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Optimization And Testing Of A Double-Glazed Solar Dryer Using The Design Of Experiments Method

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SUMMARY - In several countries, including the Central African Republic, sunlight is widely used as a direct source of energy for drying and dehydrating food products. With the high cost of fossil fuels, direct or indirect solar drying will become increasingly important worldwide as a food preservation method. Fortunately, unlike other countries, the Central African Republic enjoys abundant sunshine, making this alternative particularly attractive when continuous drying is required. In this article, we have undertaken an experimental study of drying using a foldable and portable dryer designed at the Laboratoire d'Energétique Carnot (L.E.C). For the purposes of the study, this dryer was modified to switch from natural convection mode to forced convection mode, enabling it to operate efficiently at all times thanks to fans powered by photovoltaic cells with a storage battery for energy storage.
Keywords: solar dryer, forced convection.

INTRODUCTION

The Central African Republic, also known informally by the acronym CAR, is a country in Central Africa with an estimated population of around 6,100,000 in 2023 and an area of approximately 623,000 km². [1]. It is located in the heart of Africa.

The CAR has two alternating seasons: the dry season and the rainy season. The rainfall pattern varies from one region to another. Savannah covers most of the country.

Efforts in the field of drying are mainly based on techniques used to improve the preservation of agri-food products by introducing new cultural techniques. There are several types of processing methods for agri-food products that allow them to be stored for long periods of time while preserving their nutritional quality.

Our work has led us to refer to certain authors who have caught our attention and whose work on drying will allow us to better understand the phenomenon. We have compiled a bibliographic summary of some of this work, as follows:

MOUSSA BOUDJEMA Fethi (2024) in his thesis entitled "Contribution to improving the thermal performance of a solar thermal converter intended for drying" confirmed that improved heat transfer can be achieved by using a zigzag shape for the absorber and, from a dynamic point of view, the outlet velocity of the narrowing model of the passage section at the sensor outlet can be increased by up to 250% compared to the inlet velocity, which ensures a strong flow in the drying chamber. This study showed that a 14-row collector has an outlet temperature difference of 24°C compared to a single collector and an efficiency of 54%.

Paul Ayihadji Ferdinand Houssou (May 2023) worked on evaluating the technical performance of three improved solar dryers. The aim was to test the effectiveness of solar dryers for drying onions with a view to improving preservation. The results of his work showed that onion bulbs dried faster in solar dryers than in traditional open-air drying. The hourly processing capacities of the tent dryer and the forced convection dryer were similar (1.72±0.08 kg/h and 1.41±0.08 kg/h) but significantly higher ($p<0.05$) than that of the traditional method (1.06±0.09 kg/h) and the box dryer (0.84±0.04 kg/h), which are statistically similar. The sensory quality assessment of the onions revealed that those dried with solar dryers were pleasantly appreciated by 100% of producers compared to those from the control group, considering the color, texture, and overall acceptability of the onion bulbs, which were dried to an optimal water content of approximately 10%. It was found that the box solar dryer was preferred because of its ease of use and relatively low acquisition cost compared to the other two.

Mahouton Simeon Parfait Noukpozounkou et al (July 2023) evaluated the performance of two dryers to ensure the quality of tomato fruit drying in southern Benin. Methods. Two types of dryers built at the African Center for Energy Conversion Research were tested in real-world conditions for tomato drying. To do this, the thermal performance of the devices was studied and the influence

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of various drying conditions (temperature, air humidity) on the quality of the dried product was evaluated using standard methods. Results: The results showed that the hybrid dryer has better thermal performance than the box dryer, with drying times of 5 hours and 20 hours respectively, compared to 30 hours for traditional drying. The lowest final water content values (9.08%) for dried tomatoes were obtained with the hybrid dryer. The latter best preserved the color of the dried tomatoes, which were most appreciated by the panelists in terms of color (4.2/5) and taste (4.4/5). A significant difference at the 5% threshold ($p<0.05$) was observed in the value and pH of the dried tomatoes regardless of the dryer used.

Ali Djegham et al (November 2021) in their useless study "Experimental study of a dehydrator using a hybrid aerovoltaic (photovoltaic-thermal) system" used a hybrid solar dryer that works with a hybrid solar panel, and this panel provides heat and electricity at the same time. Their research consists of recovering this thermal energy by heating or drying. Previous dryers worked with thermal collectors using the greenhouse effect, which only provides heat. They developed and used a hybrid solar panel that powers fans to circulate air and accelerate drying. Drying is done with hot air, as it reduces and absorbs moisture in agricultural products.

Hajar Essalhi (2019), in her study on the design and construction of an indirect solar dryer, focused on evaluating the efficiency of the solar air collector, as well as the overall efficiency of the indirect solar dryer and the effect of energy storage on the drying process during the night. This study revealed that natural convection mode is best suited for her dryer, allowing her to achieve a high drying air temperature, adequate flow rate, and 65% collector efficiency. During a drying operation, some products are not dried under constant air conditions:

- all products except those placed at the air inlet are in contact with air whose

-You can choose to modify the air temperature during drying (low at the beginning to prevent crusting, higher to accelerate drying at the end).

is therefore now necessary, based on the knowledge acquired concerning the behavior of a product dried under constant air conditions, to be able to predict the behavior of a product drying under variable conditions. The simplest assumption is to consider that when the air temperature jumps from T1 to T2, the drying of a piece of product with an average water content W will continue as if this water content had been achieved by drying with air at a constant temperature T2 since the start of drying. This assumption of a product with no memory cannot be strictly accurate because two products with the same average water content after being dried at two different temperatures will not have the same internal water content profile. However, this assumption may be acceptable for products with high water content.

DESCRIPTION OF THE FOLDABLE AND PORTABLE SOLAR DRYER

It should be noted that in this section we will highlight the shortcomings of existing solar dryers while proposing a new type of solar dryer.

Figure 1: photograph of the foldable and portable double-glazed dryer

The portable mixed dryer shown above consists of three parts: first, there is a flat double-glazed air collector (greenhouse effect), then a drying chamber. The two parts are connected by a hinge that allows the dryer to be folded after each drying operation. Finally, there are two fans, one to draw in hot air and the other to extract the air from the drying chamber. The transfer mode is forced

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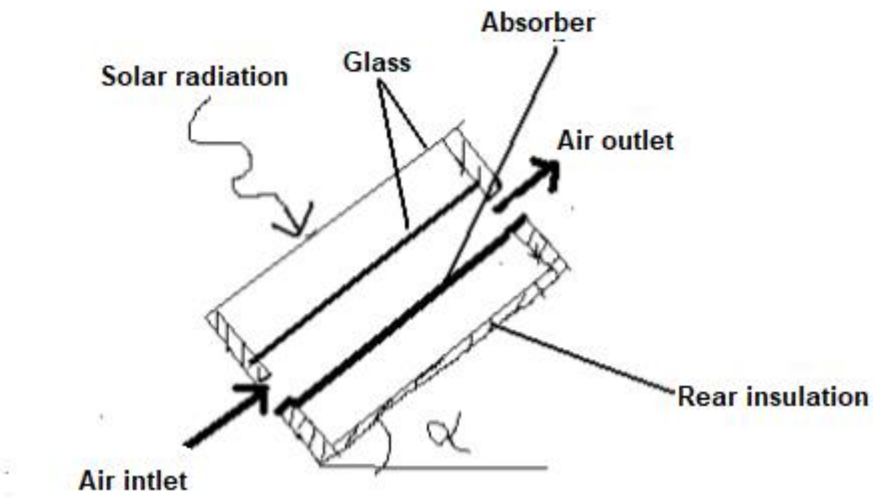
convection. The drying air passes perpendicularly over the products because literature teaches us that in this mode of air passage perpendicular to the products, the heat transfer coefficient is greater than when the air passes over the products horizontally [12].

The double-glazed flat plate collector in this dryer was designed using modeling that takes into account various parameters, including the fluid, wind speed, and both external and internal parameters, which allows us to calculate the efficiency [12]. In practice, this efficiency depends on the useful energy, which we are always seeking to increase. By increasing the heat received by the absorber by increasing the proportion of radiation absorbed (coating the absorber with a matte black dye), By reducing heat loss to non-receiving areas (requiring good insulation) and to the front of the collector (between the absorber and the environment).

DESCRIPTION OF THE FLAT-PLATE COLLECTOR

A parallelepiped solar collector 100 cm long, 40 cm wide, and 14 cm thick, equipped with two 3 mm thick panes of glass and an absorber (smooth sheet metal painted black) that can be tilted at an angle equal to the latitude of the location on the horizontal plane is used to receive the maximum solar flux with an air inlet at the base and an air outlet at the other end. It heats the ambient air that circulates through the collector by natural convection.



Mathematical modeling

This system of equations represents the heat balance calculated for various parameters, with the equations solved analytically.

$$m_{v1}.C_{p1}.\frac{dT_{v1}}{dt} = S.\alpha_v.E_g + S(h_{cv1} + h_{r1}).(T_{v2} - T_{v1}) - S.(h_{cv0} + h_{r0}).(T_{v1} - T_0) \quad (1)$$

$$m_{v2}.C_{p2}.\frac{dT_{v2}}{dt} = S.\alpha_v.\tau.E_g + S(h_{cv2} + h_{r2}).(T_3 - T_{v2}) - S.(h_{cv1} + h_{r1}).(T_{v2} - T_{v1}) \quad (2)$$

$$m_3.C_{p3}.\frac{dT_3}{dt} = S.\alpha_3.\tau^2.E_g - S(h_{cv2} + h_{r2}).(T_3 - T_{v2}) \quad (3)$$

$$\lfloor m_4.C_{p4}.\frac{dT_4}{dt} + \frac{mC_{p4}}{l}.\frac{dT_4}{dx} = S.h_f.(T_3 - T_4) \quad (4)$$

Terms in

$$mC_p.\frac{dT}{dt} = 0 \quad (5)$$

The overall efficiency that justifies the thermal performance of the dryer is defined by the following expression:

$$\eta = \alpha.\tau^2 - U_{p2}.\frac{T_p - T_0}{S.E_g} \quad (6)$$

International Journal of Engineering Research & Technology (IJERT)
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Eg: Total solar radiation

α: Absorptivity of the plate (α = 0.95)

τ: Transmittance of the glass

Up: Total loss coefficient

Tp: Temperature of the hot plate (absorber)

T0: Ambient temperature

In order to obtain satisfactory efficiency, we have represented η as a function of ΔT/E_g . Above a certain value of ΔT/E_g , there is a choice between different collector configurations.

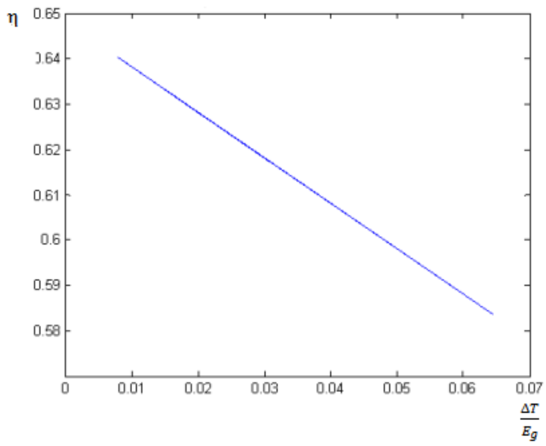

Figure 3: Efficiency η as a function of ΔT/E_g

Experimental procedures

The drying chamber is parallelepiped in shape, with a square base and a height of 100 cm, equipped with a chimney for the evacuation of hot, humid air. It has three separate racks, each 29 cm apart, on which the product is placed.

Figure 4.a: photo of the drying chamber Figure 4.b: cross-section of the banana

Cutting facilitates the drying [12] of certain products (bananas cut into slices), which reduces the time needed for water diffusion and increases the total evaporation surface area. This operation is essential for all thick products, otherwise drying takes too long [13].

International Journal of Engineering Research & Technology (IJERT)
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Vol. 14 Issue 12 , December - 2025

Figure 5: Dried banana

The analysis of drying kinetics is based on the following three parameters: the mass of water in the product, its temperature, and the drying rate.

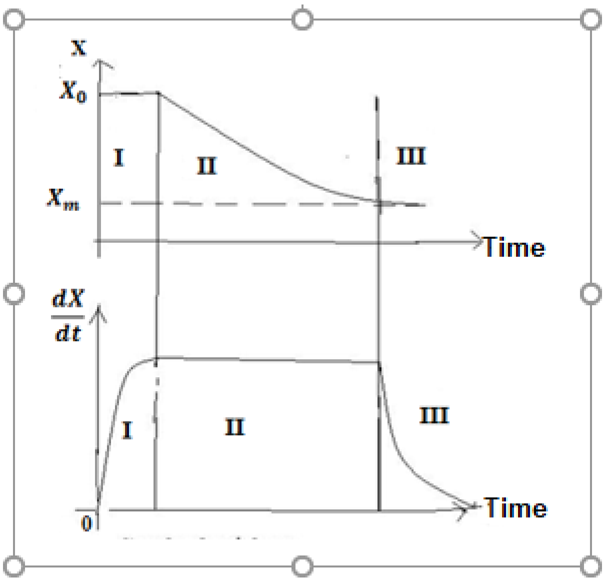

Figure 6: Drying kinetics analysis diagram

The study of these two drying curves shows the existence of three (3) drying phases.

Phase I: The heat from the air is mainly used to heat the product. Evaporation gradually increases. This phase is also called the temperature rise phase.

Phase II: The product is hot and releases its free water at a constant rate. The cooling of the product through the evaporation of its water exactly compensates for the heat it receives from the air. The temperature of the product remains constant.

Phase III: All free water has evaporated; the extraction of bound water is more difficult and the drying rate slows down. The rate of water vaporization is no longer sufficient to compensate, through cooling, for the heat supplied by the air: the temperature of the product increases [7].

These two curves clearly show the coupled phenomena of heat transfer and mass transfer during the drying of an agri-food product.

The optimization method using design of experiments was therefore chosen for this experiment.

RESULTS AND DISCUSSIONS

Design of experiments in forced convection [14]

International Journal of Engineering Research & Technology (IJERT)
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The factors studied and the ranges of variation for the experimental design are shown in the following table:

Table 1: Factors and study area of experimental designs

Factors Level -1 Level +1

X1: Fan speed 1 (m/s) 1 2

X2: Fan speed 2 (m/s) 1 2

X3: Mass (g) 300 500

The experimental design that was constructed is therefore a centered composite design [14]. With three factors, the number of experiments carried out is 17, including three experiments located at the center of the domain. The responses to this design are the drying time and the moisture content measured on the three racks. Indeed, the literature sometimes indicates that, depending on the position of the rack in the drying chamber, there may be differences in drying that can be reflected kinetically or in the residual moisture content. We wanted to see if we could observe this effect in the same way with the type of foldable and portable dryer that was designed as part of this work.

Table 2: Reduced centered composite matrix and experimental results

Expériences	X1	X2	X3	T(Y1)	Track1 (Y2)	Track2 (Y3)	Track3 (Y4)
1	-	-	-	5h	11,8	12	11,9
2	+	-	-	4h	11,6	11,9	11,1
3	-	+	-	4h	11,3	12,3	11,5
4	+	+	-	4h	13,2	13,5	13
5	-	-	+	6h	13,3	13,7	13,5
6	+	-	+	6h	14	14,7	14,2
7	-	+	+	5h	14,4	15	14,8
8	+	+	+	5h	13,6	14	13,8
9	$-\alpha$	0	0	5h	12,6	13	12,9
10	$+\alpha$	0	0	6h	13,5	13,9	13,7
11	0	$-\alpha$	0	7h	14,2	14,8	14,5
12	0	$+\alpha$	0	6h	13,7	14	13,9
13	0	0	$-\alpha$	4h	13,5	13,9	13,4
14	0	0	$+\alpha$	7h	14,3	15	14,7
15	0	0	0	7h	12,7	13	12,8
16	0	0	0	7h	12,8	13,1	12,9
17	0	0	0	7h	12,6	12,9	12,5

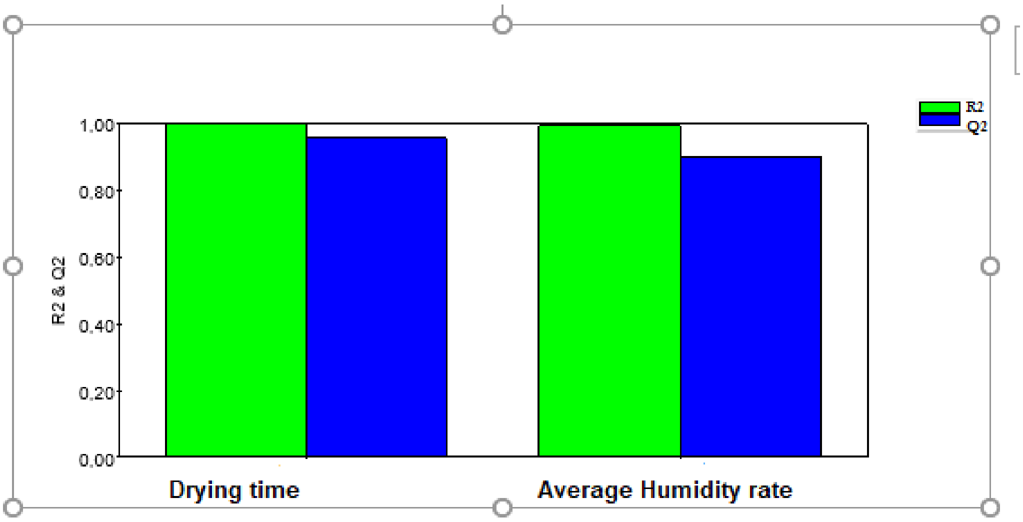

Figure 7: Histogram of responses Y1 (drying time), Y2 (average moisture content)

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 12 , December - 2025

The histogram in the figure illustrates the results for responses Y1 (drying time) and Y2 (average moisture content). We can see that for these responses, the linear regression coefficients R2 and Q2 are close to 1, which means that the results obtained are good and that more than 90% of the responses in the design are explained by the mathematical model.

Effects

The effects (also known as coefficients) of each factor, as well as the effects of interactions between factors, were determined using the formula explained in section 4.4.3 and are shown in the tables and histograms below:

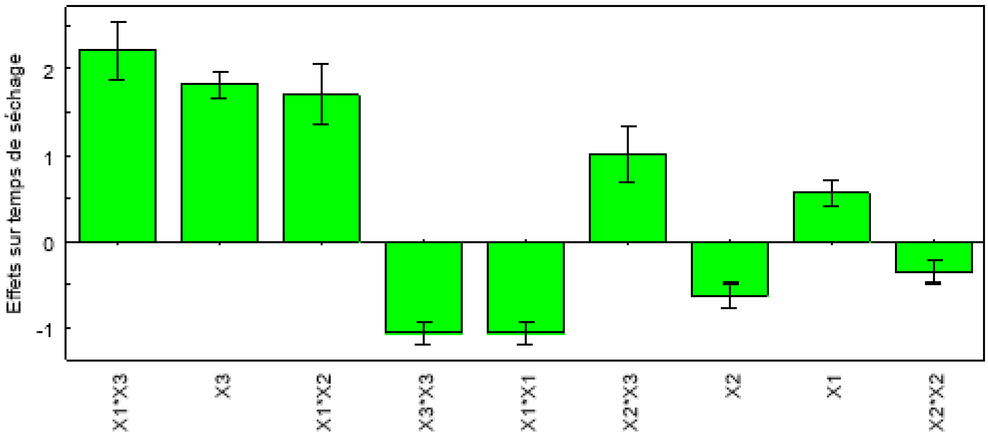

Figure 8: Histogram of effects for the drying time response

Table 3: Effect values for the drying time response

drying time	Coeff. SC
Constant	7
b_1	0.278
b_2	-0.315
b_3	0.91
b_{11}	-0.53
b_{22}	-0.176
b_{33}	-0.53
b_{12}	0.852
b_{13}	1.104
b_{23}	0.51
$Q_2 = 0.957$	$R_2 = 0.999$

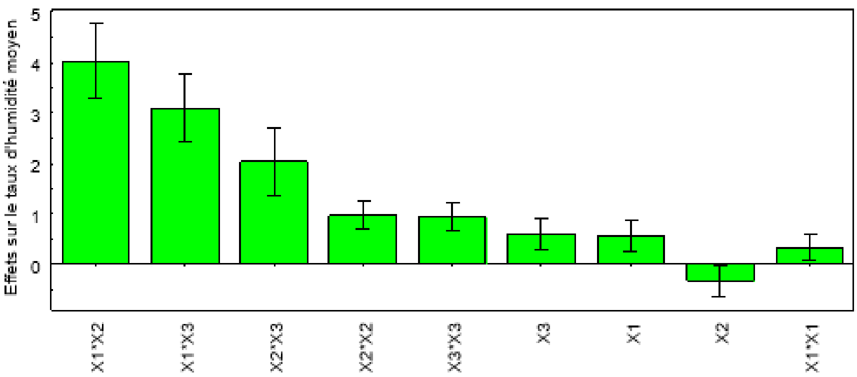

Figure 9: Histogram of effects for the average humidity response

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 12 , December - 2025

Table 4: Effect values for the average humidity response

Average humidity rate	Coeff. SC
Constante	12.806
b_1	0.277
b_2	-0.171
b_3	0.295
b_{11}	0.162
b_{22}	0.485
b_{33}	0.467
b_{12}	2.01
b_{13}	1.55
b_{23}	1.016
$Q_2 = 0.901$	$R_2 = 1.016$

In general, the factors influencing both responses are X3, which is the mass of the product to be dried, and the interaction between X3 and X1, where X1 is the speed of fan 1, and the interaction between X1 and X2, where X2 is the speed of fan 2. The experimental design allows for mathematical modeling of the model under study. Thus, for response y1, the drying time will be as follows:

$$y_1 = 7 + 0.278X_1 - 0.315X_2 + 0.91X_3 - 0.53X_1^2 - 0.176X_2^2 - 0.53X_3^2 + 0.852X_1X_2 + 1.104X_1X_3 + 0.51X_2X_3$$

For the average humidity response, the model is as follows:

$$y_2 = 2.806 + 0.277X_1 - 0.171X_2 + 0.259X_3 + 00162X_1^2 + 0.485X_2^2 + 0.467X_3^2 + 2.01X_1X_2 + 1.55X_1X_3 + 1.016X_2X_3$$

These mathematical models enable us to plot response surfaces, which can be examined below. These response surfaces were plotted based on the two ventilation speeds, i.e., the interaction X_1X_2.

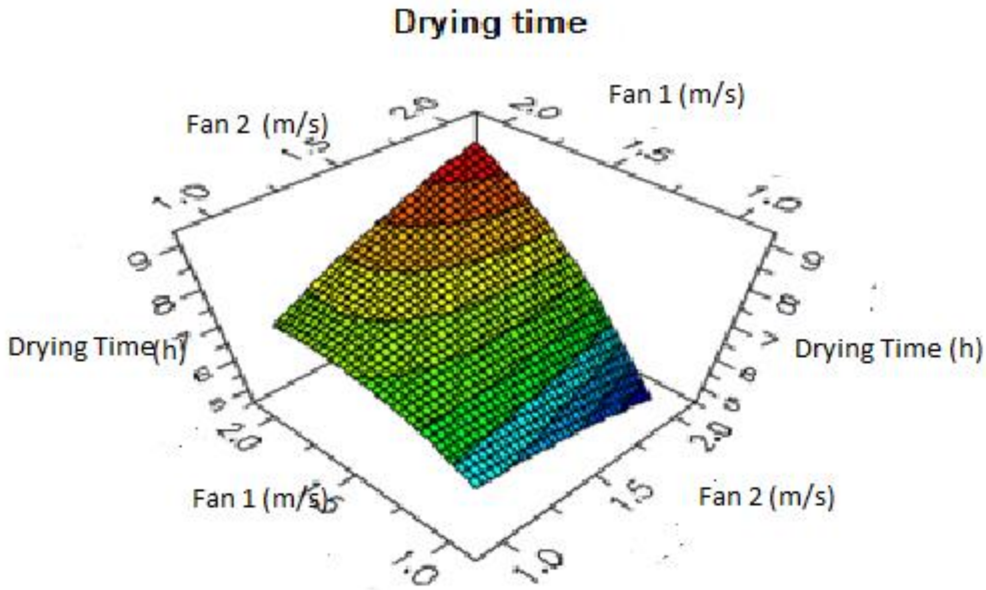

Figure 10: Response surface for drying time and for a product mass of 500g

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14 Issue 12 , December - 2025

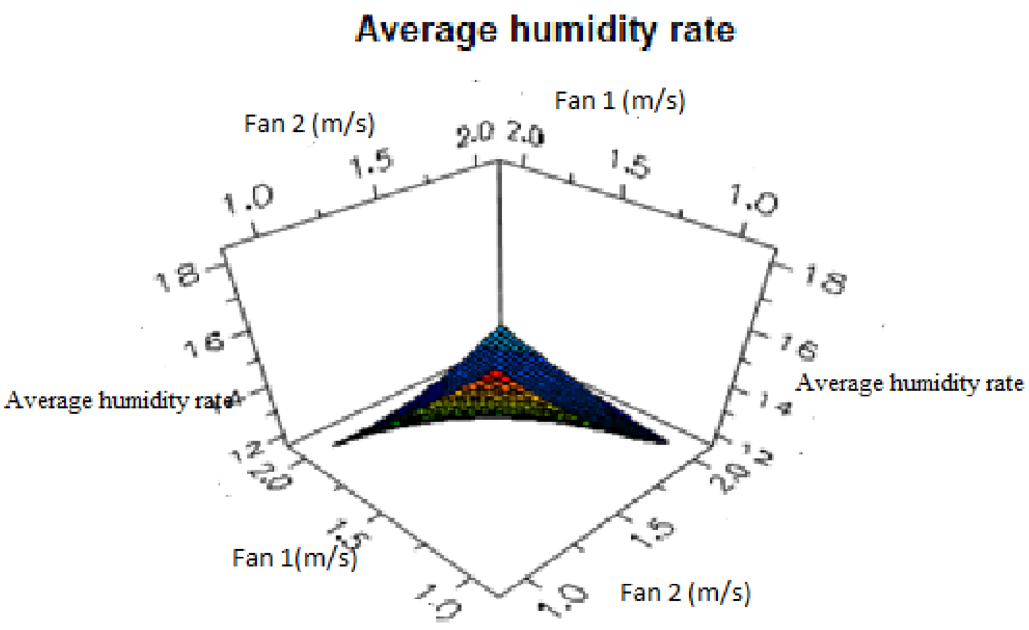

Figure 11: Response surface for average moisture content and a product mass of 300g

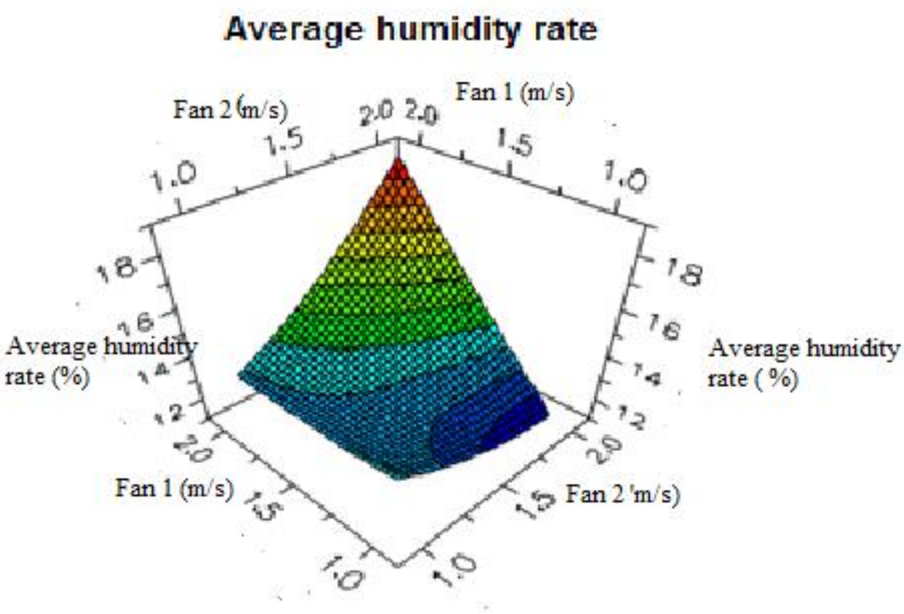

Figure 12: Response surface for average moisture content and a product mass of 500g

Looking at these response areas, we can see that to achieve minimum drying time, fan 1 must be at maximum speed, in which case the speed of fan 2 is irrelevant, and vice versa for a low mass, whereas for a higher product mass, fan 2 must be at maximum speed and fan 1 at minimum speed. With regard to the average humidity response, the same conclusions can be drawn as for the drying time, which is logical since the drying time depends on the measured humidity level.

Thus, the study on optimizing banana drying has shown that in order to achieve a minimum drying time and a minimum moisture content, fan 2 should be set to maximum and fan 1 to minimum, regardless of the mass of the product to be dried. Fan 1 is located at the sensor outlet, which is also at the bottom of the drying chamber, and must therefore bring in hot air gradually rather than abruptly. Fan 2, on the other hand, must be set to maximum, as it is used to remove moisture-laden air.

CONCLUSION

The theoretical and experimental study undertaken on the foldable and portable forced convection solar dryer consisted firstly of measuring and recording the components of solar radiation, temperatures, and humidity. It then determined the moisture loss curves for each product dried by successive weighings throughout the drying process until the mass of the products stabilized. The design of experiments method was applied to banana drying. The aim of this was to optimize drying by seeking to reduce drying time while removing as much free water as possible from the product, which is partly responsible for the deterioration of fresh products after harvesting. This reduction in moisture content therefore allows the dried products to be stored for as long as possible. It has been observed that drying is faster for smaller quantities of product, which is logical given the general principles of the drying process.

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COMPETING INTERESTS

Authors have declared that no competing interests exist or personal relationships that could have appeared to influence the work reported in this paper.

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