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Parameter and heat transfer performance evaluation of an existing dryer mixer for “*Irvingia gabonensis*” powder

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Abstract

A homogeneous mixing and drying of food substance are required prior to further processing and storage. This research was carried out to determine the heat transfer parameters of an existing dryer-mixer and evaluate its performance for the drying and mixing of *Irvingia gabonensis* powder. A 1 kg of the powdered product (~ 15 µm particle size and 24.5% initial moisture content) was dried using the mixer-dryer for 5 hours. The average temperature of the drying chamber was preset at 50°C for the drying process, with the help of a thermostat. The heat transfer parameters, which includes the air flow rate and thickness of wall lagging, were determined mechanistically. Also, the drying performance was determined based on the drying rate, drying efficiency, mixing index, and mixing rate of the machine. Results show that an air flow rate of 0.00082 kgs⁻¹ and 0.02 m thickness of a fibre-glass lagging material was required in the drying and mixing operation. Energy required to dry the product from 24.5% (wb) to 12.8% (wb) moisture content was 0.08514 kJ/s at a drying rate of 1.8 kgh⁻¹. A mixing index of 0.819 and efficiency of 82.2 % were obtained, and these may imply effective drying and a high degree of homogenization in the system.

Keywords: Energy, Air flow rate, Design, Thermal conductivity, Performance

1. Introduction

An *Irvingia gabonensis* powder can be used to formulate jelly, jam, juice and wine in the food industry. It can also be used to prepare black dye for cloth coloration [1]. Therefore, preservation of the product for latter application cannot be overemphasized. Several process technologies, which include scanning, freezing and drying, can be employed to preserve the product on a domestic and industrial scales. The most important of these methods of preservation is drying because it permits the application of heat to vaporize moisture from the product [2]. A disadvantage of the drying method is that the removal of moisture however may be accompanied by a loss of nutritional quality of the product. Therefore, drying needs to be selectively applied.

Drying can be regarded as a heat and mass transfer operations occurring simultaneously during postharvest operations [3]. A quantum of heat energy is usually conveyed from the drying medium to the food which allows it to progress by conduction. This allows a mass transfer of the moisture in the food to the surrounding by convection. The drying rate during this period is directly proportional to the rate of transfer of heat to the food. Thus, it is important to comprehend the heat and mass parameters of the product for optimal drying process. This however depends on the heat transfer coefficients of the drying medium and the surface temperatures of the food. An equilibrium moisture content is reached when the rate of moisture drift equates the dehydrating medium. The design of an optimally energy saving food dryer is therefore influenced by the magnitude of these parameters and their interactions [4, 5].

A major drawback in the design of dryers for the processing and preservation of the *Irvingia gabonensis* powder is its tendency to absorb atmospheric moisture, thereby distorting its morphology in equilibrium state. Traditionally, table salt has been used as preservative, but this may have adverse effect on human health when used in uncontrolled amounts. The product may also be exposed to the sun for several hours to remove moisture to a safe level for storage. The traditional processes described are usually labor intensive, time consuming and a thorough mixing of the preservative with the bulk sample is usually difficult to achieve. However, conventional dryers such as solar dryer, oven dryer and so on, have been successfully used in the past to preserve the product. Again, higher wall temperatures in these technologies will normally speed up the rate of drying but limited by higher quality degradation [6, 7]. However, there is no reported research on the design of a drying equipment for the product. This design will particularly help to improve timeliness in the processing of the product by combining both the mixing and drying unit operations together instead of having them separately. There is therefore the need to design an equipment for drying and mixing of the product. The objective of this research was to determine the heat transfer parameters of an existing dryer-mixer and evaluate its performance for the drying and mixing of *Irvingia gabonensis* powder.

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2. Materials and methods

2.1 Material selection

Materials used for the development of the mixer-dryer were selected locally, and they permit easy maintenance and repair. The physical and chemical properties of the materials are strong enough to withstand heat, vibration, fatigue and stress without failure during operation. Table 1 shows the materials, measurements and SI units used in the analysis.

Table 1 Materials used for dryer-mixer development

Materials	Measurements	Units
Galvanized steel sheet	1 standard size	mm
Galvanized mesh	2.4 × 1.2	mm
Mild steel sheet	2 standard size	mm
Blower	0.5	HP
Fibre-glass lagging	k = 0.04	Wm-1K-1
R- value	0.44- 0.65	m2K.W-1
Square pipe	25 × 25	mm
Heater	1000	W

2.2 Design consideration and assumptions

The strength and stability of the materials used in the fabrication of the mixer-dryer was considered. Initial moisture content of the *Irvingia gabonensis* powders used in this investigation was found to be 24.5% [8, 9]. The relevant physical and mechanical properties of the powder reported by Sahin and Samu [10] were used in this study. The energy required for the drying was generated from the heater. Environmental conditions used were: dry-bulb temperature (T1) of 28°C, average relative humidity (RH) of 70%, initial humidity ratio of 0.01 kg/kg dry air and maximum drying temperature achievable in the drying chamber (T2) of 150 °C, which is the maximum temperature calibration on the thermostat. The drying chamber has a 25 cm internal diameter and an internal cylindrical height of 70 cm from the base of the dryer to its false floor. It was designed to have a capacity of 1 kg/batch. The chamber was double walled and insulated with a fibre-glass lagging material.

2.3 General description and component parts of the existing dryer-mixer

The combined mixing and drying system consisting of several functional units including the blower, electrical heat source (heater), a combined cylindrical mixing and drying chamber, thermocouple, and an electric motor, is described in Figure 1. The blower transferred sensible heat of the heated air generated by the heater to the wet powder in the combined cylindrical mixing and drying chamber. The inlet vent, through which the air enters the system, is located at the upper part of the dryer, as shown in Figure 2. The heater, which is located close to the inlet pipe, heats up the incoming air by convection. The blower consists of centrifugal fan which blows the hot air radially in the drying chamber. A prime mover of 0.5 HP was attached to the impeller shaft for mixing the food material at a speed of 24 revolutions per second. A thermostat (0 °C to 150 °C design temperature range) was attached to the side wall of the dryer to regulate the temperature condition to a preset value of 50 °C. The hot moisture air exits the drying chamber via the opening at the bottom of the system. The temperature and relative humidity of the hot air at the exit point were 32 °C and 83%, respectively.

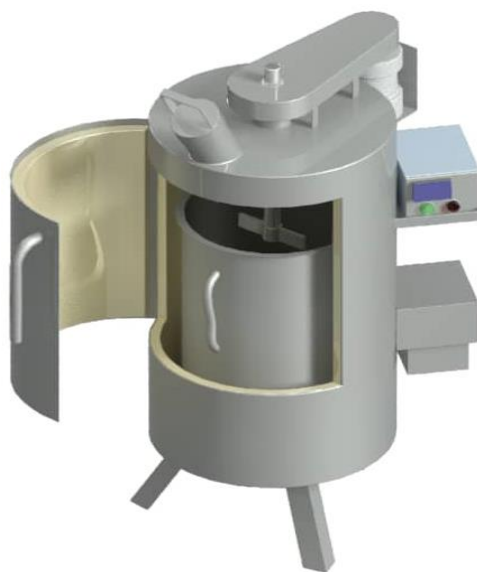


Figure 1 A model of the dryer-mixer

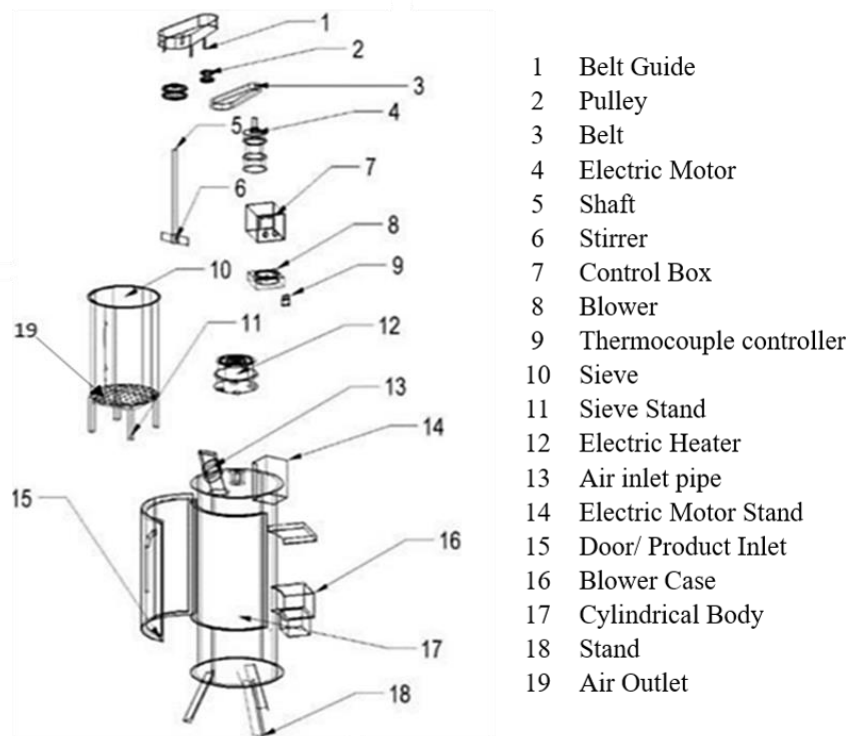


Figure 2 Component parts of the dryer-mixer

2.4 Heat transfer parameter design

2.4.1 Quantity of hot air required for drying

The quantity of hot air required for the drying of the *Irvingia gabonensis* powder was determined using Equation (1), as reported by Ichسانی and Wulandari [11]. The psychrometric properties of the heating process at 50°C heated air temperature and 70% RH were 200.6 kJkg⁻¹ enthalpy, 1.06 kgm⁻³ density, 8.643 kPa partial vapour pressure, 12.35 kPa saturated vapour pressure, 1.001 m³kg⁻¹ specific volume and 0.0580 kg.kg⁻¹ humidity ratio. Also, the psychrometric properties of the heating process at 32°C exit air temperature and 83% RH were 96.77 kJkg⁻¹ enthalpy, 1.14 kgm⁻³ density, 3.951 kPa partial vapour pressure, 4.759 kPa saturated vapour pressure, 0.900 m³kg⁻¹ specific volume and 0.0252 kg.kg⁻¹ humidity ratio.

$$M_a = \frac{M_w}{(H_{r0} - H_{r1}) \times n} \quad (1)$$

where: M_a = quantity of air required for drying (kg)

H_{r0} = initial humidity ratio at 50°C and 70% RH = 0.0580 kg.kg⁻¹ dry air

H_{r1} = final humidity ratio at 32°C and 83% RH = 0.0252 kg.kg⁻¹ dry air

M_w = amount of moisture loss = $1 \times \left(\frac{24.5 - 12.45}{100} \right) \text{kg} = 0.1205 \text{ kg}$

n = the pick-up factor, which considers the nature of the food material to be dried and the ease with which it releases moisture to the air. Base on this therefore, we assumed a pickup factor of 0.25 for the drying of the *Irvingia gabonensis* powder to cater for the actual amount of moisture to be removed from the product per kg of the drying air [12].

2.4.2 Size and type of blower selection

The fan size in the blower was determined by computing the volumetric flow rate of the drying air over a 5 hours drying time using the expression in Equation (2), according to Axtell [12].

$$m_v = m_k \times v_s \quad (2)$$

where: m_v = volumetric flow rate of the drying air in m³s⁻¹

m_k = mass flow rate of the drying air = $\frac{M_a}{\text{drying time}} = \frac{14.695}{5 \times 3600} = 0.00082 \text{ kgs}^{-1}$

v_s = specific volume of the drying air at 50°C and 70% RH = 1.001 m³kg⁻¹

2.4.3 Volumetric capacity of the drying chamber

The volume of the drying chamber was calculated using the expression in Equation (3) [13].

$$V = \pi r^2 h \quad (3)$$

where: V = volume of cylindrical chamber (m^3)

r = radius of the cylindrical chamber = $\frac{\text{diameter}}{2} = \frac{25}{2} = 12.5 \text{ cm} = 0.125 \text{ m}$

h = height of the cylindrical chamber = 0.70 m

2.4.4 Bulk density of the material

The bulk density was determined using the empirical expression in Equation (4) as reported by Liu and Bakker-Arkema [14].

$$\rho_{wm} = 10^{-5} [7 \times 10^4 + \frac{0.016}{10^{-5}} m_o - 116 m_o^2 + 1.8 m_o^3] \quad (4)$$

where: ρ_{wm} = bulk density at a given moisture content, kgm^{-3}

m_o = initial moisture content of the product in % wet basis = 24.5% wb [14]

2.4.5 Determination of energy required for drying

The quantity of heat energy required for the dryer-mixer was calculated using Equation (5), as expressed by Axtell [12].

$$q = m_k(h_2 - h_1) \quad (5)$$

where: q = amount of heat energy in kJ s^{-1} ;

m_k = air mass flow rate = 0.00082 kgs^{-1} as obtained earlier

h_1 = specific enthalpy of inlet air at 50°C and 70% RH = 200.6 kJ.kg^{-1} air;

h_2 = specific enthalpy of outlet air 32°C and 83% RH = 96.77 kJ.kg^{-1} air.

2.4.6 Thickness of lagging material

We considered the theory of heat flow through a cylindrical wall since the heat was to be transferred radially from the ambient air environment through the fibre glass lagging material to exit the surrounding as a damped hot air, as shown in Figure 3 [13-15].

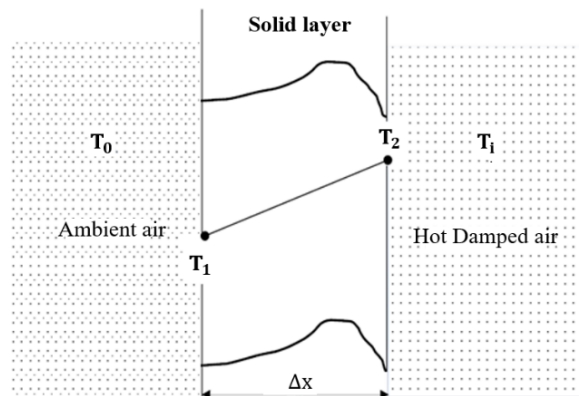


Figure 3 Heat transfer through the fibre glass arrangement in the dryer

The heat was first transferred from the ambient air at the temperature T_0 to the fibre-glass lagging material at the temperature T_1 . The rate of heat transfer is directly proportional to the temperature difference between the fibre glass material, the mass of the air and the area of cross-section. This relationship was mathematically expressed according to Newton's law, in Equation (6) [16-18].

$$q = hA(T_0 - T_1) \quad (6)$$

The heat is then transferred by conduction through the fibre glass material of thickness Δx with a temperature difference of $T_2 - T_1$. Finally, the heat is transferred by convection process as a damped hot air from the other surface of the material to the surrounding. Therefore, we evaluated the total heat flow across all the sections of the material according to Equation (7) [17].

$$q = h_o A(T_0 - T_1) + h_i A(T_2 - T_i) - \frac{kA(T_2 - T_1)}{\Delta x} \quad (7)$$

Where: T_0 is the ambient air temperature = 28°C .

T_i is the air temperature at the surrounding ($^\circ\text{C}$).

T_1 is the Preset temperature in the drying chamber = 50°C

T_2 is the temperature of the damped air at the exit = 32°C

h_i and h_o are inside and outside heat transfer coefficients, respectively ($\text{W/m}^2.\text{K}$)

A is the cross-sectional area of the lagging material (m^2)

However, since the lagging material is to prevent heat loss in the drying chamber, it is in fact an adiabatic system [16-19], which involves no transfer of heat energy to the surrounding [19]. Therefore, the total heat loss is approximately zero (ie. $q = 0$). Based on this, we modified Equation (7) as follows:

$$0 = h_o A(T_o - T_1) + h_i A(T_2 - T_1) - \frac{kA(T_2 - T_1)}{\Delta x}$$

$$\frac{kA(T_2 - T_1)}{\Delta x} = h_o A(T_o - T_1) + h_i A(T_2 - T_1)$$

But we know that for adiabatic process, $T_o = T_i = 28^\circ\text{C}$ and $h_o = h_i = U$ (overall heat transfer coefficient, $\text{W/m}^2\cdot\text{K}$), so that:

$$h_o A(T_o - T_1) + h_i A(T_2 - T_1) = UA(T_2 - T_1) = \frac{kA(T_2 - T_1)}{\Delta x}$$

$$\text{Thus, } \frac{kA(T_2 - T_1)}{\Delta x} = UA(T_2 - T_1)$$

$$\Delta x = \frac{kA(T_2 - T_1)}{UA(T_2 - T_1)}$$

$$\Delta x = \frac{k}{U}$$

Since $U = 1/R$

$$\Delta x = \frac{k}{1/R}$$

$$\Delta x = kR$$

The R-value and k-value for fibre-glass has been given, by McQuiston et al. [20] and reported by the American Society of Heating, Refrigerating and Air-Conditioning Engineer [21], in the range of $0.44\text{--}0.65 \text{ m}^2\text{K/W}$ and $0.04 \text{ Wm}^{-1}\text{K}^{-1}$, respectively. Also, the k-value for the fibre-glass was reported as $0.04 \text{ Wm}^{-1}\text{K}^{-1}$. We therefore choose $R = 0.5$ and $k = 0.04 \text{ Wm}^{-1}\text{K}^{-1}$ in this analysis.

$$\Delta x = 0.04 \times 0.5 = 0.02 \text{ m}$$

Therefore, the fibre-glass material thickness was 0.02 m

2.5 Heat transfer evaluation of the *Irvingia gabonensis* powder

Hot air drying and mixing of food powder around 150°C may lead to drying of the food in a very short time [22]. The low thermal conductivity and heat transfer coefficient of the powder at that temperature maybe responsible for the drying behaviour of the food [23]. The heat transfer method in this study involves making powder from the sample of the *irvingia gabonensis* and placing it in an existing dryer mixer, which was designed specifically for the product. The temperature on the surface of the equipment was monitored throughout the experiment using a thermostat. A small variation in the inside temperature was initially observed ($< 4^\circ\text{C}$) in the first 30 minutes of loading but this became constant as the drying continues with time. A 1 kg of the freshly harvested *irvingia gabonensis* of 24.5% moisture content was ground into powder using an attrition mill, until the particle size was $15 \mu\text{m}$. The powdered material was poured into the existing dryer-mixer, as shown in Figure 4, and operated for 5 hours. The temperature of the drying chamber was maintained between $40\text{--}60^\circ\text{C}$ throughout the drying process, with the help of the thermostat. After drying, the final moisture content of the *Irvingia gabonensis* powder was found to be 12.8% (wb). The heat treatment of the product was adequately achieved by this approach.



Figure 4 Pictorial view of the existing dryer-mixer

2.5.1 Drying rate

The drying rate can be defined as the ratio of the amount moisture removed from the product to the length of time required for the drying process. The amount of the moisture removed increases with the temperature and time of drying until a certain threshold moisture content was reached, called the critical moisture content. In our analysis, this critical moisture value of the product was found to be 10.69% (dried basis). Beyond this moisture level, the material becomes bone-dried and obsolete for its intended use at the falling drying period. Thus, the drying rate of the product was computed, at constant drying rate, using the expression in Equation (8) [24-26].

$$R_a = m_i \left(\frac{m_{db} - m_c}{t} \right) \quad (8)$$

where: R_a = drying rate, kg/h

m_i = mass of the product = 1 kg

m_c = critical moisture content % (dried basis) = 10.69 % db

m_{db} = initial moisture content of the product in % dried basis = $\frac{100m_o}{100+m_o} = 19.68$ % db

t = drying time = 5 hours.

2.5.2 Drying efficiency

This indicates the performance of the machine for drying the *Irvingia gabonensis* powder. It is necessary we determine the drying efficiency of the machine since it provides information about the machine performance. It also gives insight about the drying pick-up factor, which is a necessary parameter for evaluating the quantity of hot air required in the drying process. The drying efficiency was computed using Equation (9) [25].

$$E_d = \frac{w_3}{w_2} \times 100(\%) \quad (9)$$

where: w_2 = weight of fresh *Irvingia gabonensis* powder (kg)

w_3 = weight of dried *Irvingia gabonensis* powder (kg)

E_d = drying efficiency (%)

2.5.3 Mixing index

This was calculated in order to understand the extent or degree of mixing of the material in the machine. We determined the moisture content of the powder for the 5 h drying period at interval of 30 minutes. This gives a total of 10 moisture samples of the powder from the performance analysis. Therefore, the expression in Equation (10) was used to compute the mixing index of the machine for drying the *Irvingia gabonensis* powder [25].

$$D_m = \frac{\sigma_i^2 - \sigma^2}{\sigma_i^2 - \sigma_f^2} \quad (10)$$

where: σ^2 = Average standard deviation of the powder moisture content

σ_i^2 = Initial standard deviation of the powder moisture content at time $t = 0$ s of drying,

σ_f^2 = Final standard deviation of the powder moisture content at time $t = 5$ hours of drying,

D_m = Mixing index

2.5.4 Mixing rate

In order to calculate the time required for any desired degree of mixing, we assumed that bending forces are not likely in the machine operation so that the mixing rate constant, β takes a unit value. Thus, the mixing rate of the dryer-mixer was computed using the expression in Equation (11) [26].

$$t = \frac{1}{\beta} \ln \left(\frac{1 - \frac{1}{\sqrt{\alpha}}}{1 - D_m} \right) \quad (11)$$

where: α = number of moisture samples of powder from the performance analysis (10)

β = mixing rate constant (s^{-1})

t = mixing rate (s)

3. Results and discussion

3.1 Conductive heat transfer performance

At constant pressure, heat supplied to the system of the dryer-mixer would contribute to both the work done and the change in internal energy. The results of the conductive heat transfer parameters of the dryer-mixer is presented in Table 2. The drying system required 0.08514 kJs-1 of energy to dry and mix the *Irvingia gabonensis* powder to safe moisture level. The heat energy supplied may end up as energy of motion and energy stored in force fields [27], both at macroscopic and atomic scales. Then the change in temperature will depends on the path that the system followed through its phase space between the initial and final states. The presence of 0.02 m thick lagging material helps to ensure that only negligible heat energy is lost to the surrounding. Therefore, the bulk of the heat energy supplied was utilized in the drying and mixing process.

Table 2 Conductive heat transfer parameters of the dryer-mixer for the product

s/n	Heat process parameter	Value	SI Unit
1	Quantity of hot air required for drying	14.6950	kg
2	Volumetric flow rate of the hot air	0.00082	m^3s^{-1}
3	Volumetric capacity of the drying chamber	0.03436	m^3
4	Bulk density of the material	0.00385	kgm^{-3}
5	Mass of material in the drying chamber	1.00000	kg
6	Energy required for drying	0.08514	kJs^{-1}
7	Thickness of lagging material	0.02000	m

3.2 Performance of the mixer-dryer

A measure of how well the operation of an equipment is utilized in terms of the available facilities, time and material compared to its full potential, during the periods when it is scheduled to run is referred to performance evaluation. It identifies the percentage of manufacturing time that is truly productive. In this investigation, the results of the performance evaluation of the dryer-mixer is thus presented in Table 3. The rapid rate of drying and mixing reveals its ability to dry and mix the *Irvingia gabonensis* powder. The drying rate of 1.80 kg h^{-1} obtained was quite enough to remove substantial amount of the moisture from the powder within the constant drying period, thereby enhancing the keeping quality of the product. This means only 0.03 kg of the moisture content of material is evaporated per minute or 0.0005 kg per seconds. This was also enough to homogenize the system with a mixing index of 81.9%. The research findings of Aregbesola et al. [27] corroborate the present investigation, in their work on the formulation of mathematical modeling for predicting the thin layer drying characteristics of *Irvingia gabonensis* nuts and kernels. Also, Fadeyibi et al. [28] reported similar findings in their work on the effects of diameter of holes in breaker plate and glycerol on the performance of a single screw mixer. The authors suggested a food mixer will perform optimally if the mixing index is greater or equal to 80%. Thus, in the case of the mixer-dryer a homogeneous product is expected since the mixing index exceed this threshold. A significant effect of many drying methods on the physicochemical properties of ready-to-cook *Irvingia gabonensis* have been reported [29]. The authors reported that tray drying was superior to the oven drying because of their different drying rates. This may therefore mean that the greater the drying rate, the greater the amount of moisture drift from the product.

Table 3 Performance evaluation of the dryer-mixer

S/N	Parameters	Values	SI Unit
1	Mass of moisture removed	0.1205	kg
2	Drying Rate	1.8000	kg h ⁻¹
3	Drying Efficiency	82.160	%
4	Mixing Index	0.8190	-
5	Mixing Rate	1.3290	s

4. Conclusions

The performance of a mixer-dryer for *Irvingia gabonensis* powder was evaluated based on its heat transfer parameters. The drying system required 0.085 kJ s^{-1} of energy to dry and mix the product to safe moisture level. A drying rate of 1.800 kg h^{-1} was obtained, and this was quite enough to remove substantially the moisture present in the powder within the constant drying period, thereby enhancing the keeping quality of the product. This was also enough to homogenize the system with a mixing index of 81.9%. The bulk of the heat energy supplied was utilized in the drying and mixing process. Thus, the heat transfer parameters are needed for the analytical prediction of the drying behaviour and in the design of postharvest handling and processing systems for *Irvingia gabonensis*.

5. Acknowledgements

The authors acknowledge the technical assistance provided by the staff of the Food Engineering Laboratory of the University of Ilorin.

6. Abbreviations

Symbol	Meaning	SI Unit
M_a	Quantity of air required for drying	kg
H_{i0}	Initial humidity ratio at 50°C and 70% RH	kg.kg ⁻¹ dry air
H_{f1}	Final humidity ratio at 32°C and 83% RH	kg.kg ⁻¹ dry air
M_w	Amount of moisture loss	kg
m_v	Volumetric flow rate of the drying air	m ³ /s
m_k	Mass flow rate of the drying air	kg s ⁻¹
v_s	Specific volume of the drying air at 50 °C and 70% RH	m ³ /kg
V	Volume of cylindrical chamber	m ³
r	Radius of the cylindrical chamber	m
h	Height of the cylindrical chamber	m
ρ_{wm}	Bulk density at a given moisture content	kg/m ³
m_o	Initial moisture content of the product in % wet basis	% wb
m_{db}	Initial moisture content of the product in % dried basis	% db
q	Amount of heat energy	kJ s ⁻¹
h_1	Specific enthalpy of air at inlet at temperature of 50 °C and 70% RH	kJ kg ⁻¹ air
h_2	Specific enthalpy of air at the exit with a temperature of 32°C and 83% RH	kJ kg ⁻¹ air
T_o	Ambient air temperature	°C
T_i	Air temperature at the surrounding	°C
T_1	Preset temperature in the drying chamber	°C
T_2	Temperature of the damped air at the exit	°C
m_i	Initial mass of the material	kg
m_f	Final moisture contents of the material	% wb
m_c	Critical final moisture contents of the material at constant drying rate	% wb
R_a	Drying rate	kg h ⁻¹
t	Total time	h
W_2	Weight of fresh <i>Irvingia gabonensis</i> powder	kg
W_3	Weight of dried <i>Irvingia gabonensis</i> powder	kg
E_d	Drying efficiency	%
σ^2	Average standard deviation of the powder moisture content	%, wb
σ_t^2	Initial standard deviation of the moisture content at time $t = 0$ s of drying,	%, wb
σ_t^2	Final standard deviation of the moisture content at time $t = 5$ h of drying,	%, wb
D_m	Mixing index	-
α	Number of moisture samples of powder from the performance analysis	-
β	Mixing rate constant	s ⁻¹

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