that the heater took to reach the desired drying temperature (70 °C).

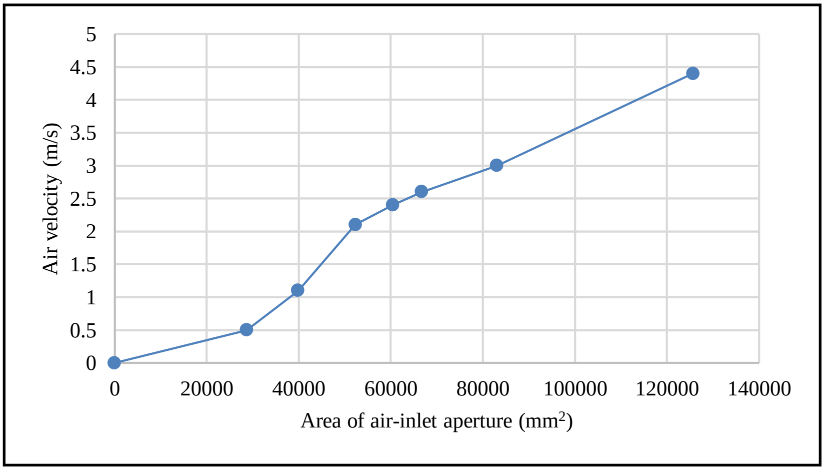

Figure 7. Variation of air velocity with air-inlet aperture

$$Air\ inlet\ aperture \propto \frac{(Air\ velocity),\ (Loss\ of\ particulates),\ (Deflection\ of\ particulates)}{Time\ taken\ for\ \ heater's\ temperature\ to\ Rise} \tag{29}$$

Olutomilola (2019) underscored that drying is a critical process in a plant that converts unripe plantains into flour; what happens in the drying section determines the behavior of the entire processing plant; and material flow is critical in any processing plant. Thus, the ability of the rotary dryer to convey plantain pulp particulates from its feeding end to its discharge end, as well as the discharge of the particulates into the milling section, demonstrated the possibility of a continuous flow of materials from the washing section of the processing plant to the packaging section. This observation was also an indication that the rotary dryer's slope and flights arrangement were efficient.

The wider air-inlet aperture led to a longer time for the heater's temperature to reach the desired value (70 °C); higher velocity of the drying air; more deflection of particulates within the dryer; and greater loss or escape of particulates with exiting drying air. The first, third, and fourth observations could be attributed to an increase in the drying air velocity and volume flow rate. This meant that, regardless of the blower's speed, the drying air velocity/volume, deflection, and particulate loss can all be influenced, which can have a significant impact on the dryer's capacity and efficiency, as shown in Figure 7 and Equation 29.

4. Conclusion

A countercurrent direct-heat rotary dryer was designed and prototyped in this study. It was subjected to a preliminary test before it can be integrated into the plant that converts unripe plantain into flour. Materials were observed to pass through it and proceed to the next processing stage. Because material flow is a major factor in any processing plant for continuous production, this demonstrated the dryer's ability to serve its intended purpose. The preliminary test on the dryer revealed that varying the dryer's air-inlet aperture could still influence the drying-air velocity, particulate deflection, drying chamber temperature, residence time of plantain particulates and loss or escape of particulates from the dryer regardless of the blower's speed. It should be noted, however, that previous studies/researchers in this area did not look in this direction. Hence, further research could be used to generate enough data for tables and graphs from which the values could be selected for design purposes in the future.

The study also established the need for particulate separators to be incorporated into the dryer before and during the drying process to prevent them from sticking together while keeping the drying time under an hour at a maximum temperature (70 °C). Because the processing plant is currently a research project in Nigeria, the findings of this study are already being considered.

5. Acknowledgement

The authors would like to acknowledge the Tertiary Education Trust Fund (TETFund) Nigeria for funding this study (research grant reference number: VCPU/TETFund/155 and project number: TETF/DR&D/UNIV/AKURE/IBR/2017/VOLII). The Advanced Manufacturing and Applied Ergonomics Research Team (AMAERT), Engr. Adebola Adesina, Dr. Olagoke Z. Ayodeji (MEE, FUTA), Noel C. Mbah, Memedo Myro and Kehinde L. Ajibola are sincerely appreciated for their contributions to the success of this study.

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