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CONSTRUCTION OF AN INDIRECT EXPOSURE SOLAR DRYER FOR FRUIT DRYING

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Abstract. *Fruit drying is a very important process that has as one of its main objectives to avoid waste, helping to preserve quality and increase their storage time. Traditional drying methods such as using kilns can be expensive and using alternative methods such as using a solar dryer is a more sustainable and affordable alternative. Thus, in the present work an indirect exposure solar fruit dryer was developed and tested in the drying of bananas. The dryer was built with low-cost materials, such as wood, zinc, expanded polystyrene, alveolar polycarbonate and reused metals. The development of the dryer had the differential of providing an increase in the temperature of the drying air in the solar collector, by passing it through a metal pipe to the oven. The drying of the bananas in the lasted 8 hours and the drying parameters obtained indicate the viability of the technique used, considering the drying efficiency values of more than 80% and the humidity values on a wet basis close to those recommended by ANVISA. At the end of the research, it was verified that the fruits were successfully preserved and it can be considered that the use of such techniques will contribute to the profitability of small-scale farmers/rural producers.*

Keywords *Dryer, Drying, Humidity, Profitability, Storage.*

1. INTRODUCTION

The energy derived from the sun is essential for human beings. Through its use, many basic needs can be met, such as heating, lighting, and food production (via photosynthesis and food chains). Harnessing this energy, both as a source of heat and light, is one of the most promising energy alternatives when it comes to addressing the challenges of sustainable development and significantly contributes to solving many of today's world problems.

Among the various problems, the difficulties faced by farmers are notable, one of which is the mass waste of food resulting from their natural and rapid degradation. Factors contributing to such losses include inadequate post-harvest techniques, late harvesting, improper packaging and transportation, lack of refrigeration for storage, exposure to pathogens, among others (Cosmo et al., 2018). This affects the moisture content of fruits, contributing to the proliferation of fungi and bacteria, leading to a loss of their profitability (Gomes, 2015).

In order to minimize these losses, the alternative of fruit drying for long-term storage emerges. According to Melo (2016), drying is essentially the process involving the transfer of heat and mass, which consists of removing the liquid from a product, either partially or completely, voluntarily or involuntarily, in order to maintain it in an appropriate condition, without necessarily removing all the water from the product.

The drying process of a fruit essentially involves the removal of water from its interior, aiming to reduce its metabolism and the presence of microorganisms. This dehydration process removes most of the water content from the products while maintaining their quality, making it possible to preserve the products in good condition for a longer period.

According to Lima (1999) cited by Gomes (2015), in this process, heat needs to be applied to the moist product to facilitate the transfer of water from the inside to the surface for evaporation, thus completing the dehydration. The heat flow process to the material will be responsible for the evaporation of the water from the material.

For this process to occur optimally, the use of appropriate equipment is necessary, in this case, the dryer or fruit dehydrator, as it is commonly referred to in many commercial applications. An alternative construction approach, aiming for cost-effectiveness in the design, is the use of a solar dryer. The solar dryer is a device in which air is heated by solar radiation and naturally or forcibly circulated through a system, extracting the water from the product to be dried. Due to the significant food waste, especially fruits, many researchers are constantly seeking alternatives to benefit small-scale farmers, such as those in family agriculture (Melo, 2016).

Within the types of solar dryers, direct exposure dryers and indirect exposure dryers are noteworthy.

The direct exposure solar dryer is a straightforward device, easy to build, operate, and maintain. It is essentially composed of three elements: the body, which is a rectangular prism-shaped wooden box; two trays where the product is placed for drying; and the dryer cover, which gives it the characteristics of an oven.

Indirect exposure dryers have a structure that provides greater protection to the food compared to trays exposed to the ground. This dryer has an inclined design with a glass top that allows for thermal radiation absorption. Thus, the air is heated in this glass cabin, reducing its density and passing through the trays containing the product to be dried (Costa, 2010).

When studying solar dryers, it is important to assess the volume of the compartments being used. In the case of indirect exposure solar dryers, not only the relationship between the volumes of the panel and the drying chamber needs to be evaluated but also the composition of the elements that make up the panel, as well as the airflow direction from the panel to the drying chamber, whether it is natural or forced.

Therefore, the present study aims to present the results of the construction and testing of an indirect exposure solar dryer used for fruit drying in the city of Esperança-PB.

2. METHODOLOGY

This study was the result of a descriptive-explanatory research. According to Gil (2002), descriptive research aims to describe the characteristics of a specific population or phenomenon or establish relationships between variables. One of the most significant characteristics of descriptive research is the use of standardized data collection techniques, such as observation. On the other hand, explanatory research focuses on identifying the factors that determine or contribute to the occurrence of phenomena.

Regarding the technical procedures, this research is classified as both bibliographic and experimental. It is bibliographic in nature as it is based on existing materials, particularly scientific articles and books. According to Gil (2002), experimental research aims to test hypotheses that establish cause-and-effect relationships between variables and determine the control and observation methods that the variable produces in the object. The experimental analysis to validate the efficiency of the model involved obtaining temperature data and drying parameters from the equipment.

To develop equipment that combines good energy efficiency and low cost, and that could be utilized by small-scale producers in the Esperança region, the materials used for constructing the solar collector and the drying chamber were selected to meet these requirements.

Thus, materials readily available in the local market were employed, such as:

- Plywood: also known as "madeirite," it is a combination of several thin wood veneers that are overlaid in alternating directions to form a single wood panel.
- Alveolar polycarbonate: a material made from resin that offers high transmittance to incident solar radiation and a high level of safety.
- Nylon mesh: a synthetic fiber material that exhibits good resistance to wear and tension. It is used in the trays where the material to be dehydrated is placed. The nylon mesh allows air circulation inside the chamber and is easy to clean fruit residues.
- Zinc: a plate used as an absorber in the solar collector.
- Expanded Polystyrene (EPS): panels used as thermal insulation in the collector and the drying chamber.
- Adhesive and silicone: used as means of joining and sealing between the parts of the dryer.
- Metal tubes: used as an air circulation system from the inlet to the outlet of the collector.
- Metal roofing: used as an absorber, increasing the temperature of the air that circulates through the metal tubes.

In addition to these, some electronic components were also used in the construction of the drying equipment, which enabled the air exhaust system for drying, such as:

- Coolers: fans widely used in computer cooling systems. In the drying system, the cooler was used to force air circulation into the drying chamber, and its activation was powered by solar photovoltaic energy.
- Mini photovoltaic solar panel: a module that directly converts solar energy into electrical energy through photovoltaic cells, used to provide electricity to the coolers.
- Temperature sensors and electronic items: for the construction of the data acquisition system for the solar dryer's temperature.

The fruits used in the experiments were obtained from the local market. They were ripe and free from external deterioration factors. The tests were conducted in the city of Esperança (latitude 7° South).

After the selection of materials, the solar dryer was designed as shown in Figures 1a and 1b.

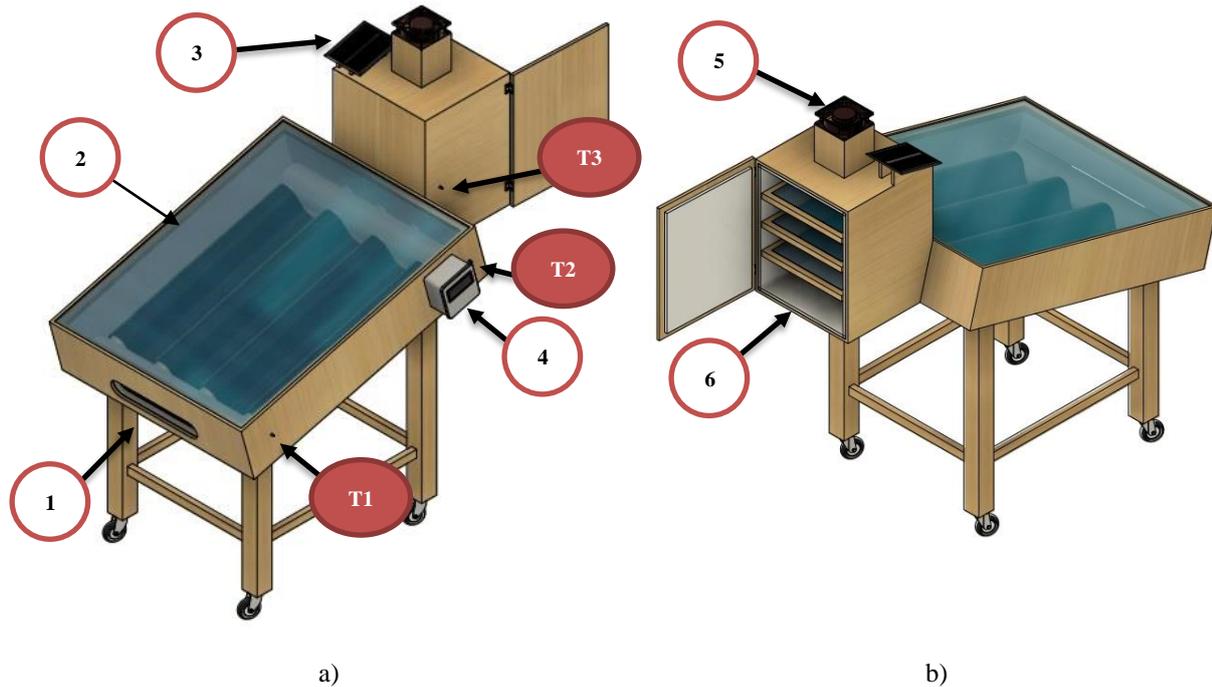


Figure 1. Solar dryer design: a) perspective view detailing the front part, and b) perspective view detailing the back part.

As shown in the presented figure, the indirect exposure solar dryer consists of two main parts: the solar collector (2) and the drying chamber (6). The drying air enters through the opening (1) of the solar collector and flows towards the drying chamber. To facilitate the airflow, a fan (5) was installed in the drying chamber, which is powered by a photovoltaic panel (3). The solar collector also includes a data acquisition system (4) responsible for reading temperatures at points T1, T2, and T3. Points T1, T2, and T3 represent regions near the air inlet of the collector, the transition between the collector and the drying chamber, and an intermediate region of the drying chamber.

Regarding the temperature data acquisition system, automation was achieved with the help of a NodeMcu with ESP8266. This microcontroller features 11 I/O pins, Wi-Fi connectivity, and other functionalities. Three DS18B20 temperature sensors were utilized for acquiring temperatures at the collector inlet, interior, and drying chamber, respectively. Additionally, a 20x4 display was used to present the measurements to the user. The schematic diagram of the data acquisition system and its final assembly are shown in Figures 2a and 2b.

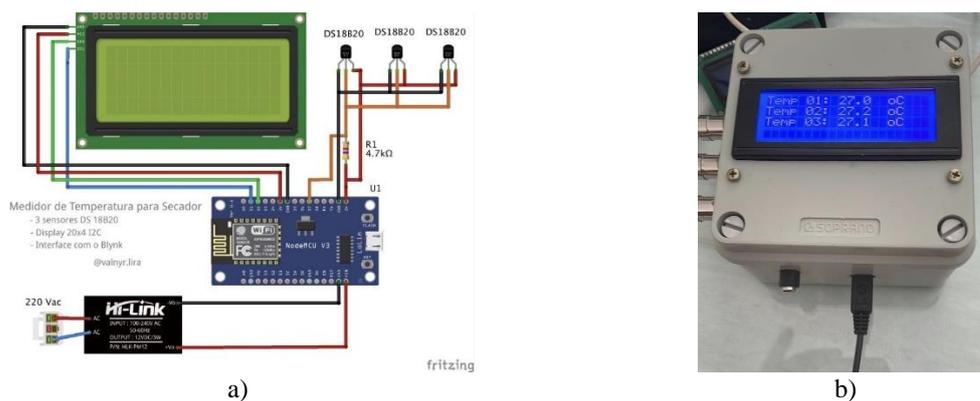


Figure 2. Temperature data acquisition system: a) schematic diagram of the system, and b) final assembly of the temperature data acquisition system.

The visualization of temperature measurements could also be remotely monitored through the Blynk application (web or mobile), as shown in Figures 3a and 3b.



a)



b)

Figure 3. Temperature measurements visualization: a) via web, and b) via mobile.

The dryer was tested with the drying of sliced bananas (in coin shape) starting at 8:00 and ending at 16:00. A precision digital mini electronic scale (0.1 to 500 g) was used to measure the mass of the bananas. The masses of the bananas were recorded before and after the tests, and the temperatures of the collector and the drying chamber were monitored during the drying process.

The tests were conducted in the city of Esperança (latitude 7° South and longitude 35° West), in the state of Paraíba, where there is an average of 7 hours of sunshine per day. The inclination of the collector was set at 17 degrees, corresponding to the latitude measurement (7 degrees South) plus 10 degrees, as recommended by Jacome Junior (2019), to ensure maximum solar capture throughout the year.

The moisture content of the bananas was expressed on a wet basis, determined by the ratio of the mass of water in the product to the total mass of the product, as shown in Eq. (1).

$$x_{wb} = \frac{m_{H_2O}}{m_t} \quad (1)$$

Where x_{wb} = moisture content, on a wet basis [%]; m_{H_2O} = mass of water contained in the banana [kg]; m_t = total mass of the banana [kg].

The efficiency of the drying process was evaluated based on the measurement of the variation in the masses of bananas subjected to the drying process, using Eq. (2).

$$\eta_p = \frac{m_{initial} - m_{final}}{m_{water}} \quad (2)$$

Where, η_p = efficiency of the process [%]; $m_{initial}$ = initial mass of the banana [kg]; m_{final} = final mass of the banana [kg]; m_{water} = initial mass of water present in the banana to be subjected to drying [kg].

According to Nunes (2016), bananas have an initial water content of approximately 70% wet basis (w.b.), which promotes microbial growth and leads to the degradation of their organoleptic characteristics, resulting in a loss of nutritional value and, consequently, commercial value. To prevent this degradation, it is desired that the fruit intended for longer storage periods has reduced water content, around 25% wet basis (w.b.).

Furthermore, according to Resolution of Collegiate Board (RDC) No. 272, dated September 22, 2005, from the National Health Surveillance Agency (ANVISA), for a fruit to be considered dried, it must have a maximum moisture content of 25% wet basis (w.b.).

3. RESULTS AND DISCUSSIONS

The constructed indirect exposure solar dryer is shown in Figures 4a, 4b, 4c, and 4d.

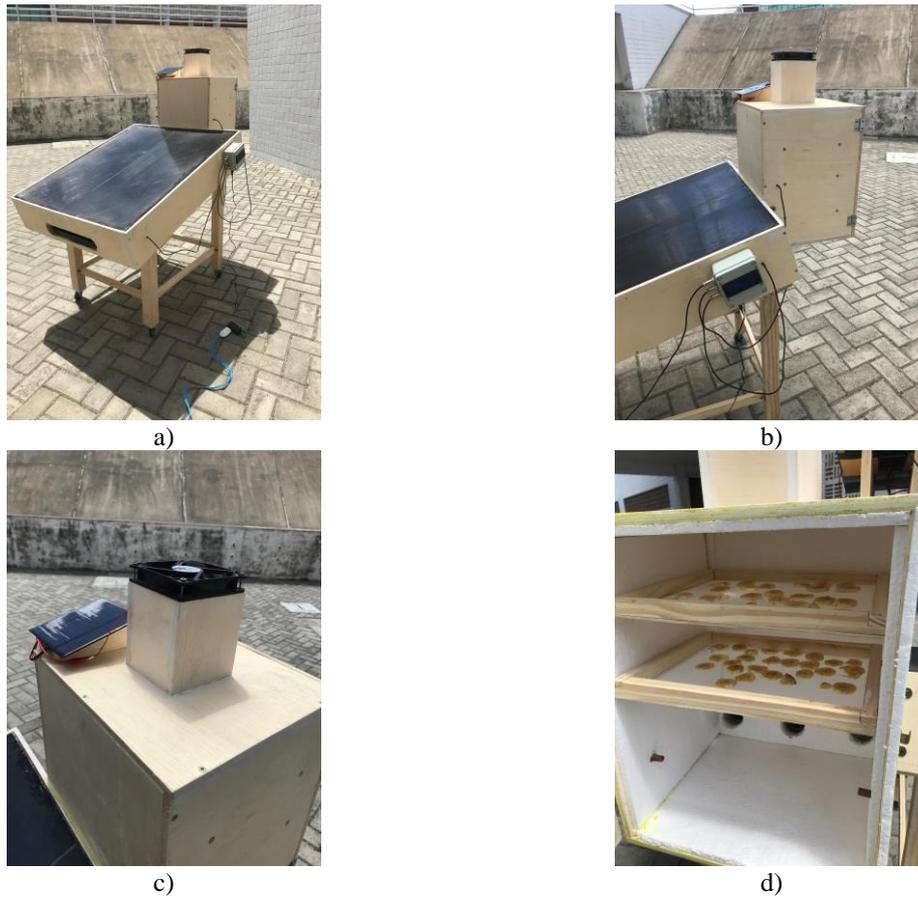


Figure 4. Solar dryer of indirect exposure constructed: a) perspective view of the dryer, b) final assembly of the data acquisition system, c) final assembly of the exhaust system, and d) trays positioned inside the oven (drying chamber).

The drying tests were conducted on February 7th and 9th, 2023. The temperatures were monitored during the tests, including ambient temperature, collector inlet temperature, temperature at the point near the collector outlet to the oven, and the oven temperature.

Tables 1 and 2 show the results of the temperature measurements taken.

Table 1 - Temperatures recorded during the experiment on 07/02/2023.

Time	Inlet Air Temperature (Collector)	Outlet Air Temperature (Collector)	Oven Temperature	Room Temperature
8:00	29.4	33.4	32.1	29
8:30	30.1	34.1	32.2	29
9:00	31.8	34.9	33.3	29
9:30	33.4	42.4	34.2	29
10:00	35.3	43.8	40.3	30
10:30	38.5	54.6	40.6	30
11:00	37.7	51.4	39.9	30
11:30	41.1	53.6	41.9	30
12:00	41.5	52.7	40.1	30
12:30	40.6	53.7	42.9	31
13:00	40.4	45.4	40.4	31
13:30	37.6	48.6	38.8	31
14:00	36.3	48.4	37.9	31
14:30	35.5	48.9	38.4	30
15:00	32.6	45.3	38.0	29
15:30	31.8	38.8	36.5	29
16:00	29.3	32.2	31.7	28

Table 2 - Temperatures recorded during the experiment on 09/02/2023.

Time	Inlet Air Temperature (Collector)	Outlet Air Temperature (Collector)	Oven Temperature	Room Temperature
8:00	31.3	31.0	28,9	26
8:30	28.8	34.4	28.7	26
9:00	29.3	32.7	28.4	26
9:30	31.9	38.1	30.9	28
10:00	36.1	42.6	33.0	28
10:30	33.9	41.1	33.4	28
11:00	38.0	46,8	35,4	29
11:30	41.2	49.4	37.1	29
12:00	42.6	58.9	42.1	30
12:30	40.0	50.3	39.6	30
13:00	40.8	55.8	42.5	30
13:30	38.1	46.4	38,6	30
14:00	40.4	53.3	41.4	29
14:30	30.9	34.6	32.2	28
15:00	29.5	31.6	29.7	27
15:30	28.5	30.1	28.6	27
16:00	27.7	29.1	27.8	27

As can be observed, the experiments started at 8:00. and ended at 16:00., which was the moment when the final measurements of the masses of bananas subjected to the drying process were taken. It can be seen that the temperature values in the region where the air exits the collector, i.e., the region where the air passes from the collector to the oven, are higher than the air temperature at the collector inlet. Thus, it can be concluded that the collector fulfills its intended functions for which it was developed.

The temperatures obtained on the 2nd day of the experiment were lower compared to the temperatures obtained on the 1st day of the experiment. This is due to the weather conditions on the 2nd day, with a lot of cloud cover, although the thermal sensation was of high temperature.

The temperatures obtained in the oven are higher than those obtained at the collector's air inlet. However, the temperature values obtained in the oven are significantly lower than the temperatures in the vicinity of the collector's air outlet, which suggests that new temperature collection points should be placed in future work to obtain data that can demonstrate a better distribution of temperature variation in the system.

With the data of the masses of bananas before and after the drying process, it was possible to determine the drying parameters presented in Equations (1) and (2). Table 3 shows the values determined during the two days of the conducted experiment.

Table 3 - Parameters determined during the drying processes on the day 1 (07/02/2023) and day 2 (09/02/2023).

	Mass of bananas before dehydration (g)	Mass of bananas after dehydration (g)	Mass loss (g)	Initial water mass (g)	Moisture content on a wet basis – x_{wb} (%)	Efficiency (%)
Day 1	183.0	72.1	110.9	128.1	23.85	86.57
Day 2	187.4	78.0	109.4	131.1	27.93	83.39
Media	185.2	75.0	110.1	129.6	25.89	84.98

According to the data presented in Table 3, both experiments showed a satisfactory loss of water mass, resulting in a moisture content on a wet basis of 23.85% for the first day of the experiment and 27.93% for the second day of the experiment. Thus, the experiment conducted on the first day met the requirements proposed by ANVISA, which is a moisture content on a wet basis of 25%. Although the results of the 2nd-day experiment exceeded the moisture value recommended by ANVISA, it is necessary to emphasize that drying processes can occur throughout the entire exposure period to the sun, and the experiments were conducted from 8:00. to 16:00. Therefore, there would still be the possibility of continuing the exposure on the following day or starting the drying processes at 7:00. and finishing at 17:00., which is a common practice, as demonstrated in research conducted by Gomes (2015).

Evaluating the results of the dryer efficiency, also known as the mass efficiency of the drying processes, the values obtained were 86.57% for the 1st day and 83.39% for the 2nd day. These results are satisfactory, as shown by Melo (2016), who obtained efficiency values around 80.19% in the research conducted, indicating that solar energy is a

competitive source compared to processes that use LPG or electricity. Thus, the developed dryer yielded good results for the banana drying process.

Figures 5a, 5b, 5c, and 5e show the sliced bananas before and after the drying procedures on the two days of tests conducted. In the figures, it is possible to observe the visual change in the texture of the bananas after the dehydration process they underwent.

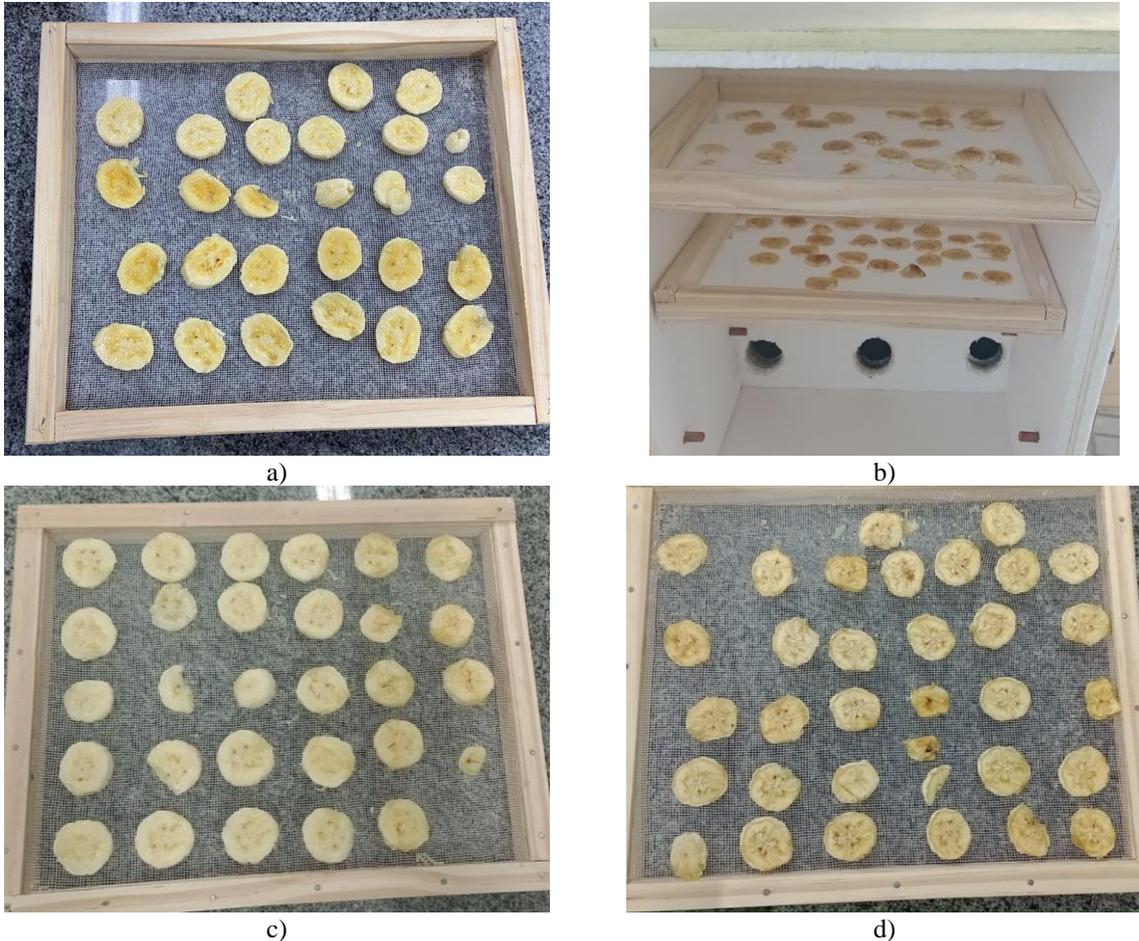


Figure 5. Bananas used in the drying process: a) banana from the 1st day of testing before drying, b) banana from the 1st day of testing after drying, c) banana from the 2nd day of testing before drying, and d) banana from the 2nd day of testing after drying.

Based on the obtained results, it is possible to verify the viability of the developed dryer and achieve a longer preservation of it, which, as stated by Araújo et al (2021), will enable small rural producers to reduce the loss of surplus material from their production and increase the added value of the product.

4. CONCLUSIONS

Based on the obtained results, it was possible to conclude that:

- The indirectly exposed solar dryer constructed proved to be effective in drying bananas. The research results, such as moisture content levels close to those recommended by ANVISA, demonstrate that solar drying can be a viable alternative for small-scale production of dried fruits.
- The results of this project show that solar drying of bananas can be efficiently carried out, resulting in a satisfactory final product quality. This could be an interesting option for producers looking to diversify their production and add value to their products.
- The research contributes to the knowledge about solar drying of fruits, specifically bananas, and opens up possibilities for further studies on the subject, including the use of other fruits. This contributes to the adoption of sustainable and low-cost practices in food production.

5. ACKNOWLEDGMENTS

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