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RESEARCH ARTICLE

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Low-cost solar dryer dehydrates silver banana with a prediction of diffusion approximation model

Secador solar de baixo custo desidrata banana prata com previsão de modelo de aproximação de difusão

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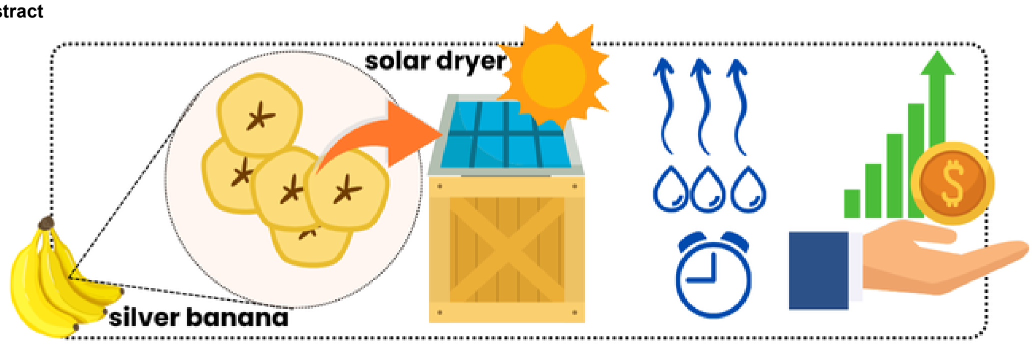
Abstract
Solar dryers made from recycled materials offer a cost-effective solution for promoting the widespread adoption of this technology and reducing food production costs. In this study, a low-cost solar dryer was constructed using repurposed materials, employing indirect exposure, and its performance was evaluated through a kinetic study on banana slice drying (*Musa* spp.). Drying was carried out until equilibrium moisture, reaching constant mass. The temperature and relative humidity (RH, %) of the drying air were monitored. Fourteen empirical models were used to fit the experimental data. The banana slices took approximately 300 min to dry, with final moisture of 1.8%. The mean operational conditions during natural drying were 59.08±9.16 °C and RH = 39±4%. The diffusion Approximation model fitted the drying curve better, as it presented the lowest reduced Chi-square ($\chi^2 = 2.9\times10^{-5}$) and a high coefficient of determination (R^2 = 0.9998). The effective diffusion coefficient (Def = 5.4×10^{-9} m^2/s, R^2 = 0.9935) was determined. Thus, the solar dryer demonstrated efficient performance in the banana drying process, requiring minimal design effort. Furthermore, despite the limitations in controlling the drying conditions, most of the mathematical models successfully predicted the drying process due to the dryer's ability to maintain the continuity of the drying curve, suggesting potential viability for this low-cost dryer.

Keywords: Diffusion coefficient, fruit drying, *Musa* spp., prediction models, solar drying.

Resumo
Os secadores solares fabricados a partir de materiais reciclados oferecem uma solução rentável para promover a adoção generalizada desta tecnologia e reduzir os custos de produção de alimentos. Neste estudo, foi construído um secador solar de baixo custo utilizando materiais reaproveitados, empregando exposição indireta, e o seu desempenho foi avaliado através de um estudo cinético sobre a secagem de fatias de banana (*Musa* spp.). A secagem foi realizada até a umidade de equilíbrio, atingindo massa constante. A temperatura e a umidade relativa (RH, %) do ar de secagem foram monitorizadas. Foram utilizados catorze modelos empíricos para ajustar os dados experimentais. As fatias de banana levaram aproximadamente 300 minutos para secar, com uma humidade final de 1,8%. As condições operacionais médias durante a secagem natural foram 59,08±9,16 °C e RH = 39±4%. O modelo de Aproximação por Difusão ajustou-se melhor à curva de secagem, pois apresentou o menor Qui-quadrado reduzido ($\chi^2 = 2{,}9\times10^{-5}$) e alto coeficiente de determinação (R^2 = 0,9998). Foi determinado o coeficiente de difusão efetivo (Def = 5,4×10-9 m^2/s, R^2 = 0,9935). Assim, o secador solar demonstrou um desempenho eficiente no processo de secagem da banana, exigindo um esforço mínimo de concepção. Além disso, apesar das limitações no controle das condições de secagem, a maioria dos modelos matemáticos previu com sucesso o processo de secagem devido à capacidade do secador de manter a continuidade da curva de secagem, sugerindo uma viabilidade potencial para este secador de baixo custo.

Palavras-chave: Coeficiente de difusão, modelos de previsão, *Musa* spp., secagem de frutos, secagem solar.

Graphical Abstract



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ROYALDATASET

1. Introduction

The world annually produces approximately one billion tons of fruit, with Brazil ranking as the third largest producer, yielding 43 million tons (FAO, 2023). Fruits are rich in essential nutrients and play a crucial role in human nutrition. However, due to their high moisture, typically ranging from 70% to 90%, they are highly perishable (Carvalho et al., 2019), which causes many losses.

In Brazil, between 40% and 50% of fruit is lost between harvest and consumption. These losses occur due to inadequate transportation and storage, premature ripening of fruits, and deficiencies in pre- and post-harvest treatments. These factors lead to estimated annual losses of millions of tons (Carvalho et al., 2019; FAO, 2021). This emphasizes the need for processes that can preserve these products for extended periods.

It is recommended to refrigerate or process fruits shortly after harvest to minimize losses. Throughout history, mankind has developed various techniques and methods to preserve food in its natural state, as it spoils easily. Different preservation techniques have varying effects and are therefore more suitable for specific products (Caballero et al., 2016).

Drying associated with hot air is a technique widely used to remove moisture offering advantages such as mass reduction, improved product preservation, and reduced transportation and storage costs. Furthermore, removing water prevents the growth of disease-causing microorganisms and prolongs the shelf life of the dried product (Jahromi et al., 2022; Almeida et al., 2023; 2024). Drying involves eliminating water from a solid food item in the form of steam through thermal evaporation at a temperature below the boiling point of water (Deamici et al., 2016; Lamidi et al., 2019).

However, conventional hot air-drying methods can be costly due to the requirement of sophisticated equipment and electricity consumption. As an alternative to these dryers, solar dryers have emerged and are already available in some models on the market. These solar dryers typically require 40% less time than natural solar drying without equipment to effectively dry food (Etim et al., 2020). Moreover, solar dryers provide protection against insect attacks and other physical agents. According to Almeida et al. (2022), solar dryers are low-cost equipment that enables the production of less perishable food products with increased nutritional and economic value. They also offer the possibility of implementation by rural producers, generating income in the process.

Replacing electrical energy with solar energy in fruit drying processes can bring positive results in terms of social inclusion, the environment, and the economy. This technology allows the involvement of small producers in industrial processing as suppliers of raw materials with greater added value compared to fresh raw materials. Consequently, dry products can serve as a source of income for disadvantaged communities (Almeida et al., 2022).

Given these considerations, this study aimed to construct a low-cost solar dryer using discarded materials powered by solar energy through indirect exposure. The performance of the dryer was evaluated through a kinetic study on the drying process of silver bananas (*Musa* spp.).

2. Materials and Methods

2.1 Construction of the solar dryer by indirect exposure

The dryer design met the specifications shown in **Fig. 1**, while the construction steps followed the flow diagram shown in **Fig. 2**.

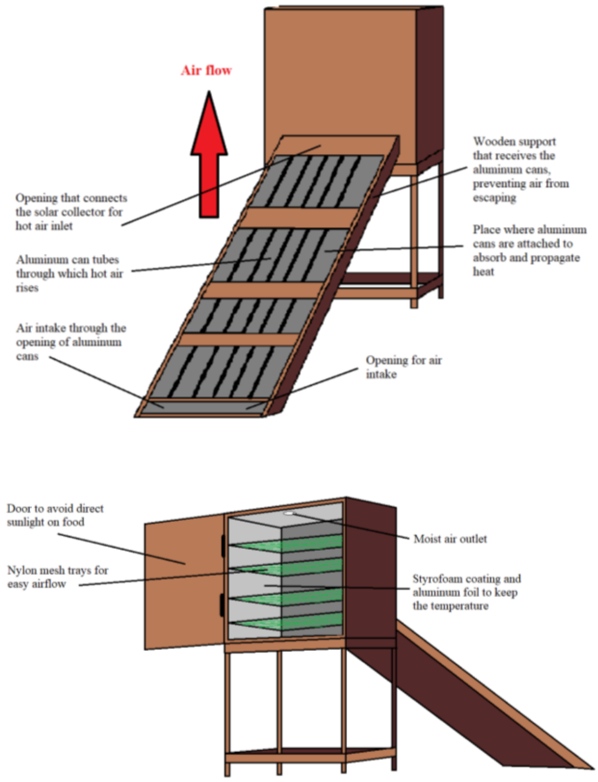

Fig. 1 Layout of solar dryer by indirect exposure.

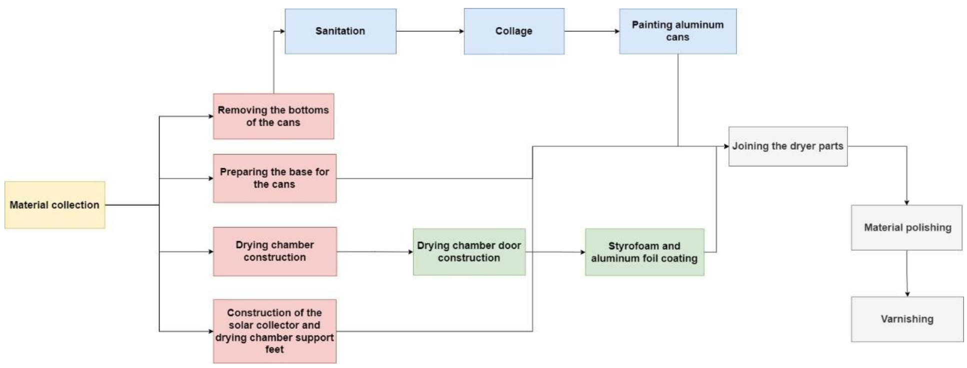

Fig. 2 Flow diagram of the indirect exposure solar dryer construction process.

The dryer's structure consisted of a wooden base that served as support feet, an upper chamber for food insertion, and a solar collector for heat absorption and propagation. The wooden base was specifically constructed to provide support for the drying chamber, ensuring the prevention of potential soil contamination. The chamber area was constructed using wood, with the interior covered in Styrofoam and aluminum foil, and an external coating of varnished wood. Careful attention was given to maintaining adequate space for shelf movement and creating an opening for fitting the solar collector. The shelves were constructed with plywood edges and a nylon mesh interior, facilitating the passage of air between the fruits and among the shelves themselves. Detailed construction aspects can be observed in **Fig. 3**.

Fig. 3 Construction of the base and drying chamber of the solar dryer by indirect exposure. Note: Indirect Solar Dryer. Where (a) is the base of the dryer; (b) is the dryer chamber; and (c) is the dryer shelves.

The solar collector consisted of a configuration of 60 aluminum cans, with their upper and lower parts removed, ensuring sanitation and sterilization to prevent potential food contamination. The cans were connected using hot glue to ensure an airtight seal, forming six tubes with ten cans each. To enhance heat absorption, the tubes made from the cans were coated with matte black paint (Sivakumar et al., 2020). The solar collector was then affixed to the wooden structure and integrated into the prototype. Construction details can be seen in **Fig. 4**.

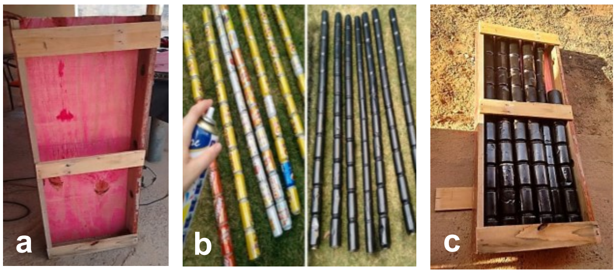

Fig. 4 Solar collector construction. Note: Indirect Solar Dryer. Where (a) is the base of the solar collector; (b) are the black painted aluminum pipes; and (c) is the joining of the parts of the solar collector.

The drying chamber had dimensions of 40 cm in length, 30 cm in width, and 75 cm in height, resulting in a total volume of 90 L. It was equipped with four shelves, each spaced approximately 10 cm apart. The base of the dryer was constructed with identical dimensions to that of the drying chamber. The solar collector measured 1.25 m in length, 40 cm in width, and 20 cm in depth, corresponding to a total area of 0.5 m².

Once the construction of the dryer was completed, a functional test was conducted. Bananas were selected as the fruit for drying in the apparatus. These bananas were purchased from the municipal market in Barreiras, Bahia state, Brazil. Careful consideration was given to selecting bananas that were in a perfect stage of ripeness, characterized by a yellow color and minimal black spots, while also ensuring that they were free from physical damage. Bananas were sliced into rectangular pieces with a thickness of 2 mm. Moisture analysis of the bananas was conducted using AOAC method 934.01 (AOAC, 2019) on a wet basis.

2.3. Solar dryer functionality test

The banana drying tests took place in Barreiras, Bahia, Brazil. At 8:30 in the morning, 30 min before drying began, the solar dryer was positioned in direct sunlight. The banana slices were placed on the dryer trays, where they were dried until constant mass, using indirect radiation. Prior to drying, the four shelves of the dryer were weighed on a digital scale while empty. They were subsequently filled with banana slices and weighed again.

The drying kinetics of the fruit was possible to be determined from data on its mass measured periodically. The mass measurements followed Almeida et al. (2022): every 2 min for the first 10 min; every 5 min for 30 min; every 10 min for another 30 min; every 20 min for 1 h; and every 30 min until constant mass. To minimize browning, the banana slices underwent pretreatment with lemon juice. During drying, the dryer was positioned in an area with direct sunlight. Weather conditions during the experiment were favorable, characterized by clear skies, ample wind, and light.

Temperature and RH within the dryer were recorded every hour using a conventional thermometer and a thermo-hygrometer (Incoterm, 7663.02.0.00, Brazil), respectively. These measurements were employed to calculate the mean drying temperature and RH.

2.4. Kinetic study and mathematical modeling of banana solar drying

For the kinetic study of solar drying of banana slices, dimensionless moisture values (RX) were measured at each time interval using **Eq. 1**.

$$RX = \frac{X - X_{eq}}{X_0 - X_{eq}} \qquad \textbf{Eq. (1)}$$

Note: X is the moisture content of the sample during drying, $\boldsymbol{X_{eq}}$ is the equilibrium moisture content, and $\boldsymbol{X_0}$ is the moisture content at the initial time. All terms were measured on a wet basis.

Equilibrium moisture was measured by the dynamic method, until constant mass. The regression analysis of the non-linear data was performed using OriginPro® software version 2022, employing the Gauss-Newton method.

The modeling of banana drying kinetics was described using experimental drying data. For this, 14 empirical models were used (**Table 1**). The initial parameter values for optimization of the fit in OriginPro® 2022 software were also provided in **Table 1**. These values were obtained from previous studies on natural and forced convective drying of bananas conducted by different researchers.

For quantitative assessment of the model's adequacy to the experimental data, the reduced Chi-square (χ^2) value (**Eq. 2**) and the adjusted coefficient of determination (R^2) value (**Eq. 3**) were used as statistical parameters (Belghith et al., 2016). These parameters were calculated using OriginPro® 2022. In turn, the effective water diffusion coefficient was determined using **Eq. 2**, derived from diffusion theory and in accordance with Fick's second law.

$$D_{ef} = -\,\alpha.\frac{4L^2}{\pi^2} \qquad \textbf{Eq. (2)}$$

Note: $\boldsymbol{D_{ef}}$ is the effective diffusion coefficient ($m^2.s^{-1}$), **L** is the characteristic length (half the thickness of the sample), and **α** is the slope of the linear fit of the data ln (X/X_0) as a function of time.

Table 1 Mathematical models used in the banana solar drying curve in an indirect dryer by natural convection.

Models	Equation	Initial parameter values for tuning optimization in OriginPro®	Reference
Page	RX = exp(-k.t^n)	k = 0.0169 n = 0.8337	Silva et al. (2009)
Henderson & Pabis	RX = a.exp(-k.t)	k = 0.0067 a = 0.9274	Silva et al. (2009)
Lewis (Newton)	RX = exp(-k.t)	k=0.034	Silva et al. (2009)
Exponential Two Terms	RX = a.exp(-k.t)+(1-a).exp(-k.t)	k = 0.0895 a = 0.0022	Silva et al. (2009)
Wang & Singh	RX = 1+a.t+b.t^2	a = -0.00487 b = 0.0000	Silva et al. (2009)
Midilli, Kucuk & Yapar	RX = a.exp(-k.t^n)+b.t	k = 0.5867 n = 0.8696 a = 0.9773 b = -0.0007	Leite et al. (2015)
Borges	RX = k_0.exp(-k_1.t)	k_0 = 0.0171 k_1 = 0.009989	Borges et al. (2010)
Diffusion Approach	RX = a.exp(-k.t)+(1-a).exp(-k.b.t).t	k = 0.1464 a = 1 b = 1	Nasri (2020)
Two Terms	RX = a.exp(k_0.t)+b.exp(-k_1.t)	k_0 = -0.2016 k_1 = 0.6358 a = 0.3861 b = 0.6177	Nasri (2020)
Page modified	RX = exp(-(k.t)^n)	k = 0.0130 n = 1.1302	Santos et al. (2021)
Logarithm	RX = a.exp(-k.t)+b	k = 1.4828 a = 0.1627 b = 0.7437	Nasri (2020)
Verma	RX = a.exp(-k.t)+(1-a).exp(-g.t)	k = -0.2161 a = 0.3635 g = 0.602	Nasri (2020)
Lima	RX = a_1.exp(-k_1.t)+a_2.exp(-k_2.t)+a_3.exp(-k_3.t)	k_1 = 0.0011 k_2 = 0.0049 k_3 = 0.0048 a_1 = 0.3395 a_2 = 0.3407 a_3 = 0.3404	Farias et al. (2020)
Thompson	RX = exp((-a-(a^2+4b.t)^{0,5})/2b)	a = -13.0686 b = 0.288870	Costa et al. (2018)

Note: **t** is the drying time (min); **k**, $\mathbf{k_0}$, $\mathbf{k_1}$, $\mathbf{k_2}$, $\mathbf{k_3}$ are drying constants (min^{-1}), and **a**, **a1, a2, a3, n**, **b**, **c, g** are mathematical constants of the model.

3. Results and Discussion

3.1 Solar dryer for indirect exposure

The structure of the solar dryer for indirect exposure (**Fig. 5**) facilitates the following process: the air is heated inside the solar collector, being the area where energy capture is concentrated. Due to the pressure difference, the heated air enters the drying chamber and meets the bananas (Mehran et al., 2019). As a result, the moisture present in the bananas evaporates through heat transfer. The moist air exits the dryer through a pre-drilled hole in the equipment's top section.

The estimated total cost of the device is 62.92 US dollars (USD) (**Table 2**). This cost is significantly lower, up to 79.03%, compared to various models of commercial dryers, which typically range between 180 and 300 USD (Meloni, 2021). It is worth noting that most of the purchased materials can be reused for other purposes and in the construction of additional dryers. This reuse potential reduces the cost of producing the subsequent equipment to USD 33.58, based on prices prevailing in Brazil in 2022. This represents a 46.63% reduction in expenses associated with the production of the first dryer, resulting in a reduction overall of 88.81% compared to commercial dryers.

Figure 5. Solar dryer by indirect exposure.

Table 2 Cost of materials for building the solar dryer.

Material	Quantity	Origin	Mean commercial value (USD)[2]	Can it be reused?
Woodite 5 mm	2 plates	Discard	7.51	No
Screws 3 mm	200 units	Discard	0.11	No
Screws 3,5 mm	30 units	Discard	0.28	No
Nails	30 units	Discard	4.40	No
Latch 06 cm chrome	1 unit	Discard	1.64	No
Silicone glue	1 tube	Trade	2.25	No
Hinge	2 units	Discard	0.50	No
Bolt	1 unit	Trade	1.62	No
Varnish	1 can	Trade	5.23	No
Aluminum foil 7.5 m	1 pack	Discard	1.70	No
Styrofoam plates	2 plates	Discard	1.52	No
Hammer	1 unit	Own material	3.19	Yes
Sledgehammer	1 unit	Own material	4.65	Yes
Drills	1 unit	Own material	0.25	No
Screwdriver	1 unit	Own material	2.44	Yes
Hot glue	10 sticks	Own material	0.83	No
Hot glue pistol	1 unit	Own material	2.49	Yes
Pencil	1 unit	Own material	0.18	Yes
Brush	1 unit	Own material	1.27	Yes
Square and compass	1 kit	Own material	2.57	Yes
Measuring tape	1 unit	Own material	1.56	Yes
Fine tip scissors	1 unit	Own material	1.27	Yes
Extension (electric	1 unit	Own material	1.83	Yes
cord)	1 unit	Own material	0.55	Yes
Fine point knife	1 tube	Trade	1.89	No
Black Spray Paint	77 units	Discard	3.85	No
Aluminum cans	1 kit	Trade	7.34	Yes
PPE[1]				
Total			**62.92**	

Note: [1]Personal protection equipment (gloves, goggles, mask, and ear protectors); [2]Total value calculated in Brazil in 2022.

According to Almeida et al. (2022), the construction cost of a Styrofoam-based direct exposure solar dryer was estimated at 20.37 USD. In comparison, the indirect solar dryer used in this study, despite being more advanced, environmentally friendly, and providing better protection against excessive drying, was only three times more expensive than the prototype developed by Almeida et al. (2022) for the first dryer, and 1.65 times more expensive for subsequent dryers.

The direct dryer described by Almeida et al. (2022) features a single shelf with dimensions like the present study, but it is inclined at 30°. In contrast, the indirect dryer has four shelves and can accommodate four times more fruit than the direct dryer. Additionally, the shelves of the indirect dryer are positioned horizontally, preventing the product from falling during the drying process.

3.2. Banana slices drying in the solar dryer

The initial moisture of the bananas was 73.3±0.85%, close to the 71.9% attributed in the literature (TBCA, 2023). The drying process was carried out efficiently, successfully dehydrating the banana slices to an equilibrium moisture content of 1.8%. Throughout the drying process, the mean temperature was 59.08±9.16 °C, with a RH of 39±4%. Temperature ranged from 45 to 75 °C, while the RH fluctuated between 36% and 47%. It is recommended to maintain a mean drying temperature between 45 and 60 °C for fruits, as temperatures above 60 °C can be detrimental to agricultural products (CPRA, 2009; Marulanda-Meza & Burbano-Jaramillo, 2021). The dryer in this study ensured the quality of drying by preventing excessive drying of the banana surface, thanks to its indirect exposure to the sun. Regarding the parameters involved in drying, temperature has the most significant influence, as it affects the drying rate and product dimensions more than air velocity, RH, and raw material pretreatments (Borges et al., 2010).

It took approximately 300 min for the samples to reach an equilibrium moisture content of 1.8%, resulting in a reduction of 97.54% in moisture content compared to the initial state of the banana. In comparison to other solar dryers with indirect exposure (**Table 3**), this dryer achieved a superior performance.

Table 3 Solar drying of bananas by natural convection in an indirect dryer.

Process conditions	Drying time (min)	Moisture reached (%)	Better fit the drying curve	R^2	D_{ef} (m^2/s)	Reference
T = 61.2 °C, varying between 38 to 81 °C	600	3.57*	--	--	--	Lingayat et al. (2017)
T = 38 to 82 °C	360	3.98**	--	--	--	Lingayat et al. (2020)
T = 41 to 73 °C, RH = 14.56 to 27.27%, AV = 0.53 m/s with variation between 0.1 to 2.45 m/s	480-600	5.22**	Midilli, Kucuk & Yapar	0.99	4.7×10^{-9}, varying between 2.3×10^{-9} to 6.2×10^{-9}	Lingayat & Chandramohan (2021)
T = 63.8 to 71.3 °C	600	18.75	Elangovan (created by the authors)	0.99	$0.9\text{-}1.6\times10^{-9}$	Elangovan & Natarajan (2021)
T = 40.5 °C ranging from 30 to 55 °C, RH = 10 to 41%	1080	20	Henderson & Pabis	0.99	--	Singh & Mall (2020)

Note: *value calculated based on data recorded by the authors. **The authors did not provide the initial moisture, so the value was calculated based on the mean banana moisture (71.1%), according to the TBCA (2023), and the final moisture ratio reported by the authors.

While other studies required drying times ranging from 360 to 1080 min to reach moisture levels between 3.57% and 20%, the indirect solar dryer constructed using recycled materials proved more efficient. Among the studies using different types of solar dryers, only Roratto et al. (2021) achieved an equilibrium moisture content below 1.8% in a shorter time of 240 min, but they employed a hybrid vacuum dryer.

On the other hand, conventional dryers typically require between 180 and 480 min to dry bananas to a moisture level below 10% at temperatures like those achieved by the indirect solar dryer (**Table 4**). These findings indicate that the dryer constructed using recycled materials was able to achieve comparable performance to conventional dryers.

Table 4 Solar drying of bananas by forced convection in conventional dryers.

Dryer type	Process conditions	Drying time (min)	Moisture reached (%)	Better fit the drying curve	R^2	D_{ef} (m^2/s)	Reference
Oven	T = 60 °C	200	0	Page	0.99	--	Silva et al. (2017)
Fixed bed	T = 70 °C, AV = 0.55 m/s	480	0	Diffusion	0.99	--	Rodrigues et al. (2015)
Trays	T = 60 °C, AV = 1.5 m/s	450	<10	Logarithm	0.99	1.4×10^{-10}	Silva et al. (2021)
Trays	T = 50 °C, AV = 0.14 m/s T = 50 °C, AV = 0.42 m/s T = 70 °C, AV = 0.14 m/s T = 70 °C, AV = 0.42 m/s	280 300 180 240	7.13* 3.57* 7.13* 1.43*	Borges (own model)	0.99 0.99 0.99 0.99	--	Borges et al. (2010)

Note: *The authors did not provide the initial moisture, so the value was calculated based on the mean banana moisture (71.1%), according to the TBCA (2023), and the final moisture ratio reported by the authors.

Several factors may have contributed to the superior performance of the dryer used in this study compared to other solar dryer models and its similarity to conventional dryers. These factors include the dimensions and initial geometric shape of the bananas, the arrangement of the raw material inside the dryer, the variety of the raw material, favorable climatic conditions in the city of Barreiras, and the design and materials used in the construction of the dryer.

During the drying process, a reduction in the dimensions of the sliced bananas was observed, including their length, width, and thickness. These changes can be attributed to the removal of water, leading to a higher concentration of dry matter and a decrease in the pressure exerted by the liquid on the cell walls of the fruit. This water removal process causes cell contraction and, consequently, a reduction in the volume of the final product (Almeida et al., 2022). Although these changes in geometric dimensions were observed, they were not measured as the focus of the study was on banana drying kinetics, and the selection of the best empirical model was to simplify the mathematical modeling by not considering shrinkage.

In this study, rectangular slices with a thickness of 2 mm were chosen for drying bananas, whereas other researchers often use cylindrical, circular, or square shapes with thicknesses ranging from 3 to 30 mm or even whole uncut fruits. Camelo et al. (2019) have reported that the geometric shape of the fruit affects the drying time, while Borges et al. (2010) recommend using thinner slices, which was implemented in this study. The dried banana samples exhibited a golden and brighter appearance compared to the fresh fruit, without excessive darkening. This is attributed to the drying process and the use of the lemon juice solution. Color changes occur due to the alteration of pigments in the fruit caused by the oxidation of these substances during drying. Browning can also result from the activity of oxidative enzymes, such as peroxidases. Apart from using citric acid or lemon juice solution, other methods can be employed to prevent or reduce browning, such as bleaching, sulfitation, and sulfuration (Food Ingredients Brasil, 2016).

Silva et al. (2022), in their study on drying silver bananas in a solar dryer with direct exposure, found no significant difference in drying time between bananas pretreated with citric acid or lemon solution and those without treatment. However, they did observe that the pretreated bananas reached the maximum drying rate faster, suggesting that these treatments facilitated the initial migration of water to the surface of the fruit.

The slices located closer to the walls of the dryer and those that were more spaced from each other dried at a faster rate. It was also observed that the slices on the lower shelf dried more quickly than those on the upper shelf, which can be attributed to the enhanced air circulation in the lower part due to its proximity to the collector. The difference in air circulation can be mitigated by installing a small fan like a cooler.

Although there are over 1000 types of bananas categorized into 50 groups of varieties (FAO, 2019), their moisture content usually exhibits minimal variation. According to TBCA (2023), the moisture content of different banana varieties ranges from 63.9% (land banana) to 75.9% (dwarf banana). Most of the species listed in the table have water content like that of silver banana (73.3±0.85%), such as apple banana (71.3%), gold banana (69%), and fig banana (70.1%). Furthermore, many researchers who conducted studies on banana drying did not specify the variety used, making comparisons between studies challenging.

Natural drying of food ingredients should only be performed in areas with satisfactory levels of solar radiation, where the mean maximum temperature ranges between 35 °C and 40 °C, and pollution levels and RH are low (Celestino, 2010). Brazil, and specifically the city of Barreiras where the performance test of the apparatus was conducted, meets all of these prerequisites.

Brazil has a high solar energy potential, as almost the entire country receives sunlight throughout the year (Almeida et al., 2022). The level of solar irradiation in the country varies between 4.25 kWh/m² and 6.8 kWh/m², with a mean of 6.2 kWh/m² (Bezerra & Santos, 2016; Imperial & Pereira, 2014). This index is approximately six times higher than that found in Germany, the country that utilizes solar energy the most worldwide (BSW-Solar, 2021).

The state of Bahia, particularly the region where the city of Barreiras is located, experiences the highest levels of solar irradiation in Brazil (Almeida et al., 2022). The city has consistently high temperatures throughout the year and receives minimal rainfall (Climate-Data.Org, 2021; INMET, 2015, 2020; Weather Spark, 2017). Recognizing the solar resource potential in Barreiras, the city is investing over R$ 400 million in the construction of a photovoltaic plant to establish a solar energy park (Almeida et al., 2022). Additionally, Barreiras boasts low pollution levels.

In a study by Almeida et al. (2022), araticum pulp (*Annona crassiflora* Mart.) was dried in Barreiras-BA, Brazil, using a solar dryer for direct exposure. The authors estimated a drying time between 360 and 420 min to achieve the equilibrium moisture content of the fruit (2.32±0.28%), which initially contained approximately 80% moisture (Almeida et al., 2022, 2023). The drying process occurred at a mean temperature of 58.62 °C and a mean RH of 37.35%. It is noteworthy that the temperature and RH values obtained in the present study are like those reported by Almeida et al. (2022), highlighting the solar drying potential of the region. However, the fact that the indirect dryer achieved comparable parameters to the direct exposure dryer may be influenced by the time of year during which the drying took place. The bananas in this study were dried in August, which is the most radiant month in the city, with a daily mean solar irradiation of 6.6 kWh/m² (Imperial & Pereira, 2014; Weather Spark, 2017).

Although the indirect dryer attained mean temperature and RH like the direct exposure dryer developed by Almeida et al. (2022), the advantage of indirect exposure was that it protected the product from excessive drying on the surface, a favorable aspect that would otherwise occur in a dryer with direct exposure to the sun.

The moisture content remaining after natural drying is generally considered suitable for storage, effectively extending the shelf life of the product. However, in terms of sensory preferences, producers may prefer a higher moisture content, as dried fruits with 15% to 20% moisture are desired (Celestino, 2010), as it speeds up the drying process. This moisture percentage is commonly used in the production of commercially available dried products, and in this study, it was achieved using the solar dryer in just 120 min (two hours). In any case, dehydrated bananas can be marketed as various products, including chips and flour (which can be used in other food products).

The design, construction, and application of solar dryers for small-scale fruit and vegetable producers align with the eighth Sustainable Development Goal (SDG) among the 17 SDGs. This goal aims to promote sustained, inclusive, and sustainable economic growth by ensuring full and productive employment and decent work for all. These goals are designed to guide present actions in a way that does not compromise the well-being of future generations (United Nations, 2022).

Promoting the use of solar dryers among small producers offers a low-cost, environmentally friendly, and efficient method of bringing new products to the market while providing high-quality raw materials for the food industry. This approach not only ensures employment opportunities and income for small producers but also fosters sustainable development. The production of dehydrated fruits using indirect solar dryers not only supports family farming but also contributes to the enhancement of the fruit industry.

3.3. Solar drying curve of banana slices and mathematical modeling

The drying curve of bananas in an indirect solar dryer (**Fig. 6**) exhibited a characteristic shape resembling a typical constant-rate stage, as described by Geankopolis (1998) in his work 'Transport Processes and Unit Operations'. In this work, the author elucidates the different stages of the drying process and their implications.

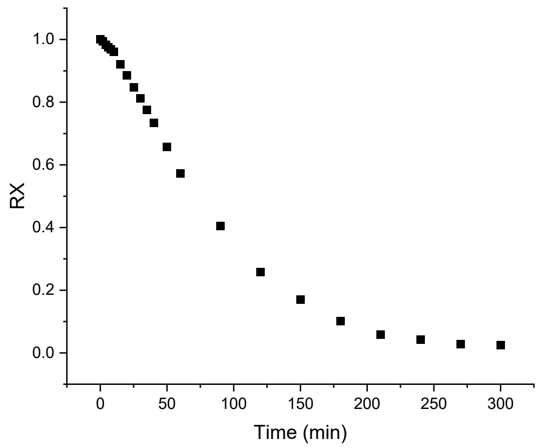

Fig. 6 Typical drying curve of sliced fresh banana in a solar dryer.

In the A-B stage (the first 15 min), the banana slices acclimated to the drying conditions. This step exhibits a similar behavior for all types of drying, regardless of the raw material or its ripeness stage. The B-C stage (between 15 and 60 min) represents the constant drying phase. Typically, this stage progresses slowly, especially for foods with high water content (Geankopolis, 1998). The C-D stage (between 60 and 240 min) displayed a declining trend as the banana slices reached their critical moisture content. At this point, an increase in internal resistance occurred, leading to insufficient water transfer from the interior to the surface of the fruit to compensate for the evaporated water. Consequently, some cracks appeared on the banana slices.

The D-E stage, between 240 and 300 min, marked a second reduction phase in slice moisture until reaching equilibrium. In solar drying processes, this period is often prolonged due to the lack of control over factors such as temperature, RH, and airflow velocity. However, in the case of banana drying, this stage occurred quickly, indicating that the drying conditions were practically stable, with only minor oscillations occurring.

Fig. 7 illustrates the adaptation of predictive models to the drying curve of banana slices. The parameter values are presented in **Table 5**, along with the corresponding R^2 and χ^2 values.

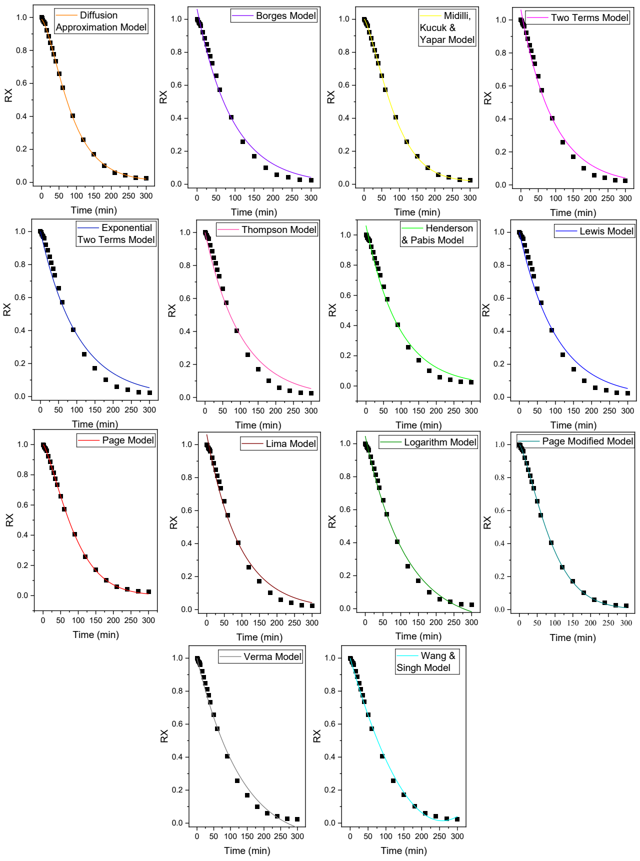

Fig. 7 Fitting of empirical models to the drying curve of bananas in a solar dryer.

When researchers employ empirical models to describe the drying behavior of a specific food, they consider various parameters to determine the model's adequacy, often relying on the R^2. A higher R^2 value indicates a more suitable model for predicting the drying behavior. In our study, nearly all models achieved R^2 values greater than 0.99, except for the Lewis, Thompson, and Exponential Two Terms models. The Midilli, Kucuk & Yapar model exhibited the highest R^2, approaching the ideal coefficient of 1. However, other models also displayed excellent coefficients, such as the Diffusion Approximation (R^2 = 0.9998), Page (R^2 = 0.9997), Henderson & Pabis (R^2 = 0.9997), and Modified Page (R^2 = 0.9997).

Models with R^2 values of 0.93 or higher are generally considered adequate (Oliveira et al., 2013). Accordingly, all the tested models in our study can be deemed satisfactory. However, relying solely on the coefficient itself is insufficient for determining the best model, as it may lead to misinterpretation of the results (Madamba et al., 1996). Many researchers tend to select the model with the highest R^2 as the best one without guaranteeing its superiority. To address this limitation, we also calculated the χ^2 since the model with the χ^2 closest to zero is considered the most accurate (Panchariya et al., 2002).

Table 5 Data found by OriginPro® 2022 comparing empirical models with the drying curve of banana slices.

Models	Equation	Parameter values adjusted in OriginPro®	R^2	χ^2
Page	$RX = exp(-k.t^n)$	k = 0.0023 n = 1.3275	0.9997	4.0×10^{-5}
Henderson & Pabis	RX = a.exp(-k.t)	k = 0.0108 a = 1.0622	0.9907	1.4×10^{-3}
Lewis (Newton)	RX = exp(-k.t)	k = 0.0098	0.9823	2.6×10^{-3}
Exponential Two Terms	RX = a.exp(-k.t)+(1-a).exp(-k.t)	k = 473.6301 $a = 2.0656 \times 10^{-5}$	0.9823	2.7×10^{-3}
Wang & Singh	$RX = 1+a.t+b.t^2$	a = -0.0077 $b = 1.4867 \times 10^{-5}$	0.9963	5.7×10^{-4}
Midilli, Kucuk & Yapar	$RX = a.exp(-k.t^n)+b.t$	k = 0.0022 n = 1.3434 a = 1.0013 $b = 4.7317 \times 10^{-5}$	0.9999	4.1×10^{-4}
Borges	$RX = k_0.exp(-k_1.t)$	k_0 = 1.0622 k_1 = 0.0108	0.9907	1.4×10^{-3}
Diffusion Approach	RX = a.exp(-k.t)+(1-a).exp(-k.b.t).t	k = 0.0156 $a = 1.8091 \times 10^4$ b = 1.9785	0.9998	2.9×10^{-5}
Two Terms	$RX = a.exp(k_0.t)+b.exp(-k_1.t)$	k_0 = 0.0108 k_1 = 0.0108 a = 0.5311 b = 0.5311	0.9907	1.6×10^{-3}
Page modified	$RX = exp(-(k.t)^n)$	k = 0.0023 n = 1.3278	0.9997	4.0×10^{-5}
Logarithm	RX = a.exp(-k.t)+b	k = 0.0088 a = 1.1455 b = -0.0985	0.9947	8.5×10^{-4}
Verma	RX = a.exp(-k.t)+(1-a).exp(-g.t)	k = 0.0049 a = 45.9000 g = 0.0048	0.9915	1.4×10^{-3}
Lima	$RX = a_1.exp(-k_1.t)+a_2.exp(-k_2.t)+a_3.exp(-k_3.t)$	k_1 = 0.0108 k_2 = 0.0108 k_3 = 0.0108 a_1 = 0.2562 a_2 = 0.4040 a_3 = 0.4020	0.9907	1.8×10^{-3}
Thompson	$RX = exp((-a-(a^2+4b.t)^{0,5})/2b)$	a = -358.6566 b = 1.8749	0.9822	2.7×10^{-3}

This time, the Diffusion Approximation model achieved the best result ($\chi^2 = 2.9 \times 10^{-5}$), closely followed by the Page models ($\chi^2 = 4.0 \times 10^{-5}$), Modified Page ($\chi^2 = 4.0 \times 10^{-5}$), Midilli, Kucuk & Yapar ($\chi^2 = 4.1 \times 10^{-4}$), Wang & Singh ($\chi^2 = 5.7 \times 10^{-4}$), and Logarithm ($\chi^2 = 8.5 \times 10^{-4}$), in descending order. A χ^2 value lower than 1.5×10^{-3} has been considered satisfactory for selecting the best drying models for various food products (Oliveira et al., 2013). Hence, all the mentioned models yielded adequate results in representing the drying curve of bananas.

The overall findings indicate that the Diffusion Approximation model offers the best fit to the banana drying curve compared to other tested empirical models. This conclusion is supported by its second-highest R^2 value and the lowest χ^2 value. However, other models such as Midilli, Kucuk & Yapar, Page, and Modified Page also demonstrated excellent fitting. On the other hand, models like Lima, Two Terms, Exponential Two Terms, Lewis, and Thompson did not adequately fit the drying curve of the fruit. The Midilli, Kucuk & Yapar model is listed as one of the best fits for drying bananas in an indirect solar dryer (**Table 3**). Additionally, Page's model is also cited as the top predictor for conventional banana drying (**Table 4**).

3.4. Effective diffusion coefficient

The effective diffusion coefficient (D_{ef}) serves as a measure of the rate at which water diffuses and considers all factors influencing water migration. It plays a critical role in selecting suitable equipment for the raw material and gaining a comprehensive understanding of its utilization (Almeida et al., 2022). **Fig. 8** was employed to determine the D_{ef}, which exclusively demonstrated a diffusion process. This observation suggests that there were no alterations in the water movement through the banana slices throughout the drying process.

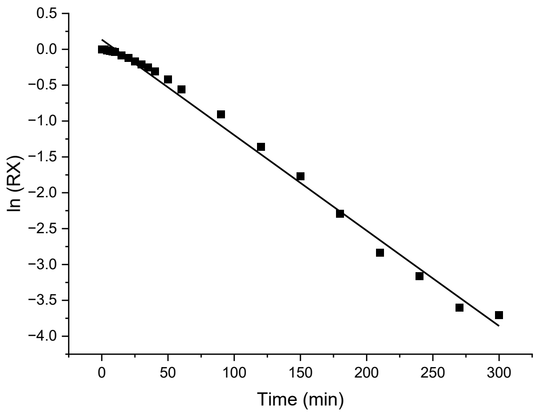

Fig. 8 Plot for determining the effective diffusion coefficient of fresh banana slices in a solar dryer.

The slope coefficient of the line (α = -0.0133, **Eq. 3**) was utilized to calculate the D_{ef} value employing **Eq. 2**, utilizing the linear regression technique. This analysis considered the characteristic length of the fresh banana, which corresponds to 1×10^{-3} m, equivalent to half the thickness of the fruit slice.

$$y = -0.0133x + 0.1348 \qquad \textbf{Eq. (3)}$$

The solar drying of the banana resulted in a D_{ef} value of 5.4×10^{-9} m^2/s, with an R^2 value of 0.9935. R^2 indicates the level of linear relationship between the dependent and independent variables in a sample, thus assessing the quality of the fit. A value closer to 1 indicates a better fit of the function to the scatterplot points. In other words, a coefficient close to 1 is considered highly reliable, while a coefficient equal to 1 is considered ideal or perfect (Almeida et al., 2022).

It is important to note that convective drying allows for the control of temperature, airflow velocity (AV), and RH of the drying air, whereas natural drying methods like solar drying only allow for the observation of these parameters. The variation in these factors contributes to the discontinuity of the drying curve, leading to the appearance of higher D_{ef} values. Nevertheless, the solar drying of bananas conducted in Barreiras-BA, using an indirect dryer, was able to maintain the continuity of the drying curve for the raw material.

In the case of banana drying in an indirect dryer by natural convection, D_{ef} typically exhibits magnitudes of 10^{-9} m^2/s (**Table 3**). Therefore, the D_{ef} value of 5.4×10^{-9} m^2/s aligns with the existing literature. Furthermore, for conventional drying, the D_{ef} of bananas ranges from 10^{-9} (Silva et al., 2009) to 10^{-11} (Santos et al., 2021), indicating that solar drying of bananas was able to maintain a D_{ef} like that of traditional drying methods.

The variation in D_{ef} values can be attributed to the specific banana species used, as it affects the composition, size, geometry, thickness, and initial moisture content of the fruit. The drying temperature, pre-treatment methods, and type of drying equipment employed also influence the D_{ef} (Tunckal & Doymaz, 2020). Additionally, discrepancies in D_{ef} values can arise from different approaches employed in solving the drying model. This study did not consider factors such as temperature distribution at different points of the banana slices or properties such as heat capacity and thermal conductivity, which change as the moisture content of the fruit changes (Baini & Langrish, 2007). However, it is worth mentioning that the obtained result falls within the range observed for agro-industrial products, which is typically between 10^{-7} and 10^{-13} m^2/s (Jangam et al., 2010).

4. Conclusion

The dryer, constructed using recycled materials, proved to be cost-effective and demonstrated efficient performance in drying silver banana slices. It only required 300 min to achieve the equilibrium moisture content of the product (1.8%), which is comparable to conventional dryers. Furthermore, the prototype maintained the continuity of the drying curve, even without controlling the traditional process parameters. This resulted in good fits of the empirical models, particularly the Diffusion Approximation model. It is also recommended to test the dryer with other raw materials to validate its effectiveness for general food drying purposes.

Authors' Contributions

R.F.A.: Conceptualization, Prototype development, and construction, Investigation, Data collection, Data Curation, Software, Writing - Original Draft preparation, Visualization; P.M.P., C.F.S., V.R.K., B.P.S., C.E.S.M.: Conceptualization, Prototype development and construction, Visualization. E.G.O.: Writing - Review & Editing, Supervision, Project administration. All authors read and approved the final manuscript.

Availability of data and materials

Almeida, R. F. (2024b). Solar drying data for banana slices [Data set]. Zenodo. https://doi.org/10.5281/zenodo.12819829

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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