

Design and Fabrication of Shea Nut Rotary Dryer for Shea Butter Production in Nigeria

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Abstract

Traditional shea nut drying is done with the aid of sun by spreading the material on the mat under the sun and since the supply of it is not specific, we cannot rely on sun for efficient production and since this is the method employed in the traditional production of shea butter, it will always constitute inefficiency in production. And this is one of the problems of traditional method of extraction of shea butter in Nigeria which involves numerous uncontrolled and non-specific practices. As a result of this, research has shown that shea kernels generally undergo hydrolytic and oxidative degradations and are also affected by aflatoxin and other harmful micro-organisms during the post-harvest processing and storage. Consequently, shea butter produced is characterized by high level of iodine number, high percentage of free fatty acid, peroxide value, microbes, and other solid and dissolved impurities. Therefore this work seeks to design and fabricate a rotary dryer whose temperature can be controlled, and the accurate moisture content required for extraction of shea butter can be known, and also address the problem of rain getting the shea kernel wet. The dryer was designed for capacity of 60 kg/batch to reduce fresh shea nut moisture content from 40% to about 7%. Briquette from shea shell was used to generate heat for the drying.

Keywords: Rotary dryer; Design; Shea nut; Shea butter; Drying

Introduction

The shea fruit consists of a pulp that surrounds a nut which has a shell that houses the kernel that is dried and stored for processing into shea butter. The main shea nut producing countries include Burkina Faso, Mali, Ghana, Nigeria, Côte d'Ivoire, Benin, Togo and Guinea. The total production capacity of these countries was estimated at 600,000 tons with 350,000 tons exported in 2008 [1].

One of the most important characteristics of biological materials is their moisture content. According to Sitkei [2], the moisture content of agricultural materials affects their physical and mechanical properties. Moisture content also affects the storability, handling and processing of biomaterials. Many researchers have studied and reported the relationship between moisture content of biomaterials and their other properties. These are, for examples, locust bean seed [3], arigo seed [4], Simarouba fruit and kernel [5], shea nut [6,7]. The physical properties of biomaterials are essential in the design and development of specific equipment and structures for transporting, handling, processing and storage and also for assessing the behaviour of product quality [8,9]. Physical properties of shea kernel are essential in the design of items of equipment for decortication, drying, cleaning, grading, storage and oil extraction. Moisture content is useful information in the dry process. As a result of poor and uncontrolled processing methods, Shea kernels generally undergo hydrolytic and oxidative degradations and are also affected by aflatoxin and other harmful micro-organisms during the post-harvest processing and storage [10]. These results in shea butter characterized by high level of iodine number, high percentage of free fatty acid, peroxide value, microbes, and other solid and dissolved impurities. Traditional processing techniques involve numerous uncontrolled and non-scientific practices. These factors lead to low yield, poor and inconsistent quality of shea butter from this method of production and consequently affect the export potentials of Shea butter from Africa and Nigeria in particular [11-13].

Drying refers generally to the removal of moisture from a substance. It is one of the oldest, most commonly used and most energy consuming

unit operation in the process industries. Drying is often necessary in various industrial operations particularly in chemical process industries to remove moisture from a wet solid, a solution or a gas to make it dry and choice of drying medium is depends on the chemical nature of the materials [14]. Drying is an operation of great commercial importance in all industrial applications ranging through the food, agricultural, mining and manufacturing sectors. Modern society requires better product quality, improved safety practices and more environmentally benign operations, as well as higher productivity, better energy efficiency and reduced material wastage. As drying is certainly one of the most energy-intensive operations in industry, and as most dryers operate at low thermal efficiency, the development, design and construction of a drying device to aid in the drying of shea nut necessary dryer operation and efficiency [15].

The rotary drier is basically a cylinder, inclined slightly to the horizontal, which may be rotated, or the shell may be stationary, and an agitator inside may revolve slowly. In either case, the wet material is fed in at the upper end, and the rotation, or agitation, advances the material progressively to the lower end, where it is discharged [16]. The rotary dryer is an equipment employed to minimize the moisture content of a feed material by bringing it in direct contact with a heated gas. It consists of an inclined long drum or cylindrical shell often fitted with internal flights or lifters; rotated slowly upon bearings through which the material to be dried flow with a tumbling/cascading action in concurrent (for heat sensitive materials) or counter-current flow with

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the heating air or gases [17].

Since sundrying and oven drying which is principally adopted by the locals lack control, the aim of this work is to design and fabricate a rotary dryer which will provide adequate control of processing temperature in the dryer. The dryer was designed for capacity of 60 kg/batch to reduce fresh shea nut moisture content from 40% to about 7%. Briquette from shea shell was used to generate heat for the drying.

Methodology

The design of the dryer was done by carrying out material balances, energy balance and equipment specification.

Material and energy balances for dryer

This shows material input and output and the energy balance across the dryer.

Basis: 60 kg Fresh Shea nut per batch was selected to allow a minimum of 30 kg of shea kernel to be obtained. Fresh shea nut contains 40% moisture with 93% of the moisture removed by the dryer. Shea nut is composed of 4% shell.

Material balance for dryer

This is the equipment where the fresh shea nut is dried (Figure 1) using heat generated from the shea shell briquette. It consists of three cylindrical chambers (the inner cylinder containing the fresh fruit, the middle chamber housing the heating medium i.e., hot air and the third chamber housing the insulator to prevent heat loss, burner and hollow pipes.

The summary of material balance around the dryer is as shown in Table 1.

$$\text{From fundamental laws: Input=Output} \quad (1)$$

Energy balance across the dryer

Basis: 60 kg/batch.

Assumptions: Specific heat of fresh shea nut was assumed to be constant within the range of the temperature used.

Ambient temperature was taken as 30°C and datum temperature is 0°C. Time taken to dry a batch was taken to be 8 h.

Specific heat of fresh shea nut=3.4 kJ/kg°C.

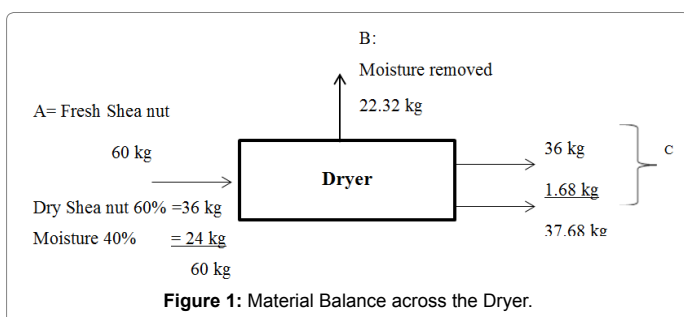


Figure 1: Material Balance across the Dryer.

Streams (kg)	Shea nut (kg)	Water (kg)	Total (kg)
A	36.0	24.0	60.0
B	-	22.32	22.32
C	36.0	1.68	37.68

Table 1: Summary of Material Balance around the Dryer.

Average rate of moisture removal was about 10% of the air flow rate.

Mass of Fresh nut entering the dryer=60 kg.

Mass of water evaporated=22.32 kg.

Mass of dry shea nut=37.68 kg.

Heat content of feed entering the dryer is:

$$Q = M_{sn} C_{p_{sn}} \Delta T \quad (2)$$

where,

M_{sn} = Mass of shea nut (kg),

$C_{p_{sn}}$ = Specific heat capacity of shea nut (kJ/kg°C),

ΔT = Change in temperature (°C),

Q = Heat content of feed (kJ).

Heat content of dried shea nut leaving the dryer is calculated by equation 3

$$Q = M_{dn} C_{p_{dn}} \Delta T \quad (3)$$

M_{dn} = Mass of dried shea nut (kg),

$C_{p_{dn}}$ = Specific heat capacity of dried shea nut (kJ/kg°C),

ΔT = Change in temperature (°C),

Q = Heat content of the product (kJ).

If the heat applied to the shea nut is measured at 130°C (average temperature).

$$\text{Heat content of evaporated water} = M_w C_v \quad (4)$$

M_w = Mass of water (kg),

C_v = Latent heat of vaporization (kJ/kg),

Taking heat balance across the dryer.

Heat In=Heat out (Assuming heat losses due to conduction, convection and radiation are negligible).

Heat In=Heat content of fresh shea nut+heat supplied by the biomass.

Heat out=Heat content of dry shea nut+heat content of evaporated water.

Heat supplied by Biomass=Heat content of dry shea nut+Heat content of evaporated water-Heat of the fresh shea nut. The summary of energy balance across the dryer is as shown in Table 2.

Dryer specification

Internal drum: Assume the shape of the dryer is made of cylindrical drums, and for cylindrical dryers. The most economical height to diameter ratio is 2:1.

$$\frac{h}{D} = 2 \quad (5)$$

But $D = 2r \Rightarrow h = 4r$

h = height (m),

D = diameter (m),

r = radius (m).

Item	Energy In (kJ)	Energy Out (kJ)
Heat content of fresh nut	6.120	-
Heat supplied by Biomass	63.384	-
Heat content of dry nut	-	12.811.2
Heat content of evaporated water	-	56.692.8
Total	69.504	69.504

Table 2: Energy Balance on the Dryer.

The bulk density of fresh shea nut at 40% moisture was determined by the standard test weight procedure and was obtained to be 0.589 g/cm³ (589 kg/m³). And from the relation volume of fresh shea nut (V_{sn}) is Volume of fresh shea nut.

$$V_{sn} = \frac{M_{sn}}{\rho_{sn}} \quad (6)$$

(V_{sn})=Volume of fresh shea nut (m³),

ρ_{sn} =Density of shea nut (kg/m³),

M_{sn} =Mass of shea nut (kg).

Assuming 25% allowance is given for safety, nut mixing, heat transfer and volume contribution by shaft, internal pipes, then:

$$V_{ID} = V_{sn} + 25\% V_{sn} \quad (7)$$

V_{ID} =Volume internal drum (m³),

V_{sn} =Volume fresh shea nut (m³).

But for Cylinders:

$$\text{Volume} = \pi r^2 h \quad (8)$$

And $h=4r$

Specification of the middle chamber (Drum):

$$\text{Rate of moisture removal } \varphi_m = \frac{\text{Mass of moisture removal}}{\text{Total time taken}} \quad (9)$$

$$\text{Volume of moisture removed } V_m = \frac{\text{Mass}}{\rho_{130^\circ C}} \quad (10)$$

Volumetric flow rate of moisture removal per pass is:

$$\varphi_{(v)m} = 10\% \text{ of } \varphi_{(v)T}$$

Volume of the annular space can be obtained as:

$$\frac{4}{3} \pi (r_3)^3 - \frac{4}{3} \pi (r_2)^3 \quad (11)$$

r_2 =External radius of the internal drum (m),

r_3 =radius of the middle drum (m).

The thickness of insulation can be obtained from the concept of critical radius as shown [18].

$$r_c = \frac{k}{h_c} \quad (12)$$

Where, r_c =critical radius of insulation (m),

k =Thermal conductivity of insulator (kJ/sm°C),

h_c =Convective heat transfer coefficient of the surrounding environment.

Using fibre glass as the insulating material at ambient temperature of 30°C:

$$r_c = \frac{0.0496}{6.5} = 0.007631 \text{ m}$$

$$r_c = r_a + rC$$

$$r_5 = r_4 + rC$$

r_4 =External radius of the middle drum (chamber) (m),

r_5 =Internal radius of the external drum (m),

r_6 =External radius of the external drum (m).

$$D = 0.2385 \times 2 = 0.477 \text{ m}$$

$$h = 0.2385 \times 4 + 2(r_c)$$

Power required by the shaft: The power required by the shaft is a function of all the three drums (internal, air drum and external drum), weight of the shea kernel, weight of the air and moisture, weight of the bearing, weight of the insulating materials and weight of the shell. It was calculated according to Khurmi and Gupta [19] as:

$$P_s = \frac{2\pi N \tau}{60} \quad (13)$$

P_s =Power required for rotating the dryer (kW),

τ =Torque (Nm),

N =Rotational speed (rpm).

$$T = F \times r_1 \quad (14)$$

$$F = M \times r_1 \times \omega^2 \quad (15)$$

F =Force (N)

ω =Angular velocity (rads⁻¹)

$$\omega = \frac{2\pi N}{60} \quad (16)$$

$$M_T = (M_{ID} + M_{Ad} + M_E + M_{Sn} + M_{ins} + M_{air} + M_B + M_s) \quad (17)$$

where M_T (kg), M_{ID} (kg), M_{Ad} (kg), M_E (kg), M_{Sn} (kg), M_{ins} (kg), M_{air} (kg), M_B (kg) and M_s (kg) are Total mass of dryer, Mass of internal Drum, mass of Air Drum, Mass of external Drum, mass of shea nut, mass of insulator, mass of air, mass of bearing and mass of shaft respectively.

Mass of the internal drum: The mass of the internal drum was obtained as reported [20] as:

$$M_{ID} = \rho V_I \quad (18)$$

$$M_{ID} = \rho (2\pi r_1 L \times T_1) \quad (19)$$

Where, ρ is density of the of Mild Steel (kg/m³),

V_{ID} is volume of the internal Drum (m^3),

r_1 is radius of internal Drum (m),

L_1 is length of the Drum (m),

T_1 is the thickness of the Mild Steel (m).

Mass of the middle (air) drum: The mass of the middle (air) drum (M_{Ad}) was similarly obtained by using equation 19.

Mass of the insulating material: The mass of the insulating material (M_{IS}) was obtained using the relation:

$$M_{IS} = \rho_{IS} (r_s^2 - r_4^2) h \quad (20)$$

Mass of rotary dryer shaft: The mass of the shaft was computed as reported [21] and is given as:

$$M_{srd} = \rho_{srd} \left(\frac{\pi d_{srd}^2}{N} \right) L_{srd} \quad (21)$$

Where, M_{srd} is mass of rotary dryer shaft (kg),

ρ_{srd} is density of rotary dryer shaft (kgm^{-3}),

d_{srd} is diameter of rotary dryer shaft (m),

L_{srd} is length of rotary dryer shaft (m).

But diameter of the central shaft was computed as [19] reported:

$$d_{srd}^3 = \frac{16}{\pi S_s} \sqrt{(k_b M_b)^2 + (k_t M_t)^2} \quad (22)$$

Where, d_{srd} = diameter of rotary dryer shaft (m),

M_t = belt torque twisting mount (Nm),

M_b = bending moment (Nm),

k_b = shock and fatigue factor applied to torsional moment for bearing,

k_t = shock and fatigue factor applied to torsional moment for shaft,

S_s = Permissible shear stress for the shaft,

π = constant.

The weight of the two bearings on the shafts was obtained by measuring the mass and multiplying by the value of acceleration due to gravity [19].

Weight of the two bearings on the shafts = 2 mg.

Torque (τ) was obtained by substituting the value of permissible pressure and diameter of shaft into the equation 3.23.

$$\tau = \frac{PD \times W}{2\pi N} \quad (23a)$$

P = Permissible Working pressure (N/m^2),

D = Diameter of shaft (m),

W = Weight of the two bearings (N).

Taking the electric motor and the gear box efficiency to be 90%, the effective torque τ_e was obtained by:

$$\tau = \frac{PD \times W}{2\pi N} \times 0.9 \quad (23b)$$

The forces (F) acting on the shaft was obtained from:

$$F = \frac{\tau_e}{r} \quad (24)$$

The total weight acting on the shaft is the summation of the weights of the shaft and tension imposed by the two bearings:

$$W_T = W_p + T_1 + T_2 \quad (25)$$

Where, W_T = Total weight on the shaft (kg),

W_p = weight of pulley (kg),

T_1 and T_2 = Tension due to the two bearing (N).

The bending moment (M_b) was also obtained as reported by Khurmi and Gupta [19] as

$$M_b = W_T \times L \quad (26)$$

L = length of shaft = length of external chamber of dryer (m).

But a diameter of 60 mm hollow pipe of thickness 5 mm was selected, to also allow a passage for hot air inside the drying chamber. Therefore mass of the shaft is:

$$M_s = \rho (\pi (r_e^2 - r_i^2)) L \quad (27)$$

Where, r_e = External radius of pipe = 30 mm = 0.030 m,

r_i = Internal radius = 25 mm = 0.025 m,

L = Length of the pipe = 960 mm = 0.960 m,

ρ = Density of the steel pipe = 8000 kg/m^3 .

The mass of bearing (M_b), and the mass of shea nut (M_{sn}) was determined by measurement on diamond scale as 1.5 kg and 60 kg respectively, while mass of air was assumed to be negligible. Therefore, total mass of dryer given by equation:

$$M_T = (M_{ID} + M_{Ad} + M_E + M_{Sn} + M_{ins} + M_{air} + M_B + M_s)$$

The diameter of the gear pulley (Figure 2) is given as:

$$N_1 D_1 = N_2 D_2$$

$$D_2 = \frac{N_1 D_1}{N_2} \quad (28)$$

Where, D_1 = diameter of the electric motor pulley (m),

N_1 = The speed of the electric motor (rpm),

N_2 = required speed of the gear box (rpm),

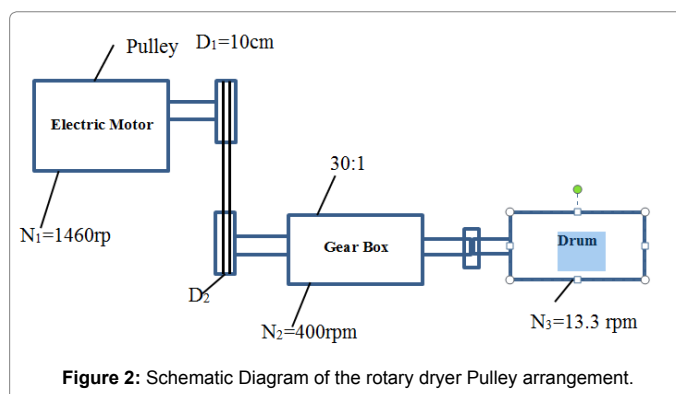


Figure 2: Schematic Diagram of the rotary dryer Pulley arrangement.

D_2 is diameter of the gear box pulley (m).

Drum shaft diameter: $N_2 D_2 = N_3 D_3$

Where, N_2 = diameter of the electric motor pulley (rpm),

D_2 = diameter of the gear box pulley (m),

N_3 = speed of the drum (rpm),

D_3 = diameter of the drum pulley (m).

Gear reducer is reducing the speed to the speed of the drum in ratio of 30:1.

Power (P_m) required by the machine is as given in equation 13:

$$P_m = \frac{2\pi N\tau}{60}$$

Angular velocity: The angular velocity is calculated as given by equation 16:

$$\omega = \frac{2\pi N}{60}$$

ω = angular velocity (rad/s),

N = rotational speed of the drum (rpm).

$$F = Mr\omega^2 \quad (29)$$

Where, F = The force (N),

M = mass of the dryer (kg),

r = radius of external drum (m),

ω = angular velocity (rad/s).

Torque (τ) = Fr

$$\text{Power: } P_m = \frac{2\pi N\tau}{60}$$

Considering safety 10% of the calculated value was added.

Volume of the burner: The volume of the burner was estimated by the determination of the calorific value of the biomass (shea shell).

Calorific value of shea shell was determined experimentally to be 427.709 kCal. As shown in Appendix C.

The total energy generated by the biomass to dry 60 kg of shea shell was 63384 kJ.

$$\text{But density } (\rho_{ss}) = \frac{M_{ss}}{V_{ss}} \quad (30)$$

Adding 20% to accommodate the blower, chimney and ash collector.

Fabrication of the fresh shea nut dryer: The dryer was fabricated according to the specifications obtained in above. It is composed of three horizontal cylindrical tanks constructed with 2 mm thick mild steel mounted on a frame as shown in plate XXIV (Figure 3).

The frame was constructed by 3×3^m angle iron with a brazing of 2×2^m angle iron. The accessories attached to the dryer are the burner, fan, detachable hopper, Sheanut collector, temperature sensor with a controller, pulleys, electric motor, gear reducer and manually operated jack. The innermost cylinder is 0.43 m in diameter, 0.86 m length and 0.12 m³ in volume. The cylinder houses the 60 kg fresh shea nut, a hollow 60 mm diameter, 5 mm thick central shaft. Connected to this central shaft are 12 number, 20 mm diameter Galvanize Iron (GI) pipe

arranged 4 by 3 at 90° to each other to aid the distribution of heat within and outside surface of this cylinder as shown in Plate XXV (Figure 4).

The mechanism of heat transfer adopted in this dryer is the indirect method. This prevents the hot air and smoke in making direct contact with the shea nut to avoid accumulation of Polycyclic Aromatic Hydrocarbon (PAH) [11].

Also welded to the walls of the innermost cylinder are four number baffles to aid parking and mixing of the nuts while the dryer is rotating as shown in plate XXVI (Figure 5). The middle chamber is 0.46 m in diameter, 0.92 m length and a hollow space of thickness 0.0129 m between the innermost cylinder and the middle chamber. This thickness corresponds to an annular space of $8.19 \times 10^{-3} \text{ m}^3$ required per pass of hot moist air. The pressure inside this chamber is controlled by a half inch opening on the chamber through the third chamber to the atmosphere.

The outmost cylinder is 0.48 m diameter, 0.96 m length and 0.17 m³. The clearance between the middle cylinder and the outmost cylinder was calculated to be 0.00763 m as critical radius of insulation using fibre glass material as described [17]. The calculated thickness of the fibre glass was attached to the external surface of the middle cylinder as shown in Plate XXVII (Figure 6). The dryer has a temperature sensor embedded inside the central shaft and connected to a fan. The Micro-controller mounted outside the dryer controls the interaction between the sensor and the fan. As the temperature of the hot air in the dryer



Figure 3: Plate XXIV: Frame where the dryer is mounted.



Figure 4: Plate XXV: Innermost Cylinder of the Dryer.



Figure 5: Plate XXVI: Shows the Baffle inside the innermost Cylinder.



Figure 6: Plate XXVII: Insulated Cylinder of the Dryer.

reaches the set temperature, the sensor sensed the heat and sends a signal to the fan to trip. Equally, when the temperature of the hot air in the dryer falls below the set temperature, the same signal is sent to the fan to pick. This mechanism is continued and ensures even drying of the shea nut and hence uniform properties of the shea nut [22,23].

Also incorporated in the dryer is a 10 Hp electric motor with a speed of 1460 rpm connected to a pulley system (10 cm and 36.5 cm) and a gear reducer (30:1) as shown in Figure 3. This arrangement provides a dryer speed of 13.3 rpm as recommended by Khurmi and Gupta [19]. Also incorporated in the dryer are a detachable hopper and collector for ease of feeding fresh shea nut and removal of dried nut respectively.

Conclusion

Rotary dryer has been designed and fabricated for shea nut processing, especially by the local producers in Nigeria to enhance the quality of shea butter produced. Instead of spreading the shea nut/ kernel under the sun which is not specific in supply, the use of rotary can be employed and since the temperature of the drier can be controlled, accurate moisture content required for extraction of shea butter can be obtained, the problem of rain getting the shea kernel wet can be alleviated, drying time can be reduced, and production of shea kernel with uniform properties can be obtained.

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