**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**

Agricultural processing involves various operations such as pre-drying, threshing, pre-cleaning, drying, cleaning, sorting, and packaging. These operations are carried out to maintain and enhance the quality of agricultural products, or to alter their form or characteristics. The primary goal of agricultural processing is to minimize any deterioration in the quality and quantity of the material after it has been harvested (Sahay and Singh, 2005). Drying is one of the oldest methods of food preservation known to man (Sobukola et al., 2007). It involves removing water to a safe level to reduce product deterioration, provide microbiological stability, and extend the life of the products (Perumal, 2007). This process substantially reduces weight and volume, minimizes packaging, storage, and transportation costs (Sagar and Suresh, 2010). By reducing the moisture content of food material to between 10-20%, the actions of bacteria, yeast, molds, and enzymes are drastically reduced (Nandi, 2009). Since microorganisms are the primary cause of food spoilage and water (moisture) is essential to their growth, it's important to remove the water to a safe level. Drying preserves and concentrates the flavor and most of the dried product’s nutritional contents (Herringshaw, 1997). Additionally, dried products do not require any special storage facility or equipment and are easy to handle and transport (Scalin, 1997).

In Nigeria, agricultural produce is primarily dried using open-air drying or sun-drying, with limited adoption of mechanical dryers or other techniques. Open-air drying, the oldest, cheapest, and most widespread method, is practiced globally, including in Nigeria. In contrast, mechanized drying is predominantly utilized in industrialized sectors, employing boilers to heat incoming air and fans to circulate it rapidly (Ajay et al., 2009). Ajay et al. (2009) noted that while solar dryers have been known for a long time, their widespread use is limited due to their reliance on weather conditions. During the rainy season, local farmers face significant challenges in drying their harvest. Early grains, such as corn harvested during the rainy season, and late irrigated maize harvested at its onset, pose a major risk to farmers, leading to losses due to the lack of available dryers. With high atmospheric humidity during this period, it becomes nearly impossible to naturally dry hygroscopic products like grains effectively.

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). This underscores the need for an improved drying approach in Nigeria, particularly during challenging weather conditions.

Most imported dryers, though efficient, often depend on electricity and require operational skills. In rural Nigeria, where consistent electric power is scarce and such machines are typically too costly for local farmers, these solutions are impractical and fail to address their needs. While open-air drying remains inexpensive and widely used, it is entirely weather-dependent, labor-intensive, unhygienic, unreliable, time-consuming, and results in non-uniform drying. It also demands a large area for spreading produce, and grains dried on bare ground are more prone to contamination by aflatoxin-producing fungi, posing health risks to humans. Therefore, there is a pressing need for accessible, efficient drying alternatives to overcome these limitations.

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.

Evaluating a hybrid grain dryer's performance is a vital scientific contribution, tackling the urgent demand for efficient, sustainable post-harvest technologies in agriculture. By analyzing its ability to integrate energy sources like solar and biomass, the study delivers key insights into improving drying efficiency, cutting energy expenses, and reducing grain spoilage—critical issues for food security and resource-scarce areas. This work deepens knowledge of hybrid systems' effectiveness across diverse conditions, providing a model for scalable solutions that can aid farmers and industries worldwide. Additionally, it connects theoretical designs with real-world applications, driving progress in agricultural engineering and advancing climate-resilient food preservation methods.

**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 |

NS=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.

Figure 2a illustrates the drying characteristics of grain using a hybrid grain drying method, highlighting the significant influence of grain depth and airflow rate on drying time. The data reveals a clear trend: at a constant airflow rate of 3.6 m³/s, drying time increases as grain depth increases. Specifically, with a grain depth of 5 cm, the average drying time was 3.5 hours. This extended to 4.5 hours when the depth increased to 10 cm, and further rose to 6.0 hours at a depth of 20 cm, all while maintaining the same airflow rate of 3.6 m³/s. These findings align closely with the observations of Okaiyeto et al. (2021), who similarly noted that drying time lengthens as grain depth increases. This consistent relationship underscores the critical role of grain depth in determining the efficiency of the drying process.

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

Figure 2b illustrates the relationship between moisture content, drying time, and drying depth in hybrid grain drying. The data reveals that both grain depth and air flow rate significantly influence the drying time. Specifically, at an air flow rate of 4.5 m³/s, the average drying time was 3.5 hours for a grain depth of 5 cm. However, as the grain depth increased to 10 cm, the drying time extended to 4.0 hours under the same air flow rate. A further increase in grain depth to 20 cm resulted in a corresponding rise in drying time to 4.0 hours, maintaining the air flow rate at 4.5 m³/s. This demonstrates that deeper grain layers require longer drying times under consistent airflow conditions.

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

Figure 2c presents the drying behavior of grain under a hybrid grain drying system, demonstrating the notable impact of grain depth and airflow rate on drying duration. The data indicates that at an airflow rate of 6.1 m³/s and a grain depth of 5 cm, the average drying time was a swift 2.0 hours. However, as the grain depth increased to 10 cm at the same airflow rate of 6.1 m³/s, the drying time extended to 3.0 hours. When the airflow rate was reduced to 3.6 m³/s and the grain depth reached 20 cm, the drying time further increased to 3.5 hours. These results highlight a clear pattern: higher grain depths, combined with variations in airflow, significantly prolong the drying process.

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

Figures 2a, 2b, and 2c illustrate that the drying rate of grain is notably elevated during the initial phase but gradually declines as the moisture content of the grain decreases. This trend suggests that early in the drying process, there is minimal resistance to moisture evaporation, allowing for rapid water loss from the surface. However, as the moisture content drops to approximately 16%, the drying rate slows considerably, indicating an increase in resistance to moisture removal. This behavior points to the presence of two distinct drying stages. The first stage involves the swift evaporation of surface moisture, while the second, slower stage entails the removal of internal moisture through diffusion, as water migrates from the grain’s interior to its surface.

**4. CONCLUSION**

The performance evaluation of the modified hybrid dryer yielded the following results: Collection efficiency was 19.8%, 15.2%, and 11.2% at air flow rates of 6.1, 4.5, and 3.6 m³/s, respectively, increasing with air flow rate but unaffected by grain depth. Drying system efficiency was 65.5%, 50.3%, and 45.4% at grain depths of 5, 10, and 20 cm, respectively, rising as grain depth decreased, with air flow rate having no significant impact. Fuel efficiency recorded 25.5%, 23.9%, and 23.6% at air flow rates of 6.1, 4.5, and 3.6 m³/s, and 29.3%, 23.8%, and 19.9% at grain depths of 20, 10, and 5 cm, respectively; interaction data showed 31.4% at 6.1 m³/s and 20 cm depth, dropping to 27.2% at 3.6 m³/s and 5 cm, indicating fuel efficiency increases with both air flow rate and grain depth. Sensible heat utilization efficiency averaged 68.0%, 65.6%, and 55.9% at air flow rates of 6.1, 4.5, and 3.6 m³/s, and 73.5%, 63.1%, and 53.0% at grain depths of 20, 10, and 5 cm, rising with both factors. Drying efficiency was 32.8%, 29.9%, and 27.7% at air flow rates of 6.1, 4.5, and 3.6 m³/s, improving from 4.5 to 6.1 m³/s but not from 3.6 to 4.5 m³/s, and recorded 37.3%, 29.8%, and 23.2% at grain depths of 20, 10, and 5 cm, increasing with grain depth. It is therefore concluded that the dryer gave optimum result.

**COMPETING INTERESTS**

Authors have declared that no competing interests exist.

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