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# Evaluation of the Performance of a Direct Mode Solar Dryer of Local Manufacture: Application to Plantain

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**Abstract:** This study focused on the evaluation of the performance of a direct solar dryer designed at the National Institute of Research in Engineering Sciences, Innovation and Technology. It aims to contribute to the reduction of post-harvest losses of agro-resources in Congo through the conservation and manufacture of new food products. Plantain (*Musa AAB x paradisiaca*) of the Agnrin variety was used as raw material. The method used was that of dimensioning the dryer, evaluating its performance to assess its capacity and also to characterize physically and chemically the banana flour obtained. The results obtained revealed that the dryer temperature was higher than the ambient temperature 86.18% on average throughout the day, at the end of the day, the temperature reached 96.88% in three hours of time shortly before noon. The drying rate and efficiency of the system were 0.1106 kg/h and 44.1% respectively. The rapid drying rate in the dryer revealed the ability to dry the food quickly to a moisture content of 34%. The analyses led to the rates of 2.23±0.39%; 0.51±0.059%; 0.5±0.0%; 9.81±0.37%; 14.4±0.11% and 82.36±0.0% in protein, ash, lipids, soluble sugars, moisture and total sugars respectively. The low water content guarantees a longer shelf life and the ash content allows the flour to be classified as type 55.

**Keywords:** Plantain, Dryer Performance, Drying

## 1. Introduction

Food and energy are the essential factors for human survival. Efforts for food production and energy dissipation can undoubtedly offer a more peaceful and secure future to mankind [13, 14]. This is why, since the dawn of time, man has never ceased to seek ways to improve his living conditions in technical, economic, health, commercial and nutritional terms. Among these conditions, man has developed certain techniques of food preservation. Indeed, he noted post-harvest losses of seasonal fruits and vegetables where the yield has been estimated between 40 and 50% in many developing countries [15, 17]. There is also sometimes a non-periodicity of these in the market which makes them expensive, which are necessary for its survival. According to surveys, about 15% of the current world population is undernourished [18]. In addition, large amounts of food are lost in developing countries because rural populations do not have sufficient technical and socio-economic information on how to properly preserve and process these foods. These food losses are therefore a real problem for small farmers who produce more than 80% of the food. Therefore, several post-harvest processing methods have been explored to maintain the quality and safety of seasonal fruits and vegetables in order to extend their shelf life. Drying is one of the ancient methods of food preservation, developed by man to this day. It is an energy intensive operation and is known to reduce the moisture content and water activity of foodstuffs. These foodstuffs usually have a much higher water content about 25-80%, but usually close to 70% for agricultural products [31], thus controlling microbial growth (bacteria, yeasts and molds) and oxidative and enzymatic reactions to a minimal level [20-23], which allows for safe storage and increases the shelf life of the product. In addition, decreasing the moisture content of the products reduces their weight, volume, facilitating packaging, storage and transportation [15, 24]. Among drying techniques, direct solar drying is one of the renewable forms of food storage that can reduce processing costs for storage [16] and does not require expertise. Nowadays, natural drying by direct exposure to the sun and open air, seems to be obsolete in favor of drying at improved dryers. This is due to the fact that open sun drying is known to be a long process, dependence on weather conditions, exposure to rain, dust, insects and animals [15]. In contrast, a large body of research [26-30] have shown that solar drying using the improved devices, can be an effective means of food preservation as the product is completely protected during drying from rain, dust, insects and animals. In addition, solar dryers use a clean and non-conventional energy source [25]. Solar dryers can be classified according to their structure, solar energy collection method, drying method [19]. Recently, with respect to the drying method, [12] classify them into direct, indirect and mixed modes. The design of different types of solar dryers was reported by [10, 11]. It includes the design of cabinet solar dryers, box solar dryers, tunnel dryers and tray solar dryers for rural farmers. However, there are traditional solar dryers still called natural dryers [8]. Africa is a continent where solar radiation is almost permanent (365 days/year) but its exploitation is not yet complete. According to [9], more and more regions of the world are becoming aware that renewable energy has an important role to play in extending the technology to farmers in developing countries to increase their productivity. The Congo, compared to other West African countries, is lagging far behind in the use of solar dryers for drying (preserving products). The National Institute of Research in Engineering Sciences, Innovation and Technology (INRSIIT), being part of this vision, has designed solar dryers that unfortunately one of them has no data on its use. Thus, we proposed to characterize the solar dryer manufactured at INRSIIT.

Therefore, the objective of this study is to characterize a solar dryer in mixed mode by making dimensional measurements and evaluating its performance. Plantain slices are dried simultaneously by both direct radiation through the transparent collectors and the roof of the cabinet and by the heated air of the solar collector. The physico-chemical composition of the obtained wet and dry flourized plantain pods were also evaluated.

# 2. Material and Methods

### *2.1. Plant Material*

In the framework of our study, we used plant material that is the plantain bought in one of the markets of Brazzaville. This is known under the scientific name of "Musa x paradisiaca L. (Figure 1). The banana used in this study is of the Agnrin variety (*Musa × paradisiaca AAB* of the French type).

***Figure 1.*** *Plantain "Musa AAB x Paradisiaca" variety Agnrin at stage "2" of maturation.*

After receiving the plantains at the INRSIIT's Food Technology Laboratory (LTA), several steps and unit operations were performed. The bananas were first weighed, then carefully washed before being peeled to remove mud and insect debris. Then, they were peeled and soaked immediately in a water bath at room temperature 25°C, to avoid oxidation reactions. After a soaking period, the banana fingers (or scraps) were chronologically washed, weighed again, cut into thin slices of about 10 mm (hygroscopic parameters) with a manual grater, in order to accelerate the drying. These plantain slices were blanched in water at a temperature of 70°C for 10 minutes. After this operation, we drained the blanched plantain slices by passing them over a wire rack; we finally obtained wet pods ready for drying.

### *2.2. Chemicals*

All chemicals used during the study were at least of analytical grade. These included: sulfuric acid ($H_2SO_4$), boric acid, nitrogen catalyst, soda tablets, anthrone and α-D-glucose.

### *2.3. Solar Dryer*

The solar dryer used in this study and represented in figure 2a was designed at INRSIIT. The interior contents are shown in Figure 2b and 2c.

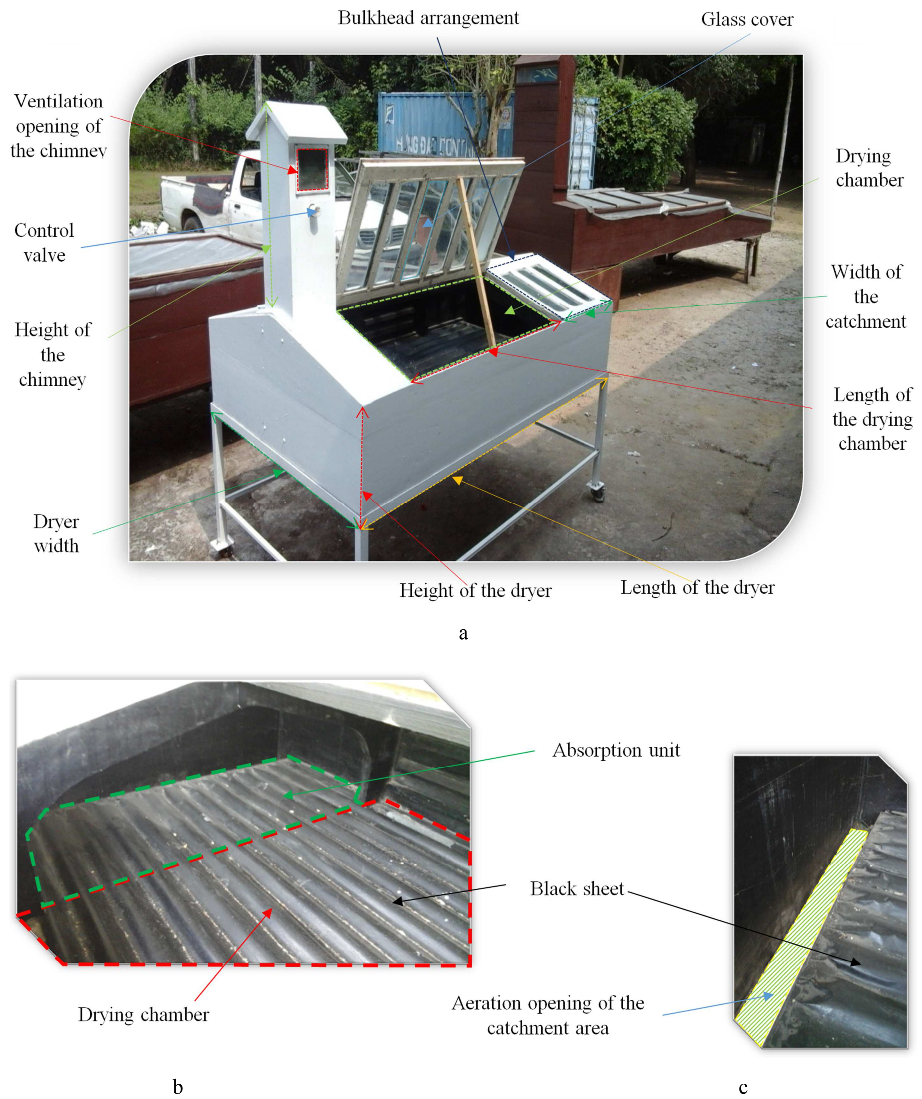


***Figure 2.*** *Solar dryer seen from outside (a) and drying chamber racks (b and c) of the solar dryer.*

The solar dryer used is made of wood, painted white on the outside and black on the inside. It is placed on top of a metal frame with a skid for its mobility, and is composed of an absorption material, which is the glass arranged in partition (figure 2a). It has in its interior bottom a sheet painted in black, extending on the surface of two parts (figure 2b). One of the rooms is used to spread the products to be dried on racks. These racks are made of two superimposed nets, one of which is made of metallic material underneath and the other of nylon, all surrounded by wood. The racks are distributed on three (03) levels superimposed on each other by small shelves placed on the side; this solar dryer also has a chimney with a valve (Figure 2a). It also has two ventilation openings located on the chimney (Figure 2a) and below the collection area.

Measurements of the solar dryer obtained with a tape measure, revealed the following data:

1) This dryer is 2.0 m long, 1.20 m wide and 0.41 m high, with a glazed absorber arranged over a length of 0.45 m and a width of 0.14 m in the form of a partition with a surface area of 0.06 m$^2$ on the roof of the dryer. It has an aeration zone 0.07 m wide and at least 1 m long located at the end of the surface of the collection zone (Figure 2a);
2) The drying chamber is 1.15 m long, 1.14 m wide, has a depth of 0.43 m and a surface area of 1.311 m$^2$ (Figure 2b and c);
3) The partitioned collection area or hot air absorption unit, whose partitions are 0.58 m long, 0.55 m wide and have a surface area of 0.32 m$^2$ (Figure 2b and c);
4) The chimney is 0.69 m high, 0.22 m long and 0.22 m wide (figure 2a);
5) The racks have a length of 1.11 m, a width of 0.99 m and a surface area of 1.09 m$^2$, which allows it to have a capacity of 3 kg or more of products to dry.

### 2.4. Experimental Drying Procedure

The direct mode natural convection solar dryer shown in Figure 2 was tested during June 2017 to evaluate its performance. During the test period (with no material to be dried), the temperature and relative humidity profiles inside the drying chamber of the dryer were determined by measuring them with the hygro-thermometer at regular half-hour intervals between the local times of 09:00 and 16:00. Given the location of the research site and the dryer in a forest area, in addition to the period of the end of the dry season in Congo, the humidity is basic and very fluctuating, so that only the ambient air temperatures were also measured at the same local time in order to better assess the effectiveness of the dryer to capture solar energy.

The blanched and drained plantain slices were spread on the solar dryer racks and put at an initial temperature of 35.2 °C after an initial weighing. After a period of drying, we obtain dried plantain cossettes. These cossettes are then first weighed, then reduced to powder with the help of a stainless steel electric grinder (brand moulinex) during one minute. Then, the powder is sieved to separate the coarse particles from the fine ones thanks to a 50 µm sieve, then weighed before being packed in a plastic and waterproof film, labelled and finally stored for a later use.

To determine the drying kinetics, we weighed at regular intervals of half an hour until a constant mass was obtained with 3 x 25 g of samples of plantain slices, which we put in the dryer for a period of four (4) hours.

Using the hygro-thermometer probe placed in the drying chamber, the temperature and humidity of the air in the dryer during the drying stage at these same time intervals (30 min), were measured. The drying process was stopped at the time when no further weight loss (final weight) of the plantain flakes was observed.

The performance of the dryer was evaluated using the drying rate and the efficiency of the collector or radiation sensor. The drying rate, which is the amount of moisture removed from the food in a given time, also known as the moisture content on a dry basis, was calculated from Equation 1, defined as follows:

$$X = \frac{m - MS}{MS} \qquad (1)$$

With, X: water content dry basis (kg water/ kg dry matter);
m: mass of the product in g;
DM: mass of dry matter in g.

This equation 1 is similar to the one defined by Itodo et al. [2] used by many authors. The efficiency of the drying system was evaluated by the drying rate (equation 2) of the plantain samples, by the following formula:

$$-\frac{dX}{dt} = \frac{-[X(t+\Delta t) - X(t)]}{\Delta t} \qquad (2)$$

With, -dX/dt: drying rate in (kg water/kg DM/min);
X: water content dry basis (kg water/kg DM);
Δt: time difference in minutes.

### *2.5. Analytical Methods of the Finished Product: Plantain Flour*

The analyses carried out were related to:

1) Dry matter: where it was determined after desiccation by carrying 10 g of sample placed on a dish in an oven at 105°C for 24 hours [4];
2) Total ash: where it was obtained after incineration of 2 g of powder samples placed in a porcelain crucible and in a muffle furnace heated to 450 - 550°C for 8 hours [3];
3) The lipid content: where it is obtained after extraction in 30 g of sample by the method with soxhlet with hexane for 6h [4];
4) The protein content: it is determined from 0.5 g of sample by the determination of the total nitrogen present in it according to the method of Kjeldahl [6];
5) Determination of total soluble sugars: The determination of total soluble sugars is carried out according to the colorimetric method with anthrone in sulfuric medium [7];
6) The sugars, by hot dehydration in concentrated sulfuric acid, give furfuric derivatives reacting with anthrone to form a blue chromophore. The optical density of the chromophore obtained is measured at 620 nm. A calibration curve is previously made from solutions of anhydrous α-D-glucose (reference solution) of increasing concentrations ranging from 0.25 mg/mL to 1.00 mg/mL.
7) Total carbohydrate content: which was deduced by difference by the method of Egan et al., [5] according to the formula:

$$Carbohydrate\ content = 100 - [P(\%) + \mathrm{L}(\%) + \mathrm{Te}(\%) + C(\%)] \qquad (3)$$

### *2.6. Statistical Analysis*

The experiments were performed in triplicate, the results were presented by the mean with its standard deviation. The plots were performed using a Microsoft Excel 2010 software.

## 3. Results and Discussion

### *3.1. Performance Evaluation of the Direct Solar Dryer*

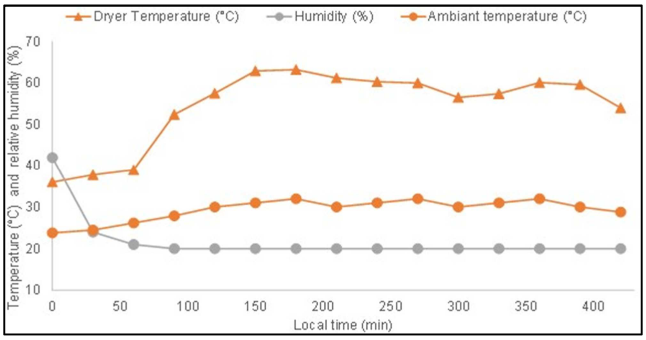


***Figure 3.*** *Variation of temperature and relative humidity of the air inside and outside (ambient) the dryer as a function of time.*

Figure 3 compares the temperature recorded inside the solar dryer and the ambient temperature throughout a typical day of drying. It was observed that the temperature developed in the dryer is always higher than the ambient temperature with a considerable difference. The temperature in the dryer varied between 36°C and 63.2°C, while the temperature observed in the ambient condition varied between 23.8°C and 32°C. The temperature in the dryer increases remarkably around 180 min, as the sun has reached the highest position in the sky and is generally above our heads. The insolation angle at this point became closest to 90°, which leads to intense solar radiation.

The average temperatures in the dryer and the ambient air were 54.53°C and 29.35°C respectively during daylight, therefore, the heating temperature inside the dryer was higher than the ambient temperature by an average of 25°C (85.18%) throughout the daylight hours and up to 31°C (96.88%) for about three hours immediately before noon. This indicates the prospect of better performance than outdoor sun drying, as for most food materials the recommended drying temperature is 60-70°C [1]. These data confirm that the current solar dryer can be effectively used for drying agricultural products such as plantain.

Figure 3 also shows the variation in relative humidity in the drying chamber. The relative humidity varied between 20% and 42% with an average of about 21.8%. Comparison of this curve with the temperature curves shows that the drying processes would be enhanced by the heated air at very low humidity.

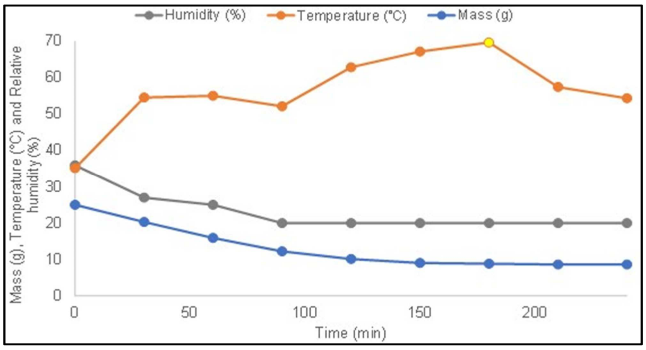


***Figure 4.*** *Evolution of product mass, temperature and humidity in the dryer as a function of time.*

Figure 4 shows the variation with time, temperature, relative humidity and mass loss of plantain slices in the direct mode solar dryer during the experiment.

The temperature vs. time curve increases exponentially until it reaches a peak of 69.7 °C in the drying chamber after 180 min; this shows the earlier and faster removal of moisture from the food to be dried by mass loss (from 25 to 8.8 g). But during the drying kinetics, we noticed slight temperature drops at the 90th minute (52.2°C) and during the last 60 minutes (57.5°C and 54.4°C respectively) marked by the end of the drying operation. This phenomenon can be attributed to the influence of solar radiation on the collector which plays an important role in heating the air circulating inside the solar collector. The average temperature recorded was 56.53°C.

Regarding the water content, it was observed that the mass of the plantain slices decreased continuously (from 25 to 8.6 g) with time, where in the first 90 minutes of the drying operation. A considerable loss of water content (see in figure 5) was noted (from 2 kg water/kg M.S. to 0.4 kg water/kg M.S.) by the loss of mass. This explains why the evaporation of a large amount of water from the plantain slices goes perfectly well in the drying chamber of the dryer. The remaining 150 minutes show a less important decrease between 90 and 180 min (0.4 kg water/kg D.M. to 0.02 kg water/kg D.M.), and which stabilizes around 180 min or even 240 min where the final value of the water content is almost zero.

The relative humidity inside the dryer during the experiment, also shown in Figure 4, shows that it varies between 20% and 40% with an average of 23.11%. Its evolution as a function of time is presented in a decreasing manner and progressively until it stabilizes from 90 min. It is clear that the humidity curve is the inverse of the temperature curve. We can also note from the curve, that the relative humidity keeps almost the same value during the rest of the drying process.

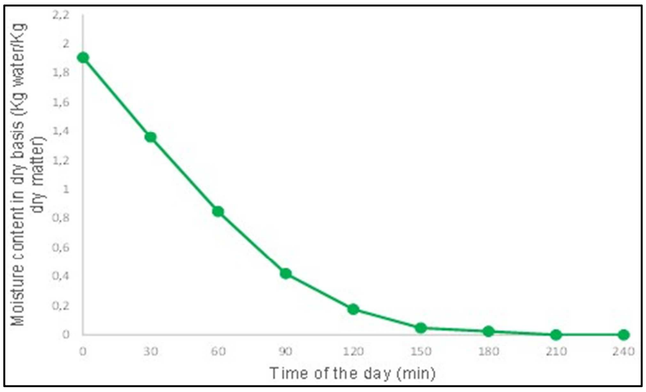


***Figure 5.*** *Evolution of the dry base water content of plantains as a function of time.*

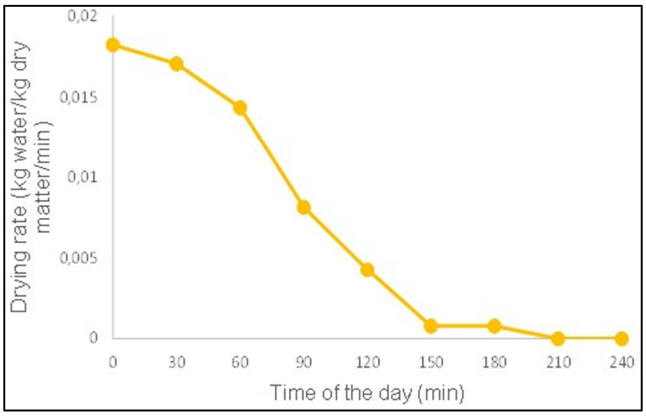


***Figure 6.*** *Evolution of the drying speed of plantains as a function of time.*

Figure 6 shows the experimental curve of the drying speed over time of plantain slices in the direct mode solar dryer.

The air velocity inside the dryer depends on the ambient air velocity outside the dryer, and increasing the drying velocity promotes convective exchange while accelerating the drying process. In order to achieve a high drying speed, the air must circulate continuously. Referring to the curve in figure 6, we can see that it corresponds to the rate of water loss from the product inside the dryer. But again, we notice that the initial value of the speed is 0.018 kg of $H_2O$/kg MS/min, a very low value especially since there is no renewed air circulation. This low velocity justifies the circulation mode where air convection occurs naturally. The speed of water loss decreases progressively until it is cancelled around 210-240 min.

For a better drying, three parameters must be combined: temperature, air speed and intrinsic parameters. In our case, only two parameters (temperature and intrinsic parameters) are involved. Hence the need to incorporate a fan (hybrid systems) to increase the air speed of the dryers in order to increase the performance of the various dryers manufactured at INRSIIT and reduce the drying time of food products.

In conclusion, the dryer was able to remove a total of 34.40% of the moisture, on a dry basis, from 1.106 kg of plantain slices in a drying time of 04h00, i.e. a drying speed of about 0.1106 kg/min. The collector efficiency of the direct mode solar dryer during the test period was found to be 44.1%.

### *3.2. Physicochemical Composition of the Finished Dry Product: Plantain Flour*

After the drying operation was stopped, we obtained well dried banana pods (Figure 7) with a total mass of 487.8 g out of 1106 g of wet product. These pods were then ground into flour for evaluation of basic physicochemical parameters.

Starting from the mass of dry cossettes (487.8 g), a flour with a mass of 450.2 g was obtained. The loss recorded is 37.6 g. The yield of flour obtained is 92.3%. This is a very high yield, showing the efficiency of the mill used for this purpose.

***Figure 7.*** *Dry plantain pods.*

The content of some biochemical constituents (total and soluble carbohydrates, ash, protein, water content and lipids) is represented in Table 1.

***Table 1.*** *Biochemical composition of plantain.*

| Nutrients | Content (%) |
|---|---|
| Ash | 0.51±0.059 |
| Water | 14.4±0.11 |
| Proteins | 2.23±0.39 |
| Carbohydrates (soluble) | 9.81±0.37 |
| Lipids | 0.5±0.0 |
| Total carbohydrates | 82.36±0.0 |
| Calories (kcal) | 342.86 |
| Energy in KiloJoules (kJ) | 1457.03 |

From Table 1, it appears that the plantain flour in our study is not a rich source of protein (2.23%), minerals through ash (0.51%). This low source in these two parameters can be justified by the stage of maturity of the banana. It is also noted that lipids are poorly represented, while sugars (82.36%) including solubles are strongly represented. We specify that this flour would provide at least more than 340 Kcal in energy. The moisture content is primarily a regulatory value to ensure the preservation and avoid alterations of the flour. It is fixed at a maximum value of 15%. The water content of our flour is about 14.4%. This means that it can be preserved for a longer period of time and can also be classified as a type 55 flour for use as a bakery flour, depending on the ash content.

## 4. Conclusion

The objective that we set for this work was achieved. The results revealed that the variation of the temperature range inside the dryer compared to the ambient temperature shows that the temperature in the dryer is always higher than the ambient temperature in average of 25°C (85.18%) throughout the day. The performance of the dryer was evaluated at 44.1% efficiency. This direct natural convection dryer is in the form of a box. The highest temperature was reached after 180 min at 69.7°C. The drying time was four (04) hours. The physico-chemical characterization of the plantain flour obtained after drying, gave contents of 0.51% ash, 14.40% water allow us to classify the flour in the category of type 55. This flour can be used for human consumption as bakery flour, and for animal consumption as cattle feed.

In the end, the results obtained revealed possible indications that solar dryers have a future, especially in food preservation. However, as far as we are concerned, there is still a lot of work to do to improve this performance by incorporating a fan (hybrid systems) in the need to increase the air speed in the dryers during the day or even at night.

## Conflicts of Interest

The authors declare that they have no competing interests.

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