Solar drying of mango in Senegal: experimentation and kinetic modeling.

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ABSTRACT

The production of mangoes holds great importance in Senegal. However, this despite substantial production, it is regrettable to note significant losses occurring throughout the supply chain, from harvest to distribution. Controlling these post-harvest losses poses a major challenge for the mango agro-food industry in the country. It is essential to better diagnose and address this issue to fully exploit the economic potential linked to mango production in Senegal.

Senegal benefits from abundant sunshine throughout the year, making it an ideal location for the development of solar energy. This study aims to conduct experimental research to determine the most suitable model for the drying kinetics of mango pulp. In this context, we conducted drying experiments using an indirectly forced convection solar dryer. These experiments were carried out with 5 kg of mango pulp cut into parallelepiped-shaped slices with a thickness of 5 mm and an initial water content of 82%. The slices were distributed across 3 rack in the dryer. Control samples were also dried in the open air, spread out on nets. Ambient aeraulic and thermal parameters, as well as those inside the chamber at different positions, were recorded. After 14 hours and 30 minutes of drying, the moisture content decreased from 82% to 5% for drying temperatures ranging between 46°C and 67°C, while in open-air drying with the same duration, the content decreased from 82% to 35%. Among the 9 different models used to represent the drying kinetics of mango pulp slices, the Midilli and Kucuk model proved most suitable, showing higher R^2 coefficients (0.99653) and lower χ^2 values (2.92292e-4) respectively for the first, second, and third trays.

Keywords: **Mango, Solar Drying, Kinetic Modeling, Post-Harvest Losses, Senegal**

I. INTRODUCTION

The origin of the mango dates back to Southeast Asia, where it originated in India [1], Bangladesh, Burma, and Malaysia. It has been cultivated for thousands of years in this region before being introduced to many other tropical regions around the world. The scientific name for mango is Mangifera Indica. It belongs to the Anacardiaceae family and is widely appreciated for its sweet and juicy fruits.

The benefits of mango as a fruit are numerous. It is an excellent source of essential vitamins and minerals such as vitamin C, vitamin A, vitamin E, potassium, and magnesium. [2] [3] [4] These nutrients help strengthen the immune system, promote healthy skin, maintain optimal vision, and support heart health.

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Mango is also rich in dietary fiber, which promotes good digestion and contributes to satiety, thus helping to maintain a balanced body weight. In addition, it contains antioxidants such as carotenoids, which protect the body's cells from damage caused by free radicals.

In Senegal, mangoes play an important role in the country's agriculture and economy. Senegal is one of the leading mango producers in West Africa, with an annual production of between 125,000 and 130,000 tones, representing 63% of the fruit and vegetable sector's production [5]. The area covered by mango orchards in Senegal is estimated at 25,0001 ha, and Senegalese mangoes are appreciated on the local market as well as for export to other countries.

However, the country experiences considerable post-harvest losses, which are close to 60% of mango production at the national level and this percentage increases to 80% in the Casamance region [5]. These losses can be due to various factors, such as lack of adequate storage and transportation infrastructure, lack of preservation technologies, poor handling of fruits after harvest, and sometimes, problems related to export.

The high rate of sunshine in Senegal, estimated at around 5.5 kWh/m2/day on the ground [6] with more than 3000 hours of sunshine per year [7], offers an opportunity for preservation through solar drying. Solar drying is a traditional food preservation method that uses solar energy to remove moisture from produce, including fruits like mangoes. Using this method, mangoes can be processed into dried mangoes, extending their shelf life and reducing post-harvest losses. Solar drying is also environmentally friendly and economical, as it does not require external energy sources.

Solar drying is a valuable technique for adding value to African crops, reducing post-harvest losses, and creating new market opportunities for farmers. However, traditional sun drying has drawbacks such as spoilage and insect infestation. Furthermore, this method does not allow for adequate control of the drying process, which can affect the quality and drying time of the produce [8].

In recent years, initiatives have been taken to enhance the value of surplus production. Experiments in thin-layer solar drying of apricots have been carried out using an indirect solar dryer with forced convection, consisting of a solar air heater with a conical concentrator and a drying cabinet [9]. Their results showed that the logarithmic drying model was found to satisfactorily describe the solar drying curve of apricots with a correlation coefficient R^2 of 0.994. In the field of mango drying, much research has been undertaken to develop solar dryers, mainly with the aim of regulating the drying process. A study on solar drying of 8 mm thick mango slices was carried out. The results showed that it took 3 days of drying to reach the desired moisture content [10] This paper presents a solar dryer with auxiliary heating for drying mangoes. Drying temperatures, dryer performance, and drying kinetics were examined. The results indicate that the Page model is most appropriate to describe the drying kinetics of mango slices [4].

II. MATERIALS AND METHODS

The objective of this article is to conduct an experimental study and modeling of the drying kinetics of mango pulp using an indirect solar dryer. By measuring operational parameters such as temperature, humidity, and drying rate, our goal is to determine the optimal model to describe the drying kinetics of these fruits. These results will contribute to a better understanding of the potential benefits of this sustainable technology in the agri-food industry, thus promoting increased valorization of mango-derived products.

II.1. System Description

There Fig 1in our study, the dryer consists of a solar thermal collector, a drying chamber, and a hot air recycling system. The solar collector includes glazing to allow solar radiation to pass through and reduce upward losses, a matte black-painted aluminum absorber that converts radiation into heat, and insulation to reduce downward heat losses. An airflow channel allows heated air to circulate toward the drying chamber through fans that promote heat transfer from the absorber to the air. The drying chamber is designed to promote efficient circulation of hot air around the products to be dried, with adequate dimensions and food-grade aluminum trays or racks. The chamber walls are insulated to minimize heat loss, and a reflective coating on the interior maximizes heat utilization. Hot air is recycled rather than being exhausted outside, maintaining a high temperature inside the dryer.

The solar dryer we developed is equipped with a set of measuring instruments that allow us to obtain data on the rack parameters of the drying process. Thermocouples and Thermochrons are used to measure temperatures inside and outside the dryer, allowing us to monitor temperature variations and evaluate heat distribution during drying. A

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precise balance is used to measure mass losses of the products to be dried, which helps us evaluate the efficiency of the dryer and adjust the parameters if necessary. A pyranometer is used to quantify the solar irradiance received by the solar collector, allowing us to determine the optimal sunlight conditions for efficient drying. The shrinkage of the products to be dried is measured using a caliper, providing an accurate indication of the reduction in product size and residual moisture content. Finally, a micro-manometer via a Pitot tube is used to measure the aeraulic parameters of the air inside the dryer, which is essential for evaluating the efficiency of forced convection and heat transfer. Thanks to these measuring instruments, we are able to obtain data on the different variables of the drying process, allowing us to evaluate the performance of the dryer, identify necessary improvements and optimize the drying process to obtain high-quality results.

II.2. Experimental procedures

The sensor and product temperatures were recorded using a K-type thermocouple probe connected to a computer running PicoLog temperature acquisition software. The relative humidity of the ambient air, as well as that inside the dryer, was recorded using Thermochrons. Mass measurement was performed using a KERN ABJ 220-4N analytical balance, a high-precision instrument with an accuracy of 1 mg, ideal for laboratory and industrial applications requiring precise and reliable weighing. This balance has a maximum capacity of 220 g.

For the solar drying experiments, five kilograms of mango were evenly distributed on three. On each tray, a 12 g sample, 5 mm thick, was weighed every 1 hour throughout the operation. The process lasted two days. A CMP21 pyranometer was used to measure the solar flux incident on the solar collector plane. A micro-manometer positioned in the air stream was used in the ventilation system for precise measurements of volume flow, temperature and pressure variations.

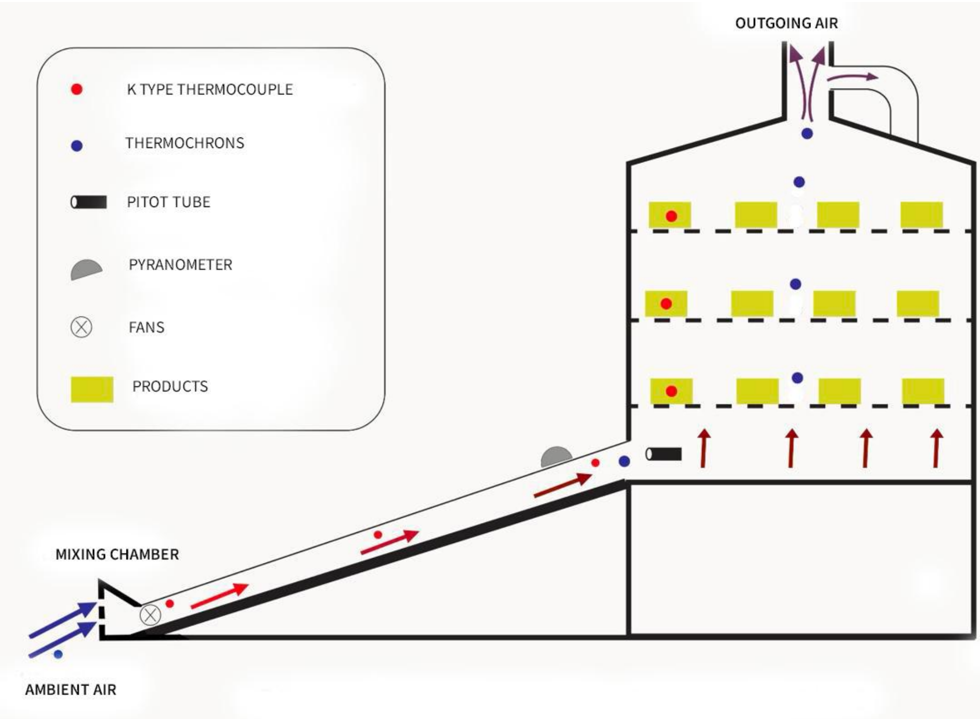

Fig 1: Instrumented diagram of the prototype

Table 1:Characteristics of the instruments.

Instruments	Measures	Measuring range	Precision
Thermocouples	Air temperature - Product temperature	0 to 1100°C	2.2% to 0.75%

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Thermochrons	Air temperature	-20°C-85°C	0.5°C
	Relative humidity of air	0-100%	5%
Micro-manometer	Air flow	0.0001 to 1.999 m3/s	0.001 m3/s
Pyranometer	Irradiance	0-2000 W/m²	< 1.5%
Balance	Sample Mass	0-220g	0.1mg
Caliper	dimension	0-150 mm	0.05mm


Fig 2: fresh mangoes


Fig 3: Peeled mangoes

Table 2: Different mathematical models of drying.

Model name	Equations	References
Page	Xr=exp(-ktn)	*[11]*
Two-term	Xr=aexp(-kt)+bexp(-gt)	*[12]*
Handerson and Pabis modified	Xr=aexp(-kt)	*[15]*
Logarithmic	Xr=aexp(-kt)+c	*[16]*
Midilli kucuk	Xr=aexp(-ktn)+bt	
Newton	Xr=exp(-kt)	*[17]*
Diffusion Approach	Xr =aexp(-kt)+(1-a)exp(kbt)	*[4]*

II.3. Study of the dehydration properties of mangoes

Mangoes in good ripeness quality are washed (fig.3), peeled (fig.4) and then sliced to a thickness of 5 mm before being placed in the dryer. At the end of drying to determine the initial humidity (m_i), the mango samples are weighed with the same balance, then placed in an oven at 70 °C for 24 h to have the dry mass (m_s).
The initial water content on a wet and dry basis is determined respectively by the following equations:

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$$X = \frac{m_i - m_s}{m_s} \qquad \text{eq1} \qquad\qquad X_w = \frac{m_i - m_d}{m_i} \qquad \text{eq2}$$

X: Water content on a dry basis (kg of water / kg of dry matter), m_d : Mass of the wet product (kg), m_s : Mass of dry matter (kg), m_i: Initial mass of the product before drying (kg), X_w: water content on a wet basis

II.4. Modeling of experimental drying curves

For the evaluation, we use Origin Pro 2022 to perform a smoothing of the experimental data to obtain the best-fitting drying model. The criteria used to evaluate the suitability of the optimal equation to represent the variations observed in the drying curves of mango slices are based on measures such as the correlation coefficient R^2, as well as statistical parameters such as the sum of squared residuals and the root mean square error. These parameters are used to evaluate the quality of the fit achieved.
Goodness of fit was assessed using the statistical parameters R^2 and χ^2. The optimal model is the one with a correlation coefficient (R^2) closest to 1 and a minimum standard error close to 0.[18].

- Correlation coefficient

$$R^2 = \left[\frac{\sum_{i=1}^{N}\left(X_{rpr,i} - X_{r\,exp,i}\right)^2}{\sum_{i=1}^{N} X_{r\,exp,i}^2}\right]^{1/2} \qquad \text{eq3}$$

- Root mean square error

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(X_{r\,pre,i} - X_{r\,exp,}\right)^2}{N - Z} \qquad \text{eq4}$$

$X_{rpr,i}$ Is the i-th predicted humidity
$X_{rexp,i}$ Is the i-th experimental humidity
N is the number of observations
Z Numbers of constants

III. Results and discussions

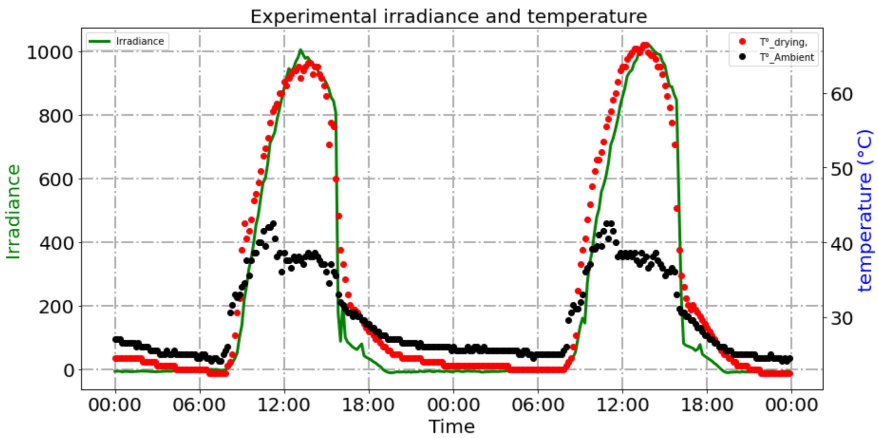

Fig 4: Evolution of irradiance and drying and ambient temperatures

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There Fig 4 shows the evolution of irradiance, ambient and drying temperatures over time during the two days of experiments. During one day of experimentation in Senegal, the daily averages recorded for ambient air temperature, air temperature at the cabin entrance and solar radiation oscillate respectively between 27.6 and 44.6 °C, 21.09 and 71.91 °C, 0 to 1130 W/m2. These values generally reach their maximum between 1 and 3 p.m. and decrease at the beginning and end of the day. During the first day, cloudy metrological conditions affected the irradiance. The ambient temperature and the drying temperature follow the daily evolution of the irradiance.

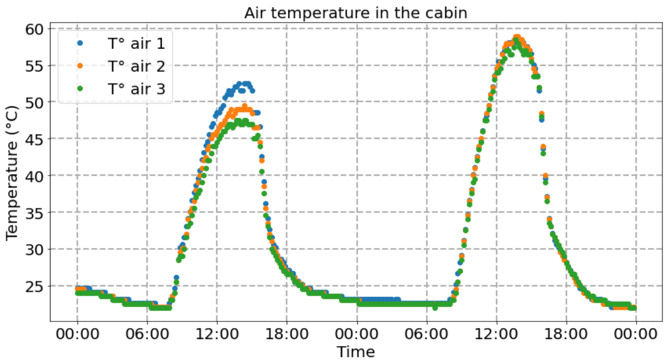

Fig 5. Evolution of air temperature on the different drying racks

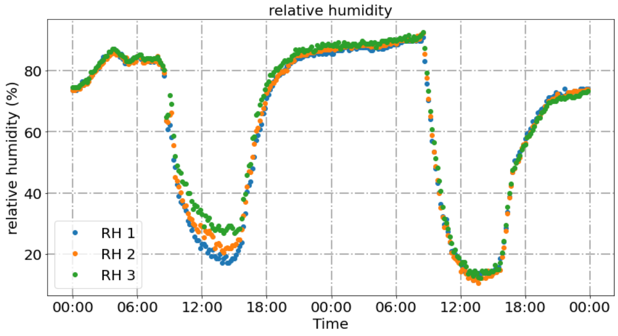

Fig 6. Evolution of the relative humidity of the air on the racks

The evolution of the air temperature on the different drying racks follows the evolution of the irradiance As the air passes through the drying racks, its temperature decreases while its relative humidity increases, as illustrated in the **Erreur ! Source du renvoi introuvable.**and the **Erreur ! Source du renvoi introuvable.** This phenomenon can be explained by the fact that, given a through flow, the hot air initially interacts with the first rack, thus increasing its relative humidity by reducing its temperature. However, this trend is more marked on the first day of drying, where the product is very humid. On the second day of drying, the drop in air temperature is less significant than on the first day, which is explained by the fact that only the water bound to the product remains. It is observed that the air temperature in the dryer is almost homogeneous with a slight difference between 1 p.m. and 3 p.m.
There Fig 7 shows the evolution of the product temperature as a function of time. The evolution of the temperature follows that of the irradiance and the drying temperature. During the first day the amplitude of the temperatures is less pronounced because the product starts with a high water content, requiring a large amount of heat to evaporate the surface water. On the second day the more pronounced amplitude is due to the fact that a significant reduction in the water content, allowing the product to rise in temperature with peaks ranging respectively from 59.05 °C, 57.23 °C and 55.43 °C for the first, second and third racks.
There Fig 8 represents the relative mass losses as a function of drying time. It illustrates a rapid migration of moisture out of the product, indicated by a steeper slope. This rapid decrease gradually decreases as the drying time extends. It then becomes more difficult to remove the water that remains tightly bound to the product, as opposed to the free and easily evaporable water. The decrease in water content is observable throughout the drying process. After 13 hours of drying, the water content has decreased from 4.23 kg water/kg dm to 0.22 kg water/kg dm, 4.34 kg water/kg dm to 0.17 kg water/kg dm, 4.35 kg water/kg dm to 0.25 kg water/kg dm of the first rack, second rack and third rack, respectively, for drying temperatures between 46°C and 71.92°C.

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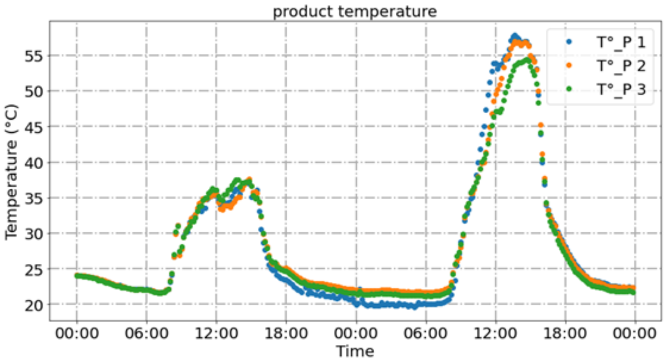

Fig 7: Evolution of the product temperature on the different racks

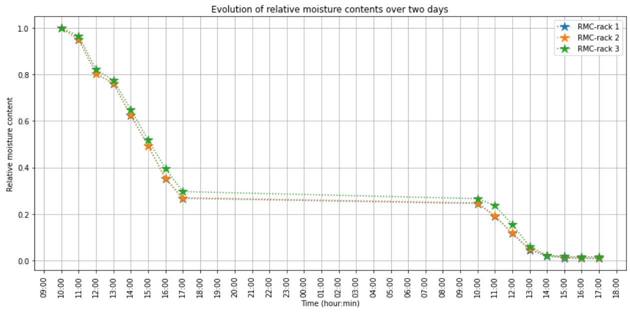

Fig 8. Relative mass loss on the different racks

Table 3 : Statistical analysis of thin-layer models for the mango drying process.

Model Name	Constants	R2	χ^2
Newton	k=3.19571	0.99243	5.73801e-4
Page	k=3.75571,n=0.94227	0.99383	4.83862e-4
Henderson and Pabis	a=0.96755,k=3.89079	0.994	4.70398e-4
Two Term	a=0.48377 k1=3.8908 b=0.48378 k2=3.89075	0.994	5.05242e-4
Logarithmic	a=0.98068 k=3.66366 c=-0.02163	0.99431	4.6194e-4
Midelli and Kucuk	**a=1.00295 k=2.78427 n=0.8156 b=-0.12881**	**0.99653**	**2.92292e-4**
Diffusion Approach	a=0.05055 k=67.71511 b=0.05631	0.99466	4.33233e-4

The Table 3 summarizes the coefficients of the 7 thin-film drying models. The experimental reduced absolute humidity is plotted versus time for this experiment and then fitted to nine mathematical drying models Table 2. It seems, according to the data of the Table 3, that the Midilli and Kucuk model is the best to describe at the same time the kinetics of the three racks, presenting a maximum R^2 and a minimum χ^2. Therefore, this model proves to be adequate to describe the behavior of reduced absolute humidity for this type of mango slice in these conditions with higher R^2 coefficients (0.99653) and lower χ^2 values (2.92292e-4) for the first, second and third rack respectively.

IV. Conclusion

In the present study, for a 13-hour drying cycle, the indirect solar forced convection dryer is able to significantly reduce the moisture content of the product, reaching 5% for an initial content of 82%. The daily variation of irradiance due to weather conditions affects the air and product temperatures. After a careful analysis of seven (7) models presented, the one that shows the highest Top of Form correlation coefficient (R^2) as well as the lowest values of χ^2 was identified. It is noted that the Midilli and Kucuk model was found to offer the most suitable results for each phase of the mango slice drying process. This finding highlights the relevance and applicability of this model in this specific context. These findings are not limited to mango drying alone. The conclusions drawn open the way to an exciting perspective: the adaptation of this system to other fruits and vegetables for the drying process. This potential development represents an exciting and promising opportunity to enhance the overall quality of dehydrated foods, thus opening new horizons in the field of food preservation.

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