**Performance Evaluation of a Hybrid Dryer for Grains**

**ABSTRACT**

The study evaluated a hybrid grain dryer prototype at Ahmadu Bello University, Zaria, Nigeria, in May 2019, focusing on air flow rate (3.6, 4.5, 6.1 m³/s) and grain depth (5, 10, 20 cm) as key factors. A 3×3 factorial experiment in a randomized design assessed the dryer's performance using maize. Metrics included collection, drying system, fuel, sensible heat utilization, and pick-up efficiencies. Data were analyzed using Statistical Analysis Software (SAS 9.0), with Analysis of Variance (ANOVA) and Duncan Multiple Range Test (DMRT) at 1% and 5% significance levels. Results showed collection efficiencies of 19.8%, 15.2%, and 11.2% at 6.1, 4.5, and 3.6 m³/s, respectively; fuel efficiencies were 25.5%, 23.9%, and 23.6%; and sensible heat utilization efficiencies were 68%, 65.6%, and 55.9%. Drying efficiencies were 65.5%, 50.3%, and 45.4% at 5, 10, and 20 cm grain depths, respectively. Pick-up efficiency increased from 1.5 to 1.7 with higher air flow rates but remained constant (1.6) across grain depths. Graphs illustrated drying characteristics, showing relationships between grain depth, air flow rate, moisture content, and time. The study demonstrated the hybrid dryer's performance under varying conditions, providing insights for optimizing grain drying processes.

***Keywords***: *Air flowrate, depth, dryer, efficiency, grain, hybrid, maize, moisture content.*

**1. INTRODUCTION**

Drying is the controlled application of heat to remove water from products through evaporation or, in freeze drying, sublimation (Fellow, 2000). It is a critical process in agricultural industries, significantly impacting product preservation and quality. Moisture removal is achieved through two primary methods: drying (dehydration) to produce solid products and evaporation to eliminate liquids (Wilhelm et al., 2004). The primary goal of drying is to reduce water activity, thereby inhibiting microbial growth and enzyme activity. However, since drying temperatures typically do not inactivate these factors, any moisture increase during storage—such as from faulty packaging—can lead to spoilage (Fellow, 2000). The optimal moisture level for preventing spoilage varies by crop due to differences in bioactive compound responses and inactivation mechanisms (Chen and Patel, 2008).

As a vital post-harvest process, drying enhances product quality, reduces losses, and lowers transportation costs by removing most of the water content. Successful drying requires sufficient heat to extract moisture without cooking the product and adequate dry air to carry away the released moisture. Improper drying conditions, such as low initial temperatures, can promote microbial growth, while excessive heat and low humidity may cause surface hardening, hindering moisture escape and leading to improper drying (Sanni et al., 2012).

Energy costs are a major factor in selecting drying methods and determining operational profitability. Various energy sources—electricity, gas (natural and liquid petroleum), solar energy, liquid fuel oil, and solid fuels (coal, wood, charcoal)—offer distinct advantages and limitations in terms of cost, safety, contamination risk, flexibility, and equipment requirements (Fellow, 2000). Key factors influencing drying efficiency include air temperature, air velocity, relative humidity, drying bed thickness, product moisture content, and surface area. These factors vary depending on the drying system used but are critical for optimizing the drying process.

**2. MATERIAL AND METHODS**

**2.1 Materials**

The dryer was successfully constructed and the following instruments were employed in taking measurements. They include Digital weighing balance (Baykon BX21) with a sensitivity of 0.02kg, Digital air flow meter (Fluke flow meter 922) with a sensitivity of 0.001, Handheld wind vane (CUP Anemometer: AM-4220) with a sensitivity of 0.9-35m/s, Digital temperature and humidity meter (Smart Sensor) with a sensitivity of 1℃, ±3%, Digital Grain Moisture Probe with a sensitivity of ±5%, and a Techno stopwatch. Statistical analysis was done using SAS Version 9.0.

**2.2 Description of the Dryer**

The hybrid dryer consists of an axial fan, solar collector, heating chamber, air duct, drying tray, drying chamber, and frame. The axial fan drives ambient air into the solar collector/heating chamber, and the heated air is dispersed more effectively through the air duct. The product to be dried is placed on a drying tray within the drying chamber. Visual views of the dryer are shown in Figure 1a, while Figure 1b-1e depict the dryer's component elements.

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**Fig. 1a: Pictorial view of the Hybrid dryer for Grain**

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**Fig 1b: Axial fan and air duct**



**Fig 1c: Solar collector**



**Fig 1d: Drying tray**



**Fig 1e: Heating Chamber**

**2.3 Experimental Procedure**

To evaluate the performance of the hybrid dryer, two factors that affect drying were considered. They include Air flow rate and drying depth. A 3×3 factors experiment in a complete randomised design was used to evaluate the effects of the factors on the hybrid dryer performance. Three levels of air flow rate (V1=3.6$m^{3}$/s, V2=4.5$m^{3}$/s, V3= 6.1$m^{3}$/s) and three levels grain depth (B1=5cm, B2=10cm, B3=20cm) were used. The experiment units were repeated three times. Data collected were analysed using Statistical Analysis Software (SAS version 9.0) and Mean separation was done for the significant factors using Duncan Multiple Range Test (DMRT). The effects of the variation of each of the independent factor and their interactions on the performance of the hybrid dryer were verified at 5 and 1 % probability levels using the analysis of variance (ANOVA).

**2.4 Performance Indicator**

The following performance indicators were used during the evaluation:

1. *Sensible Heat Utilization Efficiency (SHUE):* This is the ratio of heat utilized for moisture removal to total sensible heat in the drying air; it is given in equation 1 by: (FAO, 1994).

 $\left(SHUE\right)=\frac{Heat Utilized for Moisture Removal}{Total Sensible Heat in the Drying Air}$ (1)

1. *Fuel Efficiency:* The fuel efficiency is based only on the heat available from the fuel it is given in equation 2: (FAO, 1994).

$ E\_{f}=\frac{Heat Utilized for Moisture Removal}{Heat Supplied from Fuel}$ (2)

1. *Drying System Efficiency (*$η\_{d})$*:* This is the ratio of the energy required to evaporate the moisture to the energy supplied to the dryer. It is the measure of the overall effectiveness of a drying system as given by FAO, 1994 in equation 3.

$η\_{d}=\frac{M\_{w}h\_{fg}}{IA\_{c}t}$ (3)

Where:

$M\_{w}=$ Mass of moisture evaporated

$h\_{fg}= $Latent heat of vaporization of water at dryer temperature (kJ/kg)

$A\_{c}= $ Collector surface area ($m^{2})$

$I$ =Insolation on collector surface (W/$m^{2})$

$t$ =Time taken to evaporate the moisture (s)

1. *Collection Efficiency (*$η\_{c}$*):* It is a measure of how effectively the isolation energy is transferred to the air flowing through the collector as given by FAO, 1995 in equation 4.

 $ η\_{c}=\frac{Vρ∆TC\_{p}}{IA\_{c}}$ (4)

Where:

$V = $Volumetric air flow rate, $m^{3}/s$

$ρ= $Air density, kg/$m^{3}$

$∆T$ =Air temperature difference between collector outlet and inlet.

1. *Pick-up Efficiency:* It is the ratio of the moisture picked up by the air in the drying chamber to the theoretical capacity of the air to absorb moisture as given by FAO, 1995 in equation 5

$η\_{c}=\frac{H\_{o}-H\_{i}}{H\_{as}-H\_{i}}$ (5)

Where:

$H\_{o}$= absolute humidity of air leaving drying chamber

$H\_{i}$= absolute humidity of air entering drying chamber

$H\_{as}$= adiabatic saturation humidity of air entering the dryer

**3. RESULTS AND DISCUSSION**

**3.1 Effect of air flow rate and Grain depth on Dryer Collection Efficiency**

Table 1 reveals that the collector efficiency reached 19.8% at an air velocity of 6.1 m³/s, which is notably higher compared to the efficiencies of 15.2% and 11.2% observed at 4.5 m³/s and 3.6 m³/s, respectively. The data indicate a clear trend: higher air flow rates lead to increased collection efficiency. Specifically, the maximum efficiency of 19.8% was achieved at 6.1 m³/s, while the efficiency dropped to 11.2% at the lowest air flow rate of 3.6 m³/s. These findings align with FAO (1995), which states that collection efficiency rises with increasing air flow rates.

**Table 1: Mean Ranking for effect of air flow rate and Grain depth for Collection Efficiency**

|  |
| --- |
| Mean Collection Efficiency (%) |
| Treatments | Collection Efficiency |
| Air flow rate (V) (m3/sec) |  |
| 3.6 | 11.2c |
| 4.5 | 15.2b |
| 6.1 | 19.8a |
| SE+ | 0.497 |

S=Not significant. Mean followed by same letter(s) on the same column are not different statistically at *P=0.05* using DMRT.

**3.2 Effect of Grain depth on Drying System Efficiency**

Drying system efficiency of 66.5% was recorded, when the grain depth of 5cm was used as shown in table 2, also an efficiency of 50.3% and 45.4% was achieved when grain depth of 10 and 20cm were. The effect of grain depth is more noticeable at 5cm grain depth. This can be attributed to the fact that the smaller the grain depth the more surface area will be exposed to the drying air and the less pressure force needed for internal diffusion of products moisture. The result is in line with the findings of Isiaka (2009) and Abdullahi (2003) who reported that product with large surface area compared to their volume loose moisture more quickly when subject to the same drying conditions. It could be seen from the table that the drying system efficiency for this dryer is high above the required range as given by Brenndorfer et al., (1987) who gave a value of drying system efficiency to be between the ranges of 20-30% for a forced convection dryer. The high efficiency could be as a result of low heat loss in the heating and drying chamber.

**Table 2: Mean Ranking for effect of Grain depth on Drying System Efficiency**

|  |
| --- |
| Mean Drying System Efficiency (%) |
| Treatments | Drying System Efficiency |
| Grain depth (B) (cm) |  |
| 5 | 66.5a |
| 10 | 50.3b |
| 20 | 45.4b |
| SE+ | 2.149 |

NS=Not significant. Mean followed by same letter(s) on the same column are not different statistically at *P=0.05* using DMRT.

**3.3** **Effect of air flow rate and drying depth on fuel Efficiency**

The highest mean fuel efficiency of 25.5% was recorded when 6.1$m^{3}$/s was used, and this is significantly higher when compared to 23.9 and 23.6% fuel efficiencies obtained at 4.5 and 3.6$m^{3}$/s as shown in table 3. It was observed that when there was an increase in air velocity there is also a corresponding increase in the fuel efficiency. The air functions as medium for transferring heat to the drying material for moisture evaporation and to convey evaporated water vapour. This agrees with Isiaka, (2012) who reported that the higher the air flow rate the more of the generated heat is moved to the product and the more of the evaporate moisture is removed. For the grain depth there was a significant difference in the fuel efficiency among the three level of grain depth with maximum fuel efficiency of 29.3% at 20cm which significantly reduces to 19.9% when 5cm was used. This could be as a result of high energy utilization at higher grain depth.

**Table 3: Mean Ranking for effect of air flow rate and drying depth on fuel Efficiency**

|  |
| --- |
| Mean Fuel Efficiency (%) |
| Treatments | Fuel Efficiency |
| Air flow rate (V) (m3/sec) |  |
| 3.6 | 23.6b |
| 4.5 | 23.9b |
| 6.1 | 25.5a |
| SE+ | 0.427 |
| Grain depth (B) (cm) |  |
| 5 | 19.9c |
| 10 | 23.8b |
| 20 | 29.3a |
| SE+ | 0.427 |

\*= Significant at (P<0.05). Mean followed by same letter(s) on the same column are not different statistically at *P=0.05* using DMRT.

**3.4** **Effect of air flow rate and drying depth on Sensible Heat Utilization Efficiency**

From Table 4 the mean sensible heat utilization efficiency of 68.0% was recorded when air flow rate was 6.1$m^{3}$/s and 65.6% when air flow rate 4.5$m^{3}$/s was used and these were significantly higher compared to 55.9% sensible heat utilization efficiency when 3.6$m^{3}$/s air flow rate was used. This implies that sensible heat utilization efficiency increases with an increase in air velocity. For the grain depth, the mean sensible heat utilization efficiency of 73.5% was recorded at 20cm grain depth, which is significantly higher when compared with other values of 63.1 and 53.0% when grain depths of 10 and 5 cm were used, respectively. From the result, heat utilized for moisture removal increases when the drying depth increases.

**Table 4: Mean Ranking for effect of air flow rate and drying depth on Sensible Heat Utilization Efficiency**

|  |
| --- |
| Mean Sensible Heat Utilization Efficiency (%) |
| Treatments | Sensible Heat Utilization Efficiency |
| Air flow rate(V) (m3/sec) |  |
| 3.6 | 55.9b |
| 4.5 | 65.6a |
| 6.1 | 68.0a |
| SE+ | 2.855 |
| Grain depth (B) (cm) |  |
| 5 | 53.0c |
| 10 | 63.1b |
| 20 | 73.5a |
| SE+ | 2.855 |

NS= Not significant Mean followed by same letter(s) on the same column are not different statistically at *P=0.05* using DMRT.

**3.5 Effect of air flow rate and grain depth on Pick up efficiency**

Analysis of Variance (ANOVA) result of pick-up efficiency for hybrid grain dryer indicated that for all grain depth of 5, 10 and 20cm the pick-up efficiency was 1.6 while at air flow rate of and 6.1 and 4.5$m^{3}$/s the efficiency was 1.7 and at 3.5$m^{3}$/s the efficiency was 1.5. From the results the effects of air flow rate, grain depth and their interaction on pick-up efficiency does not significantly affect pick-up efficiency of the hybrid solar dryer for grains. These low efficiency shows that the ability of the heated air to absorb moisture is underutilized. This could be as a result of high air velocity and as such the passing air has limited time lag to fully absorb moisture from the drying material.

**3.6** **Effect of air flow rate and drying depth for drying efficiency**

From Table 5 the highest mean drying efficiency of 32.8% was recorded when air flow rate of 6.1$m^{3}$/s was used. The drying efficiency drops to 29.9% when air flow rate of 4.5$m^{3}$/s was used, this efficiency further drops to 27.7% when the flow rate was 3.6$m^{3}$/s, these efficiencies are numerically different but statistically the same, it can be deduced that increasing air flow rate from 4.5 to 6.1$m^{3}$/s significantly affect drying efficiency, but there is no significant effect when the flow rate is increased from 3.6 to 4.5$m^{3}$/s in thin layer drying of maize. For the drying depth, drying efficiency of 37.3% was recorded at 20cm drying depth, which is significantly higher when compared with respect to other values of 29.8 and 23.2% when grain depths of 10 and 5 cm were used, respectively. From the result, it shows that drying efficiency increases when the drying depth increases, this is because the energy in the drying air is more efficiently utilized, since the time lag for the drying air is increased.

**Table 5: Mean Ranking for effect of air flow rate and drying depth on drying efficiency**

|  |
| --- |
| Mean Drying Efficiency (%) |
| Treatments | Drying Efficiency |
| Air Velocity (V) (m3/sec) |  |
| 3.6 | 27.7b |
| 4.5 | 29.9b |
| 6.1 | 32.8a |
| SE+ | 0.924 |
| Grain Depth (B) (cm) |  |
| 5 | 23.2c |
| 10 | 29.8b |
| 20 | 37.3a |
| SE+ | 0.924 |

NS= Not significant Mean followed by same letter(s) on the same column are not different statistically at *P=0.05* using DMRT.

The drying characteristics of grain, using hybrid grain drying is illustrated in fig. 2a. It was observed that grain depth and air flow rate has significant effect on drying time of grain. From the graph, it shows that at air flow rate of 3.6$m^{3}$/s and grain depth of 5cm, the average drying time recorded was 3.5 hours, the drying time was increased to 4.5 hours when the grain depth was 10cm and at the same air flow rate of 3.6$m^{3}$/s the drying time recorded was 6.0 hours when the grain depth was 20cm.

**Fig. 2a: Effect of drying depth on thin layer drying of maize at air flow rate of 3.6**$m^{3}$**/s**

Figure 2b shows the drying characteristics of grain, using hybrid grain drying, it was observed that grain depth and air flow rate can affect the drying time of grain. From the figure it can be seen that at air flow rate of 4.5$m^{3}$/s and grain depth of 5cm, the average drying time was 3.5 hours, the drying time was increased to 4.0 hours when the grain depth was 10cm and at the same air flow rate of 4.5$m^{3}$/s the drying time recorded was increased to 4.0 hours when the grain depth was 20cm.

**Figure 2b: Effect of drying depth on thin layer drying of maize at air flow rate of 4.5**$m^{3}$**/s**

Figure 2c shows the drying characteristics of grain, using hybrid grain drying, it was observed that grain depth and air flow rate has significant effect on drying time of grain. From the figure it can be seen that at air flow rate of 6.0 $m^{3}$/s and grain depth of 5cm, the average drying time was 2.0 hours, the drying time was increased to 3.0 hours when the grain depth was 10cm and at the same air flow rate of 3.6$m^{3}$/s the drying time was increased to 3.5 hours when the grain depth was 20cm.

**Figure 2c: Effect of drying depth on thin layer drying of maize at air flow rate of 6.1**$m^{3}$**/s**

Fig. 2a, 2b and 2c shows that the rate of drying was high at the initial period, but decreases as the moisture content of the product reduces, it could be said that there was low resistance to moisture evaporation at the early stage of drying but when the moisture content falls to about 16% the drying rate is slow, this implies that the resistance to moisture removal was increased, these means that two drying stages exist. The first is the removal of surface moisture while the second is the removal of internal moisture by diffusion of the internal moisture.

**4. CONCLUSION**

The performance evaluation of the dryer was successfully carried out. The highest drying system efficiency of 65.5 % was obtained at grain depth of 5 cm while air flow rate on drying system efficiency remains insignificant. The highest fuel efficiency of 25.5 % and 29.3 % were obtained at 4.5 m3/s air flow rate and 20 cm grain depth respectively. The highest sensible heat utilization efficiency of 68.0 % and 73.5 % was also obtained at 6.1 m3/s air flow rate and 20 cm grain depth respectively. It is therefore concluded that the dryer gave optimum result.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist.

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