



# Energy Performance Analysis of Convective Drying of Sorghum Gruel Residue

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## Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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## ABSTRACT

This research is concerned with the energy performance analysis of convective drying of sorghum gruel residue. The process was carried out on a hot air dryer conducted at four drying air temperatures of 40, 50, 60, and 70 °C respectively, three different air velocities 0.8, 1.0 and 1.2m/s and three different varieties of sorghum gruel residue, *Caudatum*, *Durra* and *Guineense* respectively. The effects of drying temperature and air velocities on the specific energy consumption, energy efficiency, drying efficiency and thermal efficiency were investigated. The specific energy consumption for *Caudatum*, *Durra*, *Guineense* varieties ranges from 169530.001 J/kg - 71433.758 J/kg, 170557.25 J/kg - 76732.96 J/kg and 179367.266 J/kg - 83750.923 J/kg respectively while the energy efficiency for *Caudatum*, *Durra*, *Guineense* varieties ranges from 35.5% - 13.934%, 31.188% - 13.836% and 28.463% - 13.157% respectively. The results of this study also confirmed that the convective drying process is energy intensive and drying fresh agricultural produce with heated-air dryers requires a relatively large amount of energy.

**Keywords:** Drying; energy efficiency; specific energy consumption; temperature; air velocity.

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## 1. INTRODUCTION

Drying has been and continues to be a major method of preserving agricultural products especially in developing countries like Nigeria. It is an integral part of agricultural processing and is usually the last step of operation before storage [1]. Drying is widely used in a variety of thermal energy applications in food processing industries. Generally, the term “drying” refers to the removal of a relatively small amount of moisture from a solid or nearly solid material by evaporation [2], which assures microbial stability and guarantees expected shelf-life of the product [3].

Dryer theory and technology has advanced greatly, which has led to the development of different drying systems with different energy efficiency and throughput. However, dryer energy consumption is an important technical information necessary for optimal design and cost effective operation as well as proper meeting of the optimal storage conditions of agricultural products. Although drying is known for being energy intensive, in addition to the heat of vaporization of the moisture removed, energy goes into heating the solid material and into heating the drying medium used (Amos, 1998, Lwicksi, 2006); [4]. Whether it comes as a part of a process or just as a preservation method for food and agricultural products, a relatively large amount of energy is required by the dryer to carry out this operation. Since drying is highly energy intensive (due to the latent heat of evaporation required), it is equally important that drying processes be energy efficient. It is therefore not surprising that energy efficiency and product quality have been identified as the key drivers of research and development in drying technology, as a result of which over 400 design variations are currently available [5]. Although the specific heat capacity of the product is sufficiently lower than the latent heat of vaporization of water; the cost of energy provides a strong incentive to invent processes that will use energy efficiently.

Energy, which is defined as the quantitative property that must be transferred to an object or physical system in order to perform work, plays an important role in the drying process since it is required for the removal of water from food. Energy requirements for crop drying have been found to vary due to the type of crop, moisture content at harvest, desired/final moisture content, crop specific heat capacity, latent heat of

vaporization of water, intended use, gross mass, size, shape, and biological characteristics such as surface texture, crop porosity, nutritional content, drying times, production capacity, drying temperatures as well as operating pressure and the efficiency of the drying equipment [6,7,8,9].

Some works have been done on estimation of the energy consumption and performance of some common dryer. These dryers consume varying quantities of energy depending on the type of crop to be dried and the desired final moisture level. Experimental study on energy consumption of a hybrid convective electric-gas dryer for drying of onion slices was done by El-Mesery and Mwithiga [10]. The energy consumed by the electrical dryer through the heating element was determined using a digital electric counter. While that of the energy consumption of the gas dryer was determined by weighing the gas cylinder using a weighing balance. The difference in mass of the gas bottle before and after drying process was measured and converted into consumed energy ( $Q_G$ ). From the study, SEC decreases with increase in air temperature but increases with increase in air velocity in both dryer heat sources. In the electric source, when the temperature of drying air was increased from 50°C to 70°C while holding the air velocity constant at 0.5 m/s, the specific energy consumption decreased from 65.45 to 43.34 MJ kg<sup>-1</sup> of water evaporated. At the fixed air velocity of 2 m/s and for the same air temperature range of 50°C to 70°C, the specific energy consumption of the electrical dryer decreased from 84.64 to 70.59 MJ kg<sup>-1</sup> of water evaporated. The results from the study illustrates that less energy is wasted when the temperature is high and air velocity is low. In other words, increasing air temperature causes decrease in SEC values. Also, increasing air velocity causes an increase in SEC. The implication is that using high air temperature and drying conditions result in a sharp increase in the dryer energy consumption. Accordingly, low temperature level with high air velocity causes a relative decrease in moisture diffusivity, resulting in higher SEC values. Similar trends were reported by Khoshtaghaza et al. [11], Aghbashlo et al. [2] and Chayjan et al. [12] in estimating the specific energy of consumption for drying grape and berberis fruits in a convective hot air dryer in the range of 547 and 1904 MJ kg<sup>-1</sup>. They observed that increase in drying temperature caused a decrease in the specific energy consumption. The effect of air velocity on increasing specific energy value was more than the air temperature.

Results obtained indicated that increasing the drying temperature in each air velocity level affects the energy consumption inversely. In other words, increasing the air temperature shortens the drying time, thus the energy consumption is reduced. Also decreasing the air velocity, effective contact between air and fruit was increased and the specific energy consumption decreased. In general, the SEC of the gas dryer was observed to be lower than that of the electric dryer at all conditions of air temperature and air flow settings. This is probably because of the longer on/off periods of the electrical heater elements when compared to the gas burner and the fact that the electric heaters still retained a high thermal mass even when switched off.

Dryer energy consumption and performance is a function of material properties such as sample geometry and thickness, initial and final moisture contents; specific heat of product, dryer type and configuration, operating parameters like air velocity, temperature, power density, absolute pressure, crop energy requirement, drying time, etc [13,14]. Dryers often consume two or three times as much energy as required to remove a pound of water from a product which is as a result of poor efficiency and performance of some drying process/system and the poor utilization of the energy available. It has also been observed that the thermodynamic losses that occur within a system often are not accurately identified and assessed, therefore this research is based on the energy performance analysis of convective drying of sorghum gruel residue.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The three different species of fresh sorghum (*Sorghum bicolor* (L.) Moench) which are Sorghum *Guineense*, Sorghum *Durra* and Sorghum *Caudatum* was gotten from Oja Oba market in Akure, Ondo State, Nigeria. It was picked to remove the broken grains, damaged grains, dirt and foreign particles. Each variety of the grain was soaked separately for 72 hours with clean water, the soaked sorghum kernels was grinded and the starch was manually extracted to obtain the residues.

#### 2.1.1 Experimental procedure

The experiment was carried out with the cabinet dryer in Processing and Storage Laboratory of

the department of Agricultural and Environmental Engineering, Federal University of Technology Akure, Ondo State. Before drying commenced, the initial moisture content of the three varieties of sorghum residue was determined. A temperature sensor was fitted inside the drying chamber with an external digital temperature controller which was used to pre-set the dryer temperature to the desired value. The dryer was operated for 1 hour to attain the desired stable drying temperature [15,16]. After the dryer had reached steady state conditions, the sorghum residue was uniformly spread in a stainless plate on the stainless steel trays (which measure 54 × 52 cm each) of the dryer and the variation in the weight of the sample was monitored at 30 minutes interval [15,16,17], until final moisture content was attained. During the experiment, important parameters affecting the dryer performance such as air temperature, relative humidity, pressure, moisture content, and air velocity, ambient temperature and the inlet and outlet temperatures of drying air in the dryer chamber was measured and recorded. A thermometer was used to measure the drying air temperature. The relative humidity and temperature of the ambient air was measured with a hygrometer and thermometer respectively. The velocity of the drying air was measured with an anemometer at the outlet of the dryer. All this data was recorded at 1-h interval. Moisture loss was recorded at 30 minutes interval during the drying period for determination of the drying curves by a digital weighing balance. The drying experiments was carried out at 40, 50, 60, and 70°C drying air temperatures and 0.8, 1.0 and 1.2 m/s drying air velocity.

### 2.2 Methods

#### 2.2.1 Moisture content determination

The moisture content of the sample during drying was determined using equation 1 and 2 for wet and dry basis respectively.

$$M_w = \frac{W_w - W_d}{W_w} \times 100 \quad (1)$$

$$M_d = \frac{W_w - W_d}{W_d} \times 100 \quad (2)$$

Where  $M_d$  is the moisture content of the sample on dry basis (%),  $M_w$  is the moisture content of the sample on wet basis (%), while  $W_w$  is the weight of wet sample (g) and  $W_d$  is the weight of dry sample (g).

## 2.2.2 Energy utilization

For the energy analyses of the drying process, the following equations are generally employed to compute mass conservation of the drying air and moisture, the energy conservation of the process, as shown in equation 3 to 5.

According to the general equation of mass conservation of drying air [18]:

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} \quad (3)$$

Where  $\dot{m}_{ai}$  is the mass flow rate of the inlet air,  $\dot{m}_{ao}$  is the mass flow rate of the outlet air.

The general equation of mass conservation of moisture is shown in equation 4:

$$\sum(\dot{m}_{ai}w_i + \dot{m}_{mp}) = \sum \dot{m}_{ai}w_o \quad (4)$$

$w_i$  is the inflow specific humidity,  $M_p$  is the moisture of the product,  $w_o$  is the outlet specific humidity

The general equation of energy conservation is shown in equation 5:

$$\dot{Q} - \dot{W} = \sum \dot{m}_o \left( h_o + \frac{V_o^2}{2} \right) - \sum \dot{m}_i \left( h_i + \frac{V_i^2}{2} \right) \quad (5)$$

Where  $\dot{Q}$  is the net heat,  $\dot{W}$  is the energy utilization,  $h_o$  is the outlet enthalpy,  $V_o$  is the outlet velocity,  $h_i$  is the inlet flow enthalpy and  $V_i$  is the inlet velocity.

## 2.2.3 Energy consumption

The dryer energy consumption and the specific energy consumption required for drying a kilogram of sorghum residue was calculated using equations 6 and 8. [19,20,17].

$$E_t = Av\rho_a C_a \Delta T t \quad (6)$$

Where  $E_t$  is the total energy consumption in each drying bout,  $A$  is the cross sectional area of the stainless tray the sample is placed,  $v$  is the air velocity,  $\rho_a$  is the air density,  $t$  is the total drying time,  $\Delta T$  is the temperature difference while  $C_a$  is the specific heat capacity.

The air density was calculated using equations 7:

$$\rho_a = \frac{101.325}{0.287T} \quad (7)$$

$$S_{EC} = \frac{E_t}{M_w} \quad (8)$$

$S_{EC}$  is the specific energy consumption,  $M_w$  is the weight of loss water.

## 2.2.4 Thermal efficiency

Equation 9 was used to determine the thermal utilization efficiency.

$$TE = \frac{D.A.h_{fg}(M_i - M_f)}{t.(100 - M_f)} \quad (9)$$

Where  $D$  is the weight density,  $h_{fg}$  is the latent heat of vaporization,  $M_i$  and  $M_f$  are the initial and final moisture content respectively

The latent heat of vaporization is a function of the drying air temperature as stated by [16] is given as:

$$h_{fg} = 2.503 \times 10^6 - 2.386 \times 10^3(T - 273.16273.16 \leq T^\circ K \leq 338.72)$$

$$h_{fg} = (7.33 \times 10^{12} - 1.60 \times 10^7 T^2)^{0.5} 338.72 \leq T (\text{°K}) \leq 533.16 \quad (10)$$

## 2.2.5 Energy efficiency

$$\eta_{en} = \frac{Q_w}{E_t} \quad (11)$$

Where  $\eta_{en}$  is the energy efficiency and  $Q_w$  is the energy for the moisture evaporation.

The energy for the moisture evaporation was obtained using equation 12 as stated by [17]:

$$Q_w = h_{fg}.M_w \quad (12)$$

## 2.2.6 Drying efficiency

Drying efficiency is defined as the ratio of energy utilized to heating the product (sample) for moisture evaporation, to the total energy consumption.

$$DE = \frac{Q_w + Q_m}{E_t} \quad (13)$$

Where  $Q_m$  is the energy for heating the material.

The energy for heating the material was obtained using equation 14:

$$Q_m = W_d C_m (T_{m2} - T_{m1}) \quad (14)$$

Where  $W_d$  is the weight of dry material,  $C_m$  is the material specific heat while  $T_{m1}$

and  $T_{m2}$  are the inlet and outlet material temperature.

The specific heat of materials are dependent on the moisture content [17], therefore the specific heat of the material will be obtained using equation 15;

$$C_m = 1465.0 + 3560.0 \left( \frac{M_d}{1 + M_d} \right) \quad (15)$$

## 2.3 Data Analysis

The obtained data were graphically presented using the 3D surface plot while the relationship between the independent variable was established using multivariable regression analysis and analysis of variance (ANOVA) on design expert software version 11.

## 3. RESULTS AND DISCUSSION

The required data were obtained using the derived equations from the energy analysis and presented in figures and tables.

### 3.1 Specific Energy Consumption (SEC)

The specific energy consumed during convective hot air drying of three different sorghum residue varieties using different drying temperature and air velocity are presented in Fig. 1. The specific energy consumption for *Caudatum*, *Durra*, *Guineense* varieties ranges from 169530.001 J/kg - 71433.758 J/g, 170557.25 J/kg - 76732.96 J/kg and 179367.266 J/kg - 83750.923 J/kg respectively. Similar result (85.40 and 260.11 kWh/kg) amounts of SEC was recorded for quince fruit by Motevali and Tabatabaei [21] have achieved similar results in examining the drying process for dog-rose in a HA dryer. For drying apples in a HA dryer, Majdi, et al. [4] obtained an SEC amount between 5.5 and 8.9 kWh/kg. However, for all the selected varieties of sorghum, the maximum value of the specific energy consumption was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s, while, the minimum value of specific energy consumption was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s. equation 16 – 18 shows the multiple linear regression model of the specific energy consumption as a function of the different drying condition (air temperature and velocity) for different variety of sorghum; *Caudatum*, *Durra* and, *Guineense* respectively, the equation shows that the variation in the air temperature and

velocity depends on the selected parameter with high coefficient of determination ( $R^2$ ) 0.9768. Also, the analysis of variance of the specific energy consumption during the drying process is presented in Table 1, according to the table, the combination of the temperature and the air velocity can significantly explain the variation in the time taken to dry the material with high probability value less than 0.05.

$$SEC_{Cd} = 6.96 \times 10^5 + 1528.74T - 1.33 \times 10^6V - 793.66TV - 15.25T^2 + 7.41 \times 10^5V^2 \quad (16)$$

$$SEC_{Dr} = 6.40 \times 10^5 + 2374.95T - 1.31 \times 10^6V - 793.66TV - 15.25T^2 + 7.41 \times 10^5V^2 \quad (17)$$

$$SEC_{Gn} = 6.43 \times 10^5 + 1967.66T - 1.30 \times 10^6V - 793.66TV - 15.25T^2 + 7.41 \times 10^5V^2 \quad (18)$$

Where  $SEC$  is the specific energy consumption,  $V$  is the air velocity (m/s),  $T$  is the drying temperature (°C),  $Cd$  is *Caudatum* variety,  $Dr$  is the *Durra* variety and  $Gn$  is the *Guineense* variety.

#### 3.1.1 Effect of temperature

As the temperature of the input air increased, the specific energy consumption increased due to the significant increase in the drying rate at higher levels of input air temperature. In other words, the thermal power applied increases with increasing the temperature of the input air, according but due to the reduction in the drying time, thermal energy required to remove the unit of moisture from the product decreased [17]. Motevali and Tabatabaei [21] have achieved similar results in examining the drying process for dog-rose in a hot air dryer. For drying of apples in a hot air dryer, Majdi, et al. [4] obtained a specific energy consumption amount between 5.5 and 8.9 kWh. However, the increase in the air temperature of the drying chamber with 1°C significantly ( $P < 0.05$ ) increases the specific energy consumption by 1528.74 J/kg, 2373.95 J/kg, and 1967.66 J/kg, for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

#### 3.1.2 Effect of air velocity

The drying process of the sample under different test conditions shows that increase in air velocity in the drying system reduces specific energy consumption of the sample. This form of result might be due to the fact that the increase in air velocity was expected to increase the moisture migration in the system and the uniformity of the

air distribution, but the drying of the sample might face high resistance to exit the moisture when the air velocity is too high, the equilibrium moisture will be relatively higher, although, the air velocity that retard the effectiveness of the drying process are product dependent [22,14], also the low moisture level of the sample might be another reason for this observation a reasonable percentage of moisture in the

material has removed during the starch extraction process. However, the increase in the air velocity of the drying chamber with 1 m/s significantly ( $P < 0.05$ ) reduces the specific energy consumption by  $1.33 \times 10^6$  J/kg,  $1.31 \times 10^6$  J/kg and  $1.30 \times 10^6$  J/kg, for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

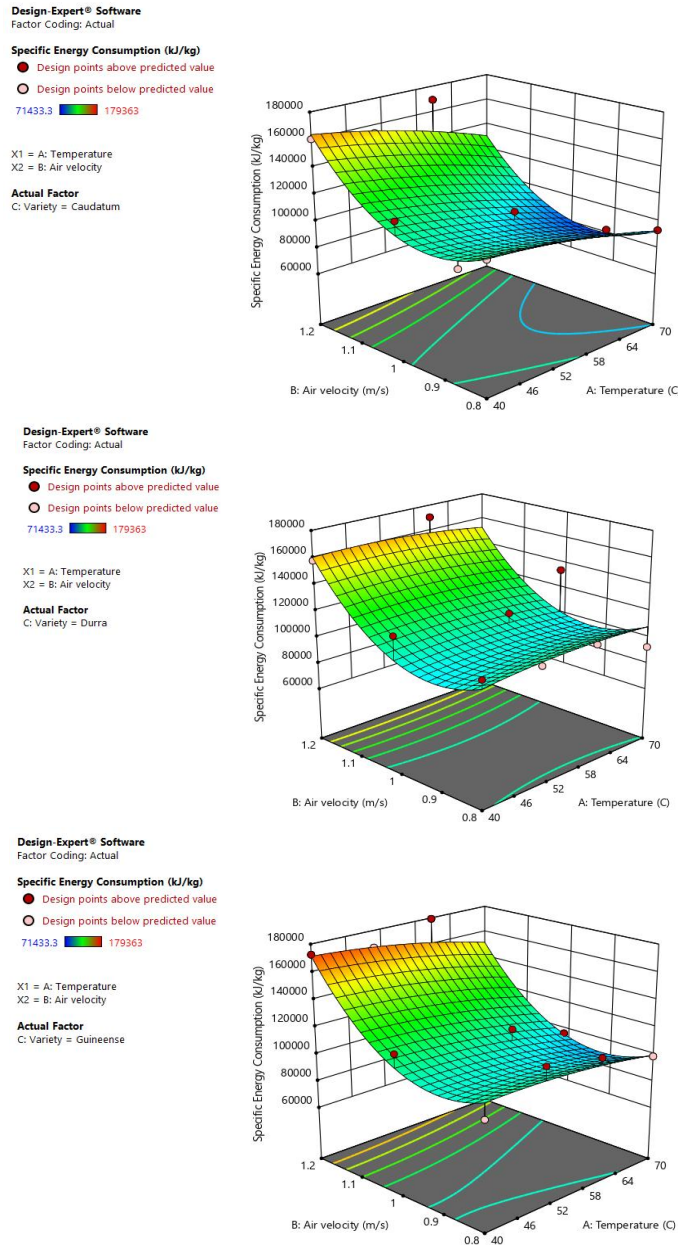


Fig. 1. The effect of air velocity (m/s) and temperature (°C) on the specific energy consumption (kJ/kg) during the drying process

**Table 1. Analysis of variance for specific energy consumption**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
<b>Model</b>	2.415E+10	11	2.195E+09	7.81	< 0.0001	significant
A-Temperature	1.189E+09	1	1.189E+09	4.23	0.0508	
B-Air velocity	1.470E+10	1	1.470E+10	52.29	< 0.0001	
C-Variety	3.362E+08	2	1.681E+08	0.5978	0.5580	
AB	7.559E+07	1	7.559E+07	0.2688	0.6089	
AC	5.373E+08	2	2.686E+08	0.9554	0.3988	
BC	2.006E+08	2	1.003E+08	0.3567	0.7036	
A <sup>2</sup>	8.373E+07	1	8.373E+07	0.2978	0.5903	
B <sup>2</sup>	7.021E+09	1	7.021E+09	24.97	< 0.0001	
<b>Residual</b>	6.749E+09	24	2.812E+08			
<b>Cor Total</b>	3.090E+10	35				

### 3.2 Energy Efficiency

The graphical representation of the energy efficiency under different dryer temperature and air velocity for three different varieties of sorghum residue was shown in Fig. 2. The energy efficiency for *Caudatum* variety ranges from 35.5% - 13.934%, the maximum value of energy efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of energy efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. For *Durra* variety, the energy efficiency ranges from 31.188% - 13.836%. the maximum value of energy efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of energy efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. for *Guineense* variety, the energy efficiency ranges from 28.463% - 13.157%, the maximum value of energy efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of energy efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. The multivariate mathematical model for predicting the energy efficiency as function of air temperature and air velocity was shown in Equation 19 -21, the equation shows that the variation in the energy efficiency of the drying process depends on the selected parameters (air temperature and velocity) with high coefficient of determination ( $R^2$ ) of 0.6633. Also, Table 2 presents the analysis of variance of the energy efficiency during the drying process, according to the table, the combination of the temperature, air velocity and varieties can significantly explain the

variation in the time taken to dry the material with high probability value less than 0.05.

$$EE_{Cd} = -92.32 \times 10^5 - 0.536T + 264.94 \times 10^5V - 0.1TV + 0.008T^2 - 137.68 \times 10^5V^2 \quad (19)$$

$$EE_{Dr} = -80.35 \times 10^5 - 0.727T + 261.89 \times 10^5V - 0.1TV + 0.008T^2 - 137.68 \times 10^5V^2 \quad (20)$$

$$EE_{Gn} = -82.60 \times 10^5 - 0.666T + 260.82 \times 10^5V - 0.1TV + 0.008T^2 - 137.68 \times 10^5V^2 \quad (21)$$

Where  $EE$  is the energy efficiency,  $V$  is the air velocity (m/s),  $T$  is the drying temperature (°C),  $Cd$  is *Caudatum* variety,  $Dr$  is the *Durra* variety and  $Gn$  is the *Guineense* variety.

#### 3.2.1 Effect of temperature

The results show that the energy efficiency reduces by increasing the temperature of the dryer chamber from 40 to 70 °C. According to the results, the energy efficiency decreases with increase in the temperature of hot air in the dryer because increasing the temperature of the dryer chamber increases energy supplied to the system which is apparently higher than the specific amount of energy required to remove specific amount of moisture from the product [23]. Also, it was deduced from the result of Aviara et al. [24] energy efficiency reduced by increasing air temperature in tray dryer during the native cassava starch. However, the increase in the air temperature of the drying chamber with 10°C significantly ( $P < 0.05$ ) reduces the energy efficiency by 5.36%, 7.27% and 6.66% for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively

#### 3.2.2 Effect of air velocity

The results show that the energy efficiency increases by increasing airspeed. Besides, increasing air velocity increases the removal of

moisture from the surface of solid material, which in turn would lead to an increase in the EUR in the hot air dryer wall [25]. Yogendrasasidhar and Setty [25] have studied on energy and exergy analysis of kodo millet grains and fenugreek seeds in fluidized bed dryer and showed that energy utilization efficiency increased with increase air temperature from 40 to 60°C and

airspeed from 1.01 to 1.7 m/s. However, a unit increase in the air velocity of the drying chamber significantly ( $P < 0.05$ ) increase the energy efficiency by  $2.64 \times 10^7$ ,  $2.61 \times 10^7$  and  $2.60 \times 10^7$  J/kg, for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

Design-Expert® Software

Factor Coding: Actual

Energy Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

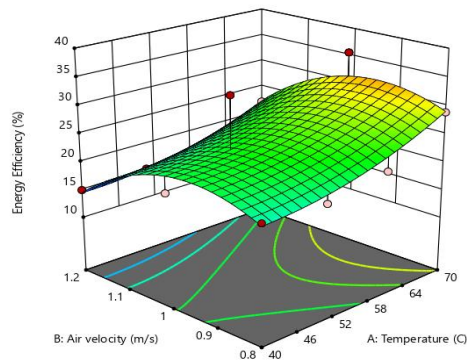
13.1569 35.4996

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Caudatum



Design-Expert® Software

Factor Coding: Actual

Energy Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

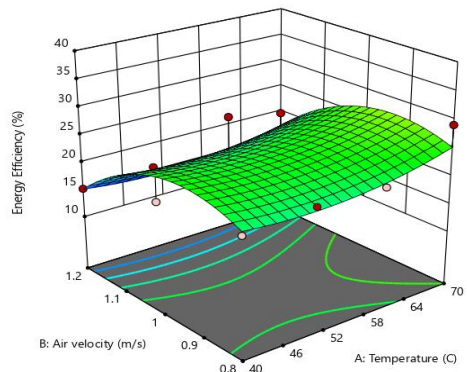
13.1569 35.4996

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Durra



Design-Expert® Software

Factor Coding: Actual

Energy Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

13.1569 35.4996

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Guineense

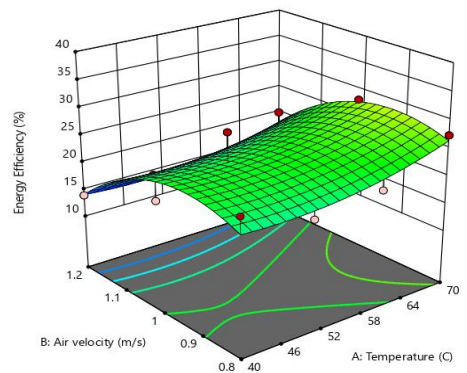


Fig. 2. The effect of air velocity (m/s) and temperature (°C) on the energy efficiency (%)



**Table 2. Analysis of variance for energy efficiency**

Source	Sum of Squares	Df	Mean Square	F-value	p-value	
Model	763.77	11	69.43	4.30	0.0014	significant
A-Temperature	129.72	1	129.72	8.03	0.0092	
B-Air velocity	314.56	1	314.56	19.47	0.0002	
C-Variety	19.61	2	9.81	0.6070	0.5531	
AB	1.11	1	1.11	0.0685	0.7958	
AC	28.61	2	14.31	0.8856	0.4255	
BC	2.92	2	1.46	0.0903	0.9140	
A <sup>2</sup>	24.59	1	24.59	1.52	0.2293	
B <sup>2</sup>	242.65	1	242.65	15.02	0.0007	
Residual	387.75	24	16.16			
Cor Total	1151.52	35				

### 3.3 Drying Efficiency

Fig. 3 shows the graphical representation of the drying efficiency under different dryer temperature and air velocity for three different varieties of sorghum residue, the drying efficiency for Caudatum variety ranges from 46.179% - 18.192%, the maximum value of drying efficiency was observed when the drying system was operated at temperature of 70°C and air velocity of 1m/s, while, the minimum value of drying efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. For Durra variety, the drying efficiency ranges from 41.164% - 17.804%. The maximum value of drying efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of drying efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. The drying efficiency for Guineense variety ranges from 37.774% - 17.625%. the maximum value of drying efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of drying efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. Equation 22-24 shows the multivariate mathematical model for predicting the drying efficiency as function of air temperature and air velocity as shown, the equation shows that the variation in the drying efficiency of the drying process depends on the selected parameters (air temperature and velocity) with high coefficient of determination ( $R^2$ ) Of 0.6955. Also, Table 3 presents the analysis of variance of the drying efficiency of the drying process, according to the table, the combination of the temperature, air velocity and varieties can significantly explain the variation in

the time taken to dry the material with high probability value less than 0.05.

$$DE_{cd} = -151.59 \times 10^5 + 0.58T + 404.90 \times 10^5V - 0.12TV + 0.009T^2 - 209.19 \times 10^5V^2 \quad (22)$$

$$DE_{Dr} = -139.03 \times 10^5 + 0.78T + 401.49 \times 10^5V - 0.12TV + 0.009T^2 - 209.19 \times 10^5V^2 \quad (23)$$

$$DE_{Gn} = -141.41 \times 10^5 + 0.72T + 400.93 \times 10^5V - 0.12TV + 0.009T^2 - 209.19 \times 10^5V^2 \quad (24)$$

Where  $DE$  is the drying efficiency,  $V$  is the air velocity (m/s),  $T$  is the drying temperature (°C),  $Cd$  is *Caudatum* variety,  $Dr$  is the *Durra* variety and  $Gn$  is the *Guineense* variety.

#### 3.3.1 Effect of temperature

The results show that the drying efficiency increases by increasing the temperature of the dryer chamber from 40 to 70°C. According to the results, the drying efficiency increases with increase in the temperature of hot air in the dryer because increasing the temperature of the dryer chamber increases energy supplied to the system which therefore increases the specific amount of moisture removed from the product [23]. Also, it was deduced from the result of Aviara et al. [2] drying efficiency increases by increasing air temperature in tray dryer during the native cassava starch. However, the increase in the air temperature of the drying chamber with 10 °C significantly ( $P < 0.05$ ) increases the drying efficiency by 5.8%, 7.8% and 7.2% for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

#### 3.3.2 Effect of air velocity

The results show that the drying efficiency increases by increasing the air velocity. Besides, increasing air velocity increases the removal of

moisture from the surface of solid material, which in turn would lead to an increase in the energy utilization [25]. Yogendrasasidhar and Setty [25] have studied on energy and exergy analysis of kodo millet grains and fenugreek seeds in fluidized bed dryer and showed that drying efficiency increased with increase air velocity

from 1.01 to 1.7 m/s. However, a unit increase in the air velocity of the drying chamber significantly ( $P < 0.05$ ) increase the energy efficiency by  $4.04 \times 10^7$ ,  $4.01 \times 10^7$  and  $4.00 \times 10^7$  J/kg, for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

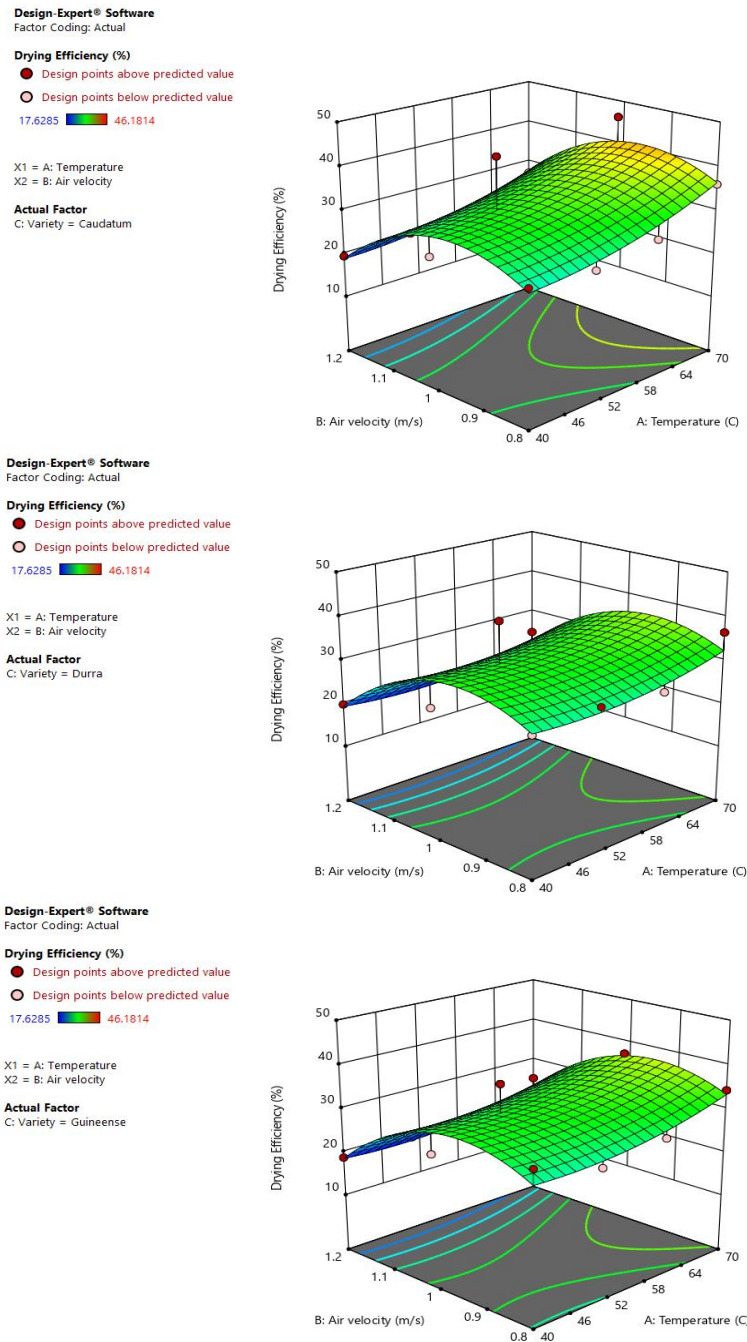


Fig. 3. The effect of air velocity (m/s) and temperature (°C) on the drying efficiency (%)

**Table 3. Analysis of variance for drying efficiency**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1325.20	11	120.47	4.98	0.0005	significant
A-Temperature	186.71	1	186.71	7.72	0.0104	
B-Air velocity	486.15	1	486.15	20.11	0.0002	
C-Variety	24.85	2	12.43	0.5139	0.6046	
AB	1.70	1	1.70	0.0705	0.7929	
AC	31.86	2	15.93	0.6588	0.5266	
BC	2.95	2	1.47	0.0610	0.9410	
A <sup>2</sup>	30.82	1	30.82	1.27	0.2701	
B <sup>2</sup>	560.16	1	560.16	23.17	< 0.0001	
Residual	580.31	24	24.18			
Cor Total	1905.51	35				

### 3.4 Thermal Efficiency

Fig. 4 shows the graphical representation of the thermal efficiency under different dryer temperature and air velocity for three different varieties of sorghum residue. For *Caudatum* variety, the thermal efficiency ranges from 10.922% - 5.087% and the maximum value of thermal efficiency was observed when the drying system was operated at temperature of 70 °C and air velocity of 1 m/s, while, the minimum value of thermal efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 0.8 m/s. For *Durra* variety the thermal efficiency ranges from 12.517% - 5.034% and the maximum value of thermal efficiency was observed when the drying system was operated at temperature of 70 °C and air velocity of 1m/s, while, the minimum value of thermal efficiency was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s. For *Guineense* variety, the thermal efficiency ranges from 9.367% - 4.248%. The maximum value of thermal efficiency was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s, while, the minimum value of thermal efficiency was observed when the drying system was operated at temperature of 40 °C and air velocity of 0.8 m/s. Equation 25 -27 shows the mathematical model for predicting the thermal efficiency as function of air temperature and air velocity, the equation shows that the variation in the thermal efficiency of the drying process depends on the selected parameters (air temperature and velocity) with high coefficient of determination ( $R^2$ ) of 0.6750. Also, Table 4 presents the analysis of variance of the thermal efficiency during the drying process, according to the table, the combination of the temperature, air velocity and varieties can significantly explain the variation in the time taken to dry the material with high probability value less than 0.05.

$$TE_{Cd} = -56.97 \times 10^5 - 0.279T + 141.46 \times 10^5V - 0.04TV + 0.003T^2 - 69.01 \times 10^5V^2 \quad (25)$$

$$TE_{Dr} = -56.35 \times 10^5 - 0.276T + 140.61 \times 10^5V - 0.04TV + 0.003T^2 - 69.01 \times 10^5V^2 \quad (26)$$

$$TE_{Gn} = -57.24 \times 10^5 - 0.289T + 141.71 \times 10^5V - 0.04TV + 0.003T^2 - 69.01 \times 10^5V^2 \quad (27)$$

Where  $TE$  is the thermal efficiency,  $V$  is the air velocity (m/s),  $T$  is the drying temperature (°C),  $Cd$  is *Caudatum* variety,  $Dr$  is the *Durra* variety and  $Gn$  is the *Guineense* variety.

#### 3.4.1 Effect of air temperature

As deduced from equation 25 – 27, shows that the thermal energy efficiency during the drying process increases with decrease in the air temperature of the drying system, this observation might be due to the fact that the thermal energy required to dry the residue is lower than the thermal energy supplied to the drying system with the increase in the input air temperature. These results are similar to those obtained by Azadbakht et al. [26] for drying a thin layer of potatoes in a fluidized bed dryer, and Aghbashlo, Kianmehr, and Arabhosseini [19] “b”, for drying potatoes in a semi-industrial continuous dryer. However, the increase in the air temperature of the drying chamber with 1 °C significantly ( $P < 0.05$ ) increases the specific energy consumption by 2.79%, 2.76% and 2.89% for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

#### 3.4.2 Effect of air velocity

The thermal efficiency of the process increases with increase in the velocity of air that enters the drying chamber. Since, the quantity of energy consumed depends on the velocity of the input air, the hidden heat of water vapor, and the

specific heat and the output air temperature, the air mass flow, therefore, the enthalpy volume of the input air will increase by increasing air velocity. These results are consistent with the results of Nazghelichi et al. [27] regarding drying carrots in the fluidized bed dryer. According to equation 25– 27, the increase in the air velocity

of the drying chamber with 0.1 m/s significantly ( $P < 0.05$ ) reduces the specific energy consumption by  $14.15 \times 10^6\%$ ,  $14.06 \times 10^6\%$  and  $14.17 \times 10^6\%$  for different variety of sorghum residue: *Caudatum*, *Durra* and *Guineense* variety respectively.

Design-Expert® Software  
Factor Coding: Actual

Thermal Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

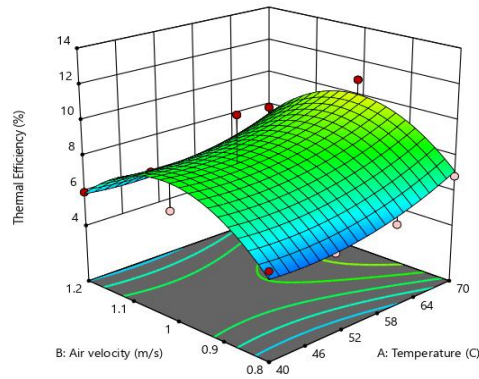
4.11692 12.3368

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Caudatum



Design-Expert® Software  
Factor Coding: Actual

Thermal Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

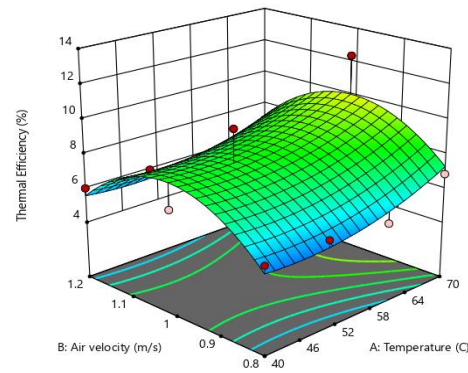
4.11692 12.3368

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Durra



Design-Expert® Software  
Factor Coding: Actual

Thermal Efficiency (%)

● Design points above predicted value

○ Design points below predicted value

4.11692 12.3368

X1 = A: Temperature

X2 = B: Air velocity

Actual Factor

C: Variety = Guineense

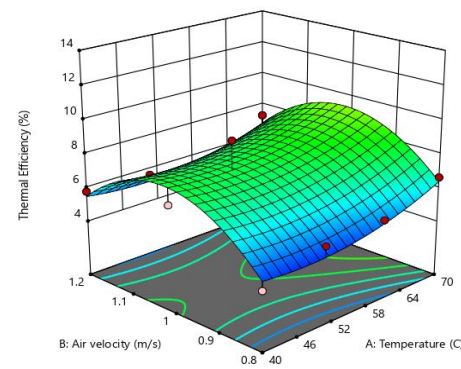


Fig. 4. The effect of air velocity (m/s) and air temperature (°C) on the thermal efficiency (%)

**Table 4. The analysis of variance for the thermal efficiency**

Source	Sum of Squares	df	Mean Square	F-value	p-value	
<b>Model</b>	84.33	11	7.67	4.53	0.0010	significant
A-Temperature	15.17	1	15.17	8.97	0.0063	
B-Air velocity	1.15	1	1.15	0.6802	0.4176	
C-Variety	2.24	2	1.12	0.6633	0.5243	
AB	0.1822	1	0.1822	0.1077	0.7456	
AC	0.1364	2	0.0682	0.0403	0.9605	
BC	0.2099	2	0.1050	0.0620	0.9400	
A <sup>2</sup>	4.27	1	4.27	2.53	0.1251	
B <sup>2</sup>	60.96	1	60.96	36.04	< 0.0001	
<b>Residual</b>	40.60	24	1.69			
<b>Cor Total</b>	124.93	35				

#### 4. CONCLUSION

From the study, the specific energy consumed during convective hot air drying of three different sorghum residue varieties *Caudatum*, *Durra*, *Guineense* ranges from 169530.001 J/kg - 71433.758 J/kg, 170557.25 J/kg - 76732.96 J/kg and 179367.266 J/kg - 83750.923 J/kg respectively. However, for all the selected varieties of sorghum, the maximum value of the specific energy consumption was observed when the drying system was operated at temperature of 60°C and air velocity of 1.2 m/s, while, the minimum value of specific energy consumption was observed when the drying system was operated at temperature of 50°C and air velocity of 1 m/s. The convective drying process is very energy intensive and drying fresh agricultural produce with heated-air dryers requires a relatively large amount of energy.

#### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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