ANALYSIS AND NUMERICAL MODELING OF SOLAR DRYERS IN AGRI-FOOD CHAINS: INVESTIGATION ON PINEAPPLE DRYING PROCESS

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Abstract

Mathematical modeling of solar drying systems is to forecast the drying time required for a product and the type of dryer in a given environment. Computational modeling provides information on solar drying problems that are geometry-specific. Numerical modeling has recently been used to develop new methods for solar drying food products. The present work aims at emphasizing existing models and delve a new heat balance model specifically for pineapple drying, which has not been addressed in previous literature. This work additionally highlights gap and proposes a comprehensive methodology that accurately reflects the unique meteorological conditions of Cotonou, Benin. Furthermore, comparing the performance of various dryer designs and configurations was done. About 1135 articles from five major academic databases was retrieved. Following a rigorous selection process, the review included 101 studies for final analysis. Pineapple is not the most studied crop. Surprisingly, none of the 101 papers addressed the development of a pineapple model in Cotonou weather conditions. The focus on local climate adaptation distinguishes this work from others, which often apply generalized models without considering specific regional factors. Three models (Page, Wang, and Singh, two terms) commonly used in the literature are selected to determine a suitable model for pineapple.

1. Introduction: -

Many developing countries lose a significant portion of their agricultural production and related products due to a lack of preservation systems [1]. According to estimations, post-harvest losses of fruits and vegetables range from 30% to 40% of total production, significantly contributing to rising agri-food inflation [1]. Open-air sun-drying, the most basic preservation method in developing countries, has several disadvantages. Uncontrolled drying, which results in under- or over-drying, as well as food contamination from dust, rain, wind, and excessive exposure to direct solar radiation [2] are all disadvantages. Drying technology can extend the shelf life and improve the overall quality of food products [1]. Tropical countries that receive excessive solar intensity for the majority of the year should ideally use solar drying technology [1]. Solar drying technology is ideal for drying food products because the drying process does not significantly reduce the moisture content of the products. Several researchers semi-industrial drying of vegetables using an array of large solar air collectors [3], [4], [5], [6], [7], and [8] have developed various types of solar dryers to dry food materials based on local needs and in multiple locations using indigenous technology. Solar dryers are an excellent choice for preserving agricultural foods due to their low initial and operating costs, as well as their ease of use [1]. They have numerous advantages over traditional drying methods, including increased drying efficiency, less product spoilage, and higher product quality. Heat flow raises product temperatures and evaporates water [9], [10]. Solar drying is becoming more popular due to the benefits it provides over other drying methods [11]. Solar energy is a free and renewable source, so solar dryers have much lower operating costs than dryers that use fossil fuels, natural gas, or electricity. Solar drying is a clean, non-polluting process that is suitable for drying a wide range of products, including agri-food crops like fruit, vegetables, and meat [3].

In the food industry, convection drying is still the most common drying method. This process is also called "hot air drying" or "oven drying"[12]. This method is relatively inexpensive and works in all countries. However, drying is a complex process that involves short-term changes in mass and heat, as well as other changes such as physical or chemical transformations, which can affect product quality and how heat and mass are transferred [7]. Drying food products under controlled humidity and temperature conditions allows them to dry quickly to the safest moisture level while preserving product quality [13]. As the world embraces green technologies and sustainable methods, the use of alternative energy-saving drying systems becomes increasingly important. Solar drying processes are proving to be the most effective methods for dehydrating food products, as they eliminate the environmental issues associated with traditional drying processes [14]. Furthermore, conventional drying systems result in longer drying times, uneven temperature exposure, and food material hardening. To avoid these issues, the food industry is motivated to improve existing drying technologies and create new drying technologies [15]. The next generation of dryers and drying technologies is expected to drive more sustainable development by increasing thermal and energy efficiency, lowering operating costs, and improving product quality [8]. Furthermore, solar dryers outperform traditional dryers in terms of thermal and electrical efficiency [16], [17].

Fruit composition and structure are complex, as are the various transport phenomena and biological variability. For these reasons, mathematical modeling and simulation are useful tools for grasping the complexities of fruit drying [9]. They also enable us to optimize the appropriate operating conditions. Mathematical modeling of fruit drying involves using mathematical equations to predict the operation's behavior, which occurs in multiple stages. Because it is difficult to measure certain variables during drying experiments, mathematical models can simulate the distribution of temperature, humidity, and speed, among other variables, at high spatial and temporal resolution [19],[20]. Furthermore, mathematical models aid in the design and evaluation of dryer performance, as well as process control and optimization, all of which are critical for maintaining food safety, sensory quality, and nutritional quality [18]. Modeling is useful not only for making process predictions but also for extracting [18] additional detail and obtaining new information. However, there is no universally valid type for modeling drying behavior that is effective for all fruits. Different approaches to drying modeling must be compared and evaluated [7]. The different models are determined by the type of product and dryer used.

Pineapple (Ananas comosus) is the world's most commercialized tropical fruit [19]. It has a pleasant sensory profile, including flavor, aroma, color, and taste. Pineapples contain 85-92% water by weight. As a result, this fruit is highly susceptible to spoilage [20]. Dried fruits provide a variety of health benefits, including improved food quality, anti-glaucoma, anti-cancer, hypolipidemia, antioxidant and anti-inflammatory, antibiotic or anti-pathogen, cardio protective, and anti-diabetic properties [21]. Furthermore, the dried form makes transportation and distribution easier. Pineapple is an excellent source of minerals and vitamins, such as potassium, manganese, copper, magnesium, vitamins C and B6, thiamine, folates, and dietary fiber. These minerals and vitamins are critical for human growth and development, particularly among low-income populations in tropical developing countries [19]. Pineapple is also a seasonal fruit, so it is scarce in the off-season but abundant during harvest, resulting in significant post-harvest losses. As a result, it must be preserved in order to remain available indefinitely. The current study is especially significant because the preliminary literature review does not take into account the development of a model under the meteorological conditions of Cotonou (Benin) for the use of solar dryers on pineapple

2. Literature Review

This review formulates research questions, identifies sources, defines selection criteria, and creates procedures for assessing the performance of models for preserving agricultural products, specifically fruit. During the implementation phase, research articles were selected using keywords from relevant academic databases. The synthesis stage entails conducting a critical analysis of existing techniques, evaluating their strengths and weaknesses, and determining their suitability for digital implementation.

2.1. Research Approach

In this study, scientific articles were collected from five well-known academic databases, including Google Scholar, Semantic Scholar, ProQuest, Scopus, and Web of Science, using the following keywords: "solar dryers for fruit advantage and disadvantage" OR "conservation by drying agri-food products" OR "pineapple conservation by solar dryer" OR "and in combination with 'modeling solar dryers for fruit' OR 'mathematical modeling' OR'CFD modeling 'OR' optimization of solar Next, we used the search selection criteria to determine which articles to include or exclude, as shown in Table 1.

Table 1. Selection criteria

Studies considered	Studies not considered
Articles published between 2014 and 2024, short notes, studies on solar modeling techniques in the food industry, and study on the different types of dryers available for preserving fruit (their advantages and disadvantages).	Inaccessibility of full-text articles Study not related to food products

2.2. Article Selection and Extraction

Articles not originally written in English or lacking essential information were excluded. From an initial pool of 1135 research articles, including original papers, reviews, conference papers, and book chapters, 432 duplicates were identified. A rigorous selection process involved examining the titles, abstracts, and content of the articles to ensure their relevance to the use of solar dryers and to detect the models used for each type of fruit. After reviewing titles and abstracts, a further 484 articles were eliminated. Of these, 319 were inaccessible due to the unavailability of full text, and 170 were classified as book reviews, editorials, conference abstracts, and seminar abstracts. This selection process resulted in a remaining set of 219 articles. Of the 219, 176 were deemed irrelevant. In the end, we identified 97 articles published between 2014 and 2024. Figure 1 illustrates the process. of selecting and filtering articles from the databases for review based on the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method [22].

2.3. Reviewing the Questions

In order to comprehensively explore the study landscape, a series of research questions have been formulated. These inquiries are strategically designed to reveal key aspects that contribute to an overall understanding of the subject. Firstly, the geographical context is addressed to discern the countries in which these studies have been conducted, taking into account potential geographical variations in results. Subsequently, attention is focused on the specific agri-food products studied (particularly pineapple), highlighting the types investigated. The type and source of data used in these studies are then explored, providing insight into the fundamentals of research methodologies. In addition, the study looks at the different types of solar dryers used in the literature to preserve fruit, as well as the different models used in modeling these dryers in the agri-food industry, aiming to propose recommendations for improving the models. Evaluation criteria for assessing the efficiency of solar drying systems are examined, revealing the measures used to assess the reliability of the study results.

In addition, the study examines techniques for improving model performance by developing a new model. Finally, a critical review of the weaknesses inherent in the approach and the authors' perspectives provide a nuanced understanding of the limitations and potential avenues for future research in this dynamic field. The research questions are listed as follows:

RQ1: In which country was the study conducted?

This question asks which countries the studies were carried out in and whether geographical differences have a significant impact on the results.

RQ2: What types of fruit are examined?

This question is crucial as it identifies the specific fruits studied, providing crucial information on the scope and focus of the research.

RQ3: What modeling techniques were used?

By integrating this study, we will evaluate the different types of modeling in the literature, the results obtained, the parameters used in the modeling, and the software used. This will give us a better understanding, as the models depend on the parameters and type of dryer used. In addition, the performance of each type of dryer will be evaluated.

RQ4: What are the weaknesses of the approach, the contributions of the model, and the author's perspectives?

Answering this question helps us learn more about the limitations or weaknesses of each study, which can help us better understand the strengths and weaknesses of the field as a whole, as well as the prospects for future research in this area.

RQ5: What is the synthesis?

Answering this question will enable us to know the choice of dryer and model chosen. This will enable us to better orient our research with the aim of obtaining results that are appropriate for the evolution of science.

3. Solar Dryers and their Role in the Food Industry

Solar dryers use the sun's energy to add a specific amount of heat to a product, extracting moisture without compromising its quality. They are primarily used in agriculture and industry to inhibit bacteria and preserve products [13]. Solar dryers are vulnerable to external conditions, which can harm or mar dryer components [23], [24]. Their operation relies on natural or forced air circulation principles. All solar dryers operate in only two modes: active and passive. In the passive mode, buoyancy and wind pressure move air through the crop. The thermosiphon effect causes heated air to rise, then escape through the greenhouse roof or ventilation. In contrast, in the active mode, an electrically powered fan or blower creates forced circulation to dry the crop. This requirement can be met by either the photovoltaic module or grid power [13]. Passive dryers are appropriate for low moisture content and small quantities, whereas active dryers are ideal for high moisture content and large quantities [25]. Furthermore, passive dryers are less expensive than active dryers because they do not require external components such as fans, photovoltaic panels, blowers, and so on. Thus, a classification of solar dryers can assist in better understanding the various options available on the market and selecting the most suitable solar dryer based on specific needs, environmental conditions, and other relevant factors (Figure 2) [25].

Figure 1. Black and white figure without shading

Hot air is used during solar drying to extract moisture from the dried product [29]. The amount of moisture removed is determined by the temperature of the dried air; warm air can capture more moisture than cold air.

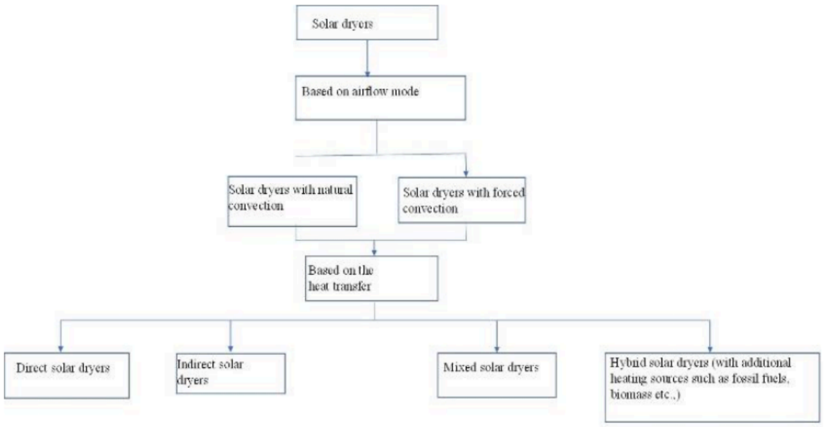

Figure 2. Classification of solar dryers [27], [28], [29].

3.1. Heat transfer mode

3.1.1. Direct solar dryer (DSD)

The product is exposed to direct sunlight, allowing the water to be easily removed. A black-painted heat-absorbing plate is included to collect and absorb sunlight, converting it into heat. The product to be dried is placed directly onto the absorbent plate [31]. Unfortunately, direct sunlight deteriorates the product's quality and color. Furthermore, inadequate moisture removal from steam causes slower drying rates and lower capacity [32]. In addition, Menon et. al. [33] compared different dryer efficiency methods using equations ranging from (A1 to A7). Convection dryer efficiency ηcov is calculated by equation (A2). The instantaneous energy efficiency of the system can be calculated by equation (A3). Equation (A4) can be used to calculate drying efficiency equations designed for applications such as continuous vacuum and microwave drying. An alternative method of calculating the energy efficiency of dryers is the specific moisture extraction rate (SMER) (kg/kWh). The equation is given in (A5). The specific energy requirement SER is determined as the ratio between the energy consumption (E_c) and the mass of water mw(g) removed from the sample during the drying process (A6 and A7). These equations (A1-A7) do not take into account the influence of renewable energy on the final value of a particular ratio.

3.12. Indirect solar dryer (ISD)

Ayadi et al. [35] were able to predict air and gravel temperatures in an unloaded indirect dryer, finding good agreement with experimental results. The numerical model considered conduction, convection, and radiation heat transfer modes and used ambient environmental conditions as inputs. To study the efficiency of a flat-plate collector and storage system, the modeling study relies on the heat balance in each element that makes up the collector. The energy balances for the cover, absorber, and working fluid are shown below [35]. The sensor output temperature can be calculated from the following expression [1]. The energy balance in the sensor cover is given by:

$$\rho_{ps} \times \delta_c \times C_{pc} \times \left(\frac{dT_c}{dt}\right) = h_{cfc}(T_f - T_c) + h_{rcs}(T_s - T_c) + h_{wca} \times (T_a - T_c) + h_{rbc} \times (T_b - T_c) + \alpha_c \times I \quad (1)$$

C_{pc} is the blanket warmth, *and* T_a, T_b, T_c, T_f *et* T_p are the ambient air temperature of, absorber, cover, air in the collector and product, respectively. h_{wca} is the coefficient of heat loss by convection of the roof due to wind, h_{cfc} is the heat transfer by convection between the air inside the collector-cover of the solar collector; h_{rbc} et h_{rcs} are the cojjefficient of heat transfer by radiation between cover-absorber and cover-sky, respectively; δ_c indicates the thickness of the cover. W_c is the width of the collector; α_c is the absorbent power of the cover; and I is the solar insolation received on the solar collector.

Energy balance of the absorbent plate is given by

$$\rho_b \times \delta_b \times C_{pb} \times \left(\frac{dT_b}{dt}\right)_b = h_{cfb} \times (T_f - T_b) + U_b \times (T_a - T_b) + h_{rbc} \times (T_c - T_b) + \tau \times \alpha \times I \quad (2)$$

where C_{pb} is the specific heat of the absorber, h_cfb is the heat transfer by convection between air absorber, U_b is the coefficient of heat loss from the rear of the solar collector to the ambient air, and ρ_c, ρ_b, ρ_a represent the density of the cover, absorber and air, respectively.

The energy balance of the airflow inside the sensor is given by

$$D_c \times G \times C_{Pa} \times \left(\frac{dT_f}{dX}\right) = h_{cfc} \times (T_c - T_f) + h_{cbf} \times (T_b - T_f) \quad (3)$$

where C_{Pa} is the specific heat of the air, D_c is the distance between the cover and the absorber, h_{cfc} is the heat transfer by convection between the absorber and the air in the solar collector, G is the mass flow rate of air in the solar collector in kg/sm^2. The radiant heat transfer coefficient between the collector covers as well as the collector cover-absorber and the convection heat transfer coefficient between the collectors and the ambient air of the cover were calculated as shown in the equations below (A11-A14). The air-to-blanket and absorber-to-air heat transfer coefficients were assumed the same. The following equation represents the Kays and Crawford correlation for determining the heat transfer coefficient (A15-A16).

They receive solar radiation from the solar collector, which warms the air outside and transfers it to the opaque drying cabinet. They include a solar collector and a drying chamber. Instead of exposing the product to direct sunlight, the collector's heat-absorbing black-painted surface heats the ambient air. After passing through the product in a drying room, the heated air absorbs moisture before exiting through the chimney [36]. Figure 5 depicts a schematic diagram for an indirect solar dryer. Indirect dryers have an advantage over direct dryers in that they can maintain a higher temperature within the drying chamber. This high temperature shortens drying time but compromises quality and texture [37]. In addition, Lingayat et al. [38] examined indirect solar dryers for food crops, including their performance, energy storage, and strengths. Flat-plate solar collectors' performance is determined by factors such as speed, ambient temperature, and humidity. In this case, the instantaneous thermal efficiency of a solar collector is defined as in equation (A30), the irradiance incident on the cabinet's coverage area (AG1) is zero (equation A31).

3.1.3. Mixed-mode solar dryer (MSD)

The mixed-mode solar dryer combines indirect and direct solar drying. It was designed with a faster drying rate. It works by combining the action of solar intensity incident on the product to be dried with air preheating in a solar collector, which provides the necessary heat for the drying process [40]. However, it is complex and has a high initial cost [37]. Figure 6 shows a schematic diagram for a mixed-mode solar dryer. César et al. [41] designed, built, and evaluated a mixed-type passive solar dryer. The solar dryer under consideration has the option of operating as an indirect-direct dryer (mixed solar dryer, MSD) or reversely. The term "drying efficiency" describes how much energy the drying device uses to heat the food and evaporate the water. According to the different drying operating modes, in the MSD mode, the input energy to the system is the useful energy from the collector plus the solar radiation that passes through the polycarbonate cover (A_{G1} = 0.96 m^2) of the drying chamber via its transmission (τ_{G1} = 0.84). In the ISD mode, the solar collector's useful energy serves as the input energy (A_{G1} = 0), (A32). However, considering the energy still remaining in the air at the dryer outlet and performing the overall energy analysis, the following equation was proposed (A33). (($H_{out} - H_{in}$)) is the difference between the enthalpy of moist air at the stack outlet and the enthalpy of moist air at ambient temperature (A34), where T is in degrees Celsius.

3.3.4. Hybrid solar dryer (HSD)

The hybrid solar dryer incorporates multiple energy sources, including solar energy, to create optimal drying conditions [27]. Typically, the hybrid dryer functions in active mode. The hybrid solar drying system has the ability to efficiently regulate the drying process of any food item and also aid in maintaining the desired quality of the product [4]. The hybrid dryer utilizes two energy sources: solar energy and an alternative source such as biomass, LPG, or any other suitable source capable of supplying warm air during periods without sunlight. Furthermore, hybrid dryers exhibit a higher price point compared to alternative types, yet they surpass them in terms of performance [4]. Ramirez et al. [42] conducted a comparative analysis to evaluate the thermal performance of an indirect solar dryer with and without phase change material (PCM). The equations presented in A35 to A39 represent the energy balance within the glass cover. The energy balance of the working fluid is expressed by the following equations (A40-A42). The energy balance in the absorber plate is presented by equation (A43).

The process of drying is essential in numerous industries, especially in the food industry, to prolong the lifespan of products, ensure their quality, and render them suitable for consumption. Multiple drying techniques exist, each possessing unique benefits and drawbacks. However, the drying chamber is an essential component in this process. Drying chambers enable meticulous regulation of the drying conditions. These factors encompass temperature, humidity, and occasionally pressure. Ensuring the quality and consistency of the final product relies on having precise control.

3.2. Type of drying chamber

3.2.1. Cabinet solar dryer

These come in a large metal or wood box. Inside the chamber, shelves hold the dried products [2]. You can install heat storage systems in the dryer [43]. These can be either direct or indirect, depending on the type of drying chamber. The chamber is transparent in the direct type, whereas it is opaque in the indirect type [26]. The reference [44] shows schematic diagrams for the direct and indirect cabinet solar dryers, respectively. The cabinet solar dryer exhibits inadequate moisture extraction and has a tendency to excessively desiccate the lower trays. The researchers conducted a study on the modeling and enhancement of cabinet solar dryers by employing fluid dynamics [45].

$$h_{af}(T_c - T) + h_{ca}(T_c - T_{am}) + h_{re}(T_c - T_s) + h_{rp}(T_c - T_p) = \{\alpha_{cs}(1 + \rho_{ps}.\tau_{cs}) - \tau_{cs} - \rho_{ps}\}I \quad (4)$$

The energy balance of the air flow inside the collector is given by equation 5.

$$\dot{m}c_p dT/w = h_{af}(T_c - T).dy + h_{af}(T_p - T).dy \quad (5)$$

Its resolution yields:

$$e^{\frac{-2Wh_{af}}{mc_p}\Delta y}B\text{-}2\,T_i B\text{-}2\,T_{i-1}B \quad (6)$$

With B= $T_p + T_c$ (7)

This article demonstrates that one method to raise the temperature of the air flow at the collector outlet is by extending the length of the collector, thereby enhancing its performance. Furthermore, adjusting the orientation of the manifold enhances the efficiency of the dryer. Lastly, by incorporating baffles in the lower section of the chamber, it becomes feasible to channel the airflow upwards from the beginning and compel it to pass through the products.

3.2.2. Greenhouse solar dryer (MSD)

The greenhouse dryer is a solar dryer that combines the operation of a solar collector with a greenhouse. The walls and roof of the dryer are made from a transparent material such as glass, fiberglass sheets, UV-stabilized plastic, or polycarbonate [41], [45] a black surface is required. It provides significant drying control compared to other types and can handle large quantities of product [44]. Nimnuan et al. [41] conducted an experimental and simulated study on the solar greenhouse dryer's performance for drying cassumunar ginger. The energy balance for polycarbonate sheet cladding can be described in equations A50 to A53. The mass balance inside the dryer chamber is given by equation (A54). The solar greenhouse dryer model consists of five equations (A55 - A56). The equation best suited to the experimental results is expressed by equation (A57), where M (decimal, db) is the moisture content of the product at time t (hour), M0 (decimal, db) is the initial moisture content, Me (decimal, db) is the equilibrium moisture content. The Table 2 shows the average efficiency of some products in indirect and hybrid dryers.

Table 2. Average dryer efficiency

References	Products	Type of dryer	Average efficiency
[46]	Onion	Indirect solar	30 à 35 %
[47]	Red seaweed	Indirect solar	27%
[48]	Roselle	Indirect solar	36.2%
[49]	Mango slices	Indirect solar	33.8%
[50]	Rice	Biomass-solar hybrid	15.4%
[51]	Orange	Indirect solar	34.4%
[52]	Okra	Indirect solar	26.1%
[53]	Tomato slices	Gas	35%
[53]	Tomato slices	Gas-solar hybrid	37%
[54]	Onion	Indirect solar	56.3 à 71.3 %
[36]	Cloves of garlic	Solar-electric hybrid	79.7%

Regrettably, the effectiveness of solar energy systems is contingent not only upon the energy retrieval component but also upon its storage capacity to mitigate the effects of solar energy's temporal intermittency. Moreover, the utilization of software applications is crucial in enhancing the efficiency of solar drying systems [45].

3.3. Type of modeling for agro-food solar dryers

3.3.1. Forced air circulation mode

Multiple prototypes of forced convection solar drying systems have been constructed, examined, and enhanced [46]. Direct-mode forced-convection solar drying systems primarily comprise a fan or blower that compels drying air to circulate through the product, along with a drying room enclosed by a transparent sheet. Indirect solar drying systems comprise a drying chamber, an air heater, and a fan that transports the heated air to the drying room [46].

3.3.2. Natural air circulation mode

Through the process of natural convection, the air is heated to an average drying temperature of 45 °C. Natural convection caused a decrease in the mass of tomatoes from 1800 g to 180 g, while forced convection caused a decrease from 1800 g to 140 g [54]. Comparing the two modes, it is evident that forced convection is more effective in removing moisture from tomatoes compared to natural convection. Additionally, the rate of heat transfer is higher in forced convection than in natural convection, as stated in reference [54]. Solar dryers can be categorized into two operating modes: natural convection and forced convection [55], [56].

3.3.3. Thermal storage systems

The intermittent and season-dependent nature of solar radiation poses a significant challenge in harnessing solar energy due to its unreliability. However, it is imperative to regulate these conditions in order to optimize the functionality of the drying system [4], [9]. In order to implement solar drying, it is essential to consider the storage and transportation of dried products [57], [58] and [59]. Therefore, possessing a solar energy storage system is crucial for efficient energy conversion and plays a vital role in the dehydration of various food items, even in situations where direct sunlight is limited or absent. Various technologies exist for the storage of energy in various forms, such as thermal, electrical, and mechanical [31]. Regarding solar dryers, we utilize three methods to store thermal energy in the Thermal Energy Storage (TES) system: sensible heat, latent heat, and thermochemical heat. In sensible heat storage systems, thermal energy is stored by increasing the temperature of the material, typically a liquid or solid. The primary benefits of a sensible heat storage system include its affordability and user-friendliness, although its main drawback is its limited storage capacity [4]. Creating a solar dryer with inexpensive latent heat storage is a relatively simple task, however, the challenge lies in the limited amount of heat that can be stored per unit volume. Utilizing a phase change material (PCM) for LH storage is a viable option due to its substantial LH capacity and ability to maintain isothermal conditions during the processes of melting and solidification [38]. II demonstrates non-isothermal behavior during heat transfer. However, there is a scarcity of data and a lack of availability regarding the utilization of LH storage in indirect solar dryers [38]. Thermochemical storage, although more intricate in its execution, still holds the greatest theoretical capacity. Table 3 provides a concise overview of the different research methodologies employed in studying thermal storage materials utilized in solar dryers.

Table 3. Research on thermal storage materials TES configuration

	Key results	**Reference approach**	**TES type and storage equipment**
Shell and tube latent heat storage as a solar dryer.	HTF has been found to be suitable for providing warm air for drying food products during sunless hours or when solar radiation is very low.	[13] numerical	Latent heat storage system (air)

Storage medium located on absorbent plate and drying chamber.	Sensitive (thermal oil) and latent (kerosene) heat accumulation.	[14] Experimental	Sensitive (thermal oil) and latent (kerosene) heat accumulation
TES in a single tank. The insertion of fins into the TES was evaluated.	The total energy efficiency of the dryer in summer was 17.76, 18.97 and 19.41% for the case without TES, with TES and with TES + fins, respectively. The CO2 emission and attenuation of the dryer integrated with TES + fins were 23.88 kg/ year- and 20.13 tons.	[15] Experimental.	Latent heat storage (kerosene)
TES in a single tank.	The hybrid direct-indirect solar heating system showed an annual performance increase of 58% in annual useful energy compared with direct mode and 42% in annual solar fraction compared with indirect mode.	[16] Numerical and Experimental	Sensible heat storage (water)
Storage medium located on the absorbent plate.	The integrated kerosene dryer reduced the moisture content of the raw material from an initial value of 84.65% (wb) to 4.50% (wb) in 9 hours. The integrated solar dryer with pebbles and the solar dryer without storage took 11 to 12 h to dry the raw material to a comparable state.	[17] Numerical and experimental.	Sensible (black pebbles) and latent (paraffin) heat accumulation
Packed-bed type TES located in the plenum chamber.	The thermal efficiency of the solar dryer increased by around 2.47% overnight compared to the case without storage. Among the various materials evaluated, granite stones showed the best performance.	[39] Numeric	Sensitive heat storage (gravel, granite and sandstone)
TES in a single tank with a PCM inside a spiral copper tube.	Thermal efficiency increased by approximately 1.51 to 7.81% compared to the system without PCM. In addition, the PCM increased exergy efficiency and ranged from 35.30 to 59.70%.	[18] Experimental	Latent heat storage (paraffin)

3.4. Numerical modeling and simulation of solar dryers

Comprehending the modeling and simulation methods for effective solar dryers is essential for evaluating and forecasting the efficiency of different solar drying systems [60]. Conducting comparative studies among various approaches would be beneficial. Understanding the purpose and use of a model is crucial. The purpose can vary depending on whether the model is being used to gather scientific information about drying or to achieve technical goals such as designing dryers, developing software, controlling processes, or optimizing efficiency [52]. This knowledge will ascertain the optimal modeling methodology. Elaborate models are more representative of reality but pose greater challenges in terms of resolution. The performance of solar dryers can be predicted using simulation models, as demonstrated by [61].

4. Results and discussion

This section addresses the research questions by providing a complex account of the contributions made by the researchers in each of the 97 research studies. The first aspect concerns geographical coverage, including continents covered, years of publication, and types of fruit considered in the articles. The second aspect focuses on the models used, model evaluation criteria considered, and software used.

4.1. Contextualization of this type of study

An analysis of the data collected for this literature review, focusing on the different types of solar dryers and the models used to model them, reveals a very wide geographical distribution of studies (see Figure 3). India predominates, accounting for 33.85% of the articles listed. This concentration emphasizes India's role in the research and development of drying preservation techniques in the agri-food sector. The representation of African countries like Nigeria (7.69%), Ethiopia (5.77%), Morocco (3.85%), and Tunisia is noteworthy, indicating a global interest in this field. On the other hand, European, American, and other countries have a more modest presence but still contribute to the geographical diversity of the studies. This distribution underlines the need to take account of specific national contexts in the research and development of these technologies in order to meet the varied needs of different regions of the world in terms of food preservation.

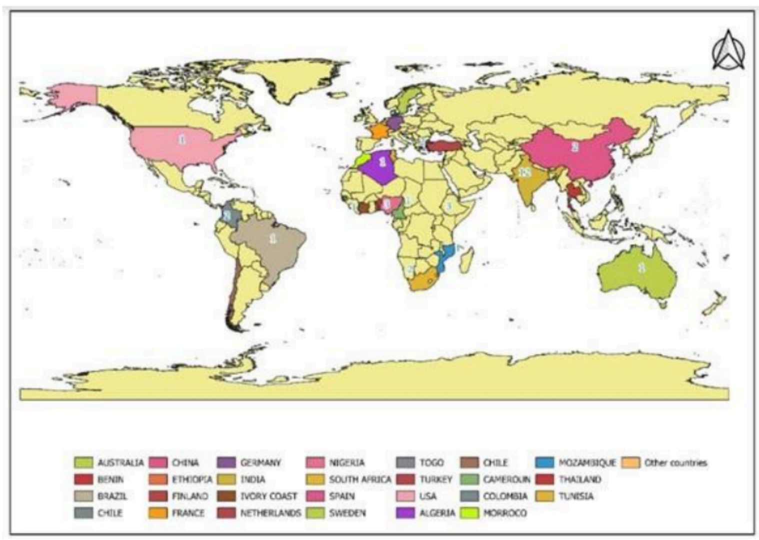

Figure 3. Geographical distribution of studies reviewed

The graph in Figure 4, illustrating the evolution of years of publication of research articles, reveals an interesting trend. Since the year 2014, this research area has seen steady growth in scientific activity until 2018, when it experienced a high rate of growth, with growth declining in 2019. The years 2019–2023 confirmed this growing interest, while the year 2024 is undergoing a significant acceleration in article production. This trend suggests a continuing commitment by the scientific community to tackling the challenges associated with vegetable crop diseases. Moreover, the presence of 2024 on the list indicates that this field is constantly evolving, with new advances expected. These findings emphasize the importance of research in the agri-food sector, particularly the fruit sector, and highlight the researchers' dedication to meeting these growing challenges.

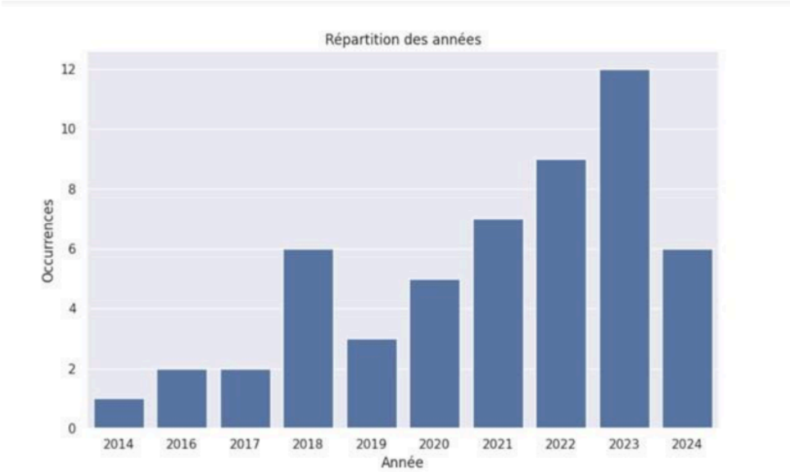

Figure 4. Graph showing the distribution of publication years for a total of 43 articles

4.2. The various fruit species examined

This review analyzed a total of 21 agri-food products, specifically: pineapple (Ananas comosus), cassava starch, plantain chips, carrots, bananas, tomato slices, cocoa beans, lemons, potato slices, mango slices, grapes, the 'akikon' tomato variety from Benin (West Africa), grated carrot, papaya, spirulina, blueberries (Vaccinium corymbosum), marula, mandarins, marsala, mapfilwa, muquaqua, white sapote slice, eggplant slice, murier, charantia, and paddy. Out of all the species that have been observed, pineapple is the one that has been studied the most extensively. As stated by reference [33], pineapple (Ananas comosus) holds the highest level of commercialization among tropical fruits worldwide, highlighting its significant economic value and widespread cultivation. Generally, although it is reasonable to prioritize research on extensively grown fruits like pineapple and bananas, expanding the scope of research to encompass a broader variety of dried fruits would enhance the thoroughness and practicality of waste reduction strategies in the agricultural and food industry. Consequently, this would help to reinforce the sector.

4.3. Solar dryer modelling techniques used for fruit in the food industry

The application of modeling techniques in the drying process of agri-food products has resulted in the development of various drying models. The primary purpose of modeling is not only to generate predictions about the drying process, but also to uncover additional details and acquire fresh perspectives on the process. There is no universally applicable drying behavior model that effectively suits all types of fruits. It is necessary to compare and analyze various methods of modeling convection drying [62]. Furthermore, it is necessary to measure and regulate temperature, humidity, air flow, solar radiation intensity, product moisture content, and other relevant parameters [63]. Within the literature, there are multiple drying models available. However, Laskar et al. [19] specifically utilized four models, as outlined in Table 4.

Table 4. Four thin-film models for carrots

Model name	Model	References
Henderson et Pabis	MR = a exp(kt),	[64]
Wang et Singh		[64]
Newton	$MR = 1 + at + bt^2$	[64]
Page model	MR = exp(-kt)	[45], [65], [66], [67],
	$MR = \exp(-kt^n)$.	[68]

These models were chosen because the drying characteristics of the cores (rectangular slabs, circular discs, and cubic samples) at temperatures of 70°C, 80°C, and 90°C, respectively, with indirect forced convection solar dryers are described, and the results show that the Henderson and Pabis model. Statistical analysis judges this model to be superior to the others. The parameters used to study drying are the moisture content and moisture content of core samples and residual errors (-0.03 to 0.03). The activation energy values ranged from 68.512 to 74.256 kJ/mol. Future work should prioritize efficient drying strategies and optimize the price of dried products to produce high-quality products at an affordable investment. Ndukwu et al. [69] designed and built a low-cost hybrid solar drying system, presenting drying kinetics, heat transfer coefficient, and thin film models for plantain chips. They built and tested two solar dryers, one equipped with biomass heating and the other without. The results show that the solar dryers developed can save between 27.78% and 58.33% of drying time compared with the sun-drying method at an ambient temperature of between 30 and 40 °C and humidity ranging from 55% to 70%. Under these operating conditions, collector efficiency ranges from 20.81% to 21.89%. Heat transfer coefficient values ranged from 0.64 to 10.5 W/m2 °C.

Table 5. Five thin-film models for carrots

Model name	Model	References
Lewis	MR = exp(kt)	[60]
Henderson and Pabis	MR = a exp(kt)	[70]
Logarithmique	MR = a exp(kt) + c	[70]
Two term exponentials	MR = a exp(-kt) + (1-a) exp (-kat)	[20], [40], [61]
Verma et al.	$MR = a \exp(k_1 t) + (1-a) \exp(k_2 t)$	[68], [71]

The determination (R2) varied from 0.8377 to 0.9905, while the sum of squared errors (SSE) varied from 0.0213 to 0.1380 for the five thin-film models (Table 5). The model by Verma et al. gave the best result for drying with biomass heating with parameters (a, k, g, R2, SSE), while the logarithmic model was the best for drying without biomass heating with parameters (a, c, k, R2, SSE). Mathematical modeling of thin-film solar tomato drying was carried out using two solar dryers, one with an HSD heat exchanger and a traditional solar dryer without a TSD heat exchanger, by Moradi et al. [73]. Demir's model MR = a exp(-kt) ^n + b is selected as the best model to fit tomato slice drying as it showed the highest value of correlation coefficient and the lowest value of RMSE with an r value of 0.99907 and an RMSE value of 0.01149 for continuous processes and an r value of 0.01646 and an RMSE value of 0.01646 for batch processes. Consequently, the model of Demir et al. is suitable for describing the drying behavior of a tomato slice. The parameters used are a, n (empirical constants), and k (drying rate constant). OriginPro 2021 software (OriginLab Corporation) was used to calculate the statistical parameters.

In their study [72], Daksa and Tolesa used two indirect solar dryers to dry white tapote and used CFD modeling (ANSYS FLUENT) to compare the speed and thermal performance of dryers with smooth and corrugated absorber plates. The results show that the maximum velocity in the solar air collector (SAC) and the average temperature value at the SAC outlet were found to be 0.58 m/s and 336 K for the smooth ISD absorber and 0.77 m/s and 350 K for the corrugated absorber. For maximum thermal efficiency, the ideal inlet velocity is 0.5 m/s. In addition, drying curves for kiln dryers, solar dryers, and open dryers were fitted with the four moisture content models as shown in Table 6 [72].

Table 6. Four thin-film models for white tapote

Nom du modèle	Models
Lewis model	MR=exp(-kt)
Simple exponential model	MR= aexp(-kt)
Page's model	$MR = \exp(-kt^n)$
Henderson and Pabis model	$MR = a\exp(-kt^n)$

For all equations, R2 values were above 0.95, indicating a good fit. The $\chi 2$ values of the Lewis model ranged from 0.00027 to 0.0.00072, from 0.0008 to 0.0051 and from 0.00049 to 0.0033 for oven, solar energy and sun drying, respectively. The highest R2 (0.999) and lowest $\chi 2$ (0.000132) of the Henderson and Pabis model were recorded. The present result suggests that Henderson and Pabis' model for oven due to drying techniques and Page's model for sodium meta-bisulfite due to pretreatments describe the drying characteristics of white sapote fruit slices. Koua et al. [73] developed a numerical model based on the heat balance of the solar collector and the drying chamber to predict the thermal behavior of the forced-air circulation indirect solar dryer for cocoa beans. The results show that this mathematical model should be used to simulate the temperature of the various components of the solar dryer and the temperature of the product to be dried during the drying process. The model developed consists of two systems of strongly coupled, non-linear equations representing the thermal behavior of the solar collector and the drying chamber, respectively. These heat balance equations for the solar collector and the drying chamber form a system of first-order differential equations of type:

$$\frac{dy}{dt} = f_1\big(t, y_1(t), y_2(t), \ldots, y_n(t)\big) \quad (8)$$

A comparison of the simulation results with those obtained experimentally showed satisfactory agreement, with a minimum correlation coefficient of 0.994, a percentage deviation of less than 1%, and a root-mean-square error of less than 0.8. The simulation results can serve as a guide for improving the indirect solar dryer's thermal performance." The finite-difference method was chosen for the numerical solution of the thermal equations developed. MATLAB version R2016a was used to solve the thermal equation systems obtained. Zoukit et al. [74] developed Takagi Sugeno Fuzzy (TSF) modeling of an indirect solar-electric hybrid dryer operating in forced convection (0.027 kg/s). The results show that the hybrid dryer was considered a nonlinear and uncertain system whose operating point varies according to weather conditions and airflow. The proposed TSF model was used to predict the drying temperature under no-load conditions. TSF modeling was tested in both solar and electric modes, where a single energy source was considered in each model. It showed that the solar dryer could not be efficient without controlling the drying parameters (temperature, humidity, and airflow).

Prakash et al. [75] modeled solar dryers using various techniques: artificial neural networks, adaptive neural-fuzzy inference system (ANFIS), FUZZY, thermal modeling, mathematical modeling, drying kinetic model, etc. However, their findings revealed no existing literature on modeling hybrid solar dryers with a model capable of producing a predictive output in a short enough time frame to enable total temperature control within the dryer.

Table 7. Two thin-film models for lemons

Nom du modèle	Models
Two terms	$MR = a \exp(k_0 t) + (1-a) \exp(k_1 t)$
Wang et Singh	$MR = 1 + at + bt^2$

Fuzzy modeling and fuzzy sets are widely used for the prediction and estimation of floating and nonlinear parameters [76]. Hao et al. [77] proposed and studied a new hybrid solar dryer with a dual-function flat plate solar collector (DF-FPSC) for drying lemon slices and developed a mathematical model of the most suitable drying characteristics for lemon slices. They proposed two models: the two-term model and the Wang and Singh model as shown in Table 7 [77].

The most suitable approach to depict the drying behavior of lemon slices under hybrid solar dryers is described by Wang and Singh, who propose the most accurate model. The variables assessed in this investigation included solar radiation intensity, ambient temperature, relative humidity, sample mass, temperature (drying air temperature and relative humidity), collector air outlet temperature, collector water inlet and outlet temperature, and collector water mass flow rate. The operational duration of the hybrid solar dryer can vary for a maximum of 4 months, contingent upon the specific climatic parameters of the local area. The payback period for the hybrid solar dryer was determined to be 3.63 years, which is less than its expected lifetime of 5 years. Furthermore, it is crucial to ensure that the lemon slices are not subjected to a hot-air drying temperature exceeding 60 °C. The collector thermal efficiency varied between 2% and 69.52%, with an average value of 44.6%. Ignacio et al. [78] conducted research on the mathematical modeling of drying thin-film pineapple (Ananas comosus) using a solar dryer in a greenhouse-type setting at a village scale. It is necessary to investigate the fundamental variables such as temperature, relative humidity, dimensions, and air flow rate based on the findings. Two sets of experimental data were used to fit nine thin-film drying models (Table 8) in order to accurately describe the drying characteristics of pineapples [78].

Table 8. Nine pineapple thin-film models

Model name	Models
Diffusion Approximation	$MR = a \exp(-kt) + (1-a) \exp(-kbt)$
Haghi and Angiz – III	$MR = [\frac{a+b*t}{1+c*t+d*t^2}]$
Haghi and Angiz – IV	$MR = a\exp = [\frac{-(t-b)^2}{2c^2}]$
Hasibuan and Daud	$MR = 1 - at^n \exp(-kt^m)$.
Hii	$MR = a \exp(-kt^n) + c \exp(-gt^n)$
Logistic	$MR = a0 / [1 + a\exp(kt)]$
Modified Midilli	$MR = \exp(-kt^n) + bt$
Page	$MR = \exp(-kt^n)$

The results show that the Hasibuan and Daud models proved to be the best. The average value of the MSRP parameters for the Hasibuan and Daud models was 11.89%, the MAE was 8.53, and the EF was 0.96. The validation of the most suitable model for Hasibuan and Daud was carried out by comparing the expected moisture content with the experimental humidity content in any particular greenhouse-effect solar dryer experiment. This greenhouse dryer was used to dry 1 cm-wide slices at a temperature between 25 and 60 °C with a relative humidity between 50 and 90%. This dryer has been used to carry out pineapple drying experiments. The estimation of parameters and nonlinear regression RMSE was done using the Matlab Optimization Toolkit. (version R2013b), allowing for design optimization tasks including estimating parameters, selecting components, and adjusting parameters. Olanipekun et al. [79] also studied mathematical modeling of the thin layer of pineapple. Slices of pineapple were dried in a hot air oven at temperatures of 50, 60, and 70 °C; microwave power levels of 385, 540, and 700 W, respectively; and under direct sunlight. Seven mathematical models were integrated into the experimental data (Table 9).

Table 9. Seven thin-film pineapple models

Model name	**Models**
Wang and Singh	$MR = 1 + at + bt^2$
Two-term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$
Page's model	$MR = \exp(-kt^n)$
Parabolic model	$MR = a + bt + ct^2$
Logarithmic model	$MR = a\exp(-kt) + c$
Generalized exponential model	$MR = a\exp(-kt)$
Exponential model	$MR = \exp(-kt)$

The nonlinear regression procedure was used to evaluate the models that best describe the variation in the humidity rate. The results show that the two-term model, Parabolic and Page, best explains the behavior of pineapple during hot air, microwave, and sun drying. The effective diffusiveness of moisture increased from 6.89×10^{-10} to 7.1×10^{-08} m^2/s while the activation energy was 12.46 kJ/mol for oven drying and 1.54 W/g for microwave drying. The quality of the adjustment was determined using the determination coefficient (R2), the reduced square chi ($\chi2$), the average square error (RMSE) and the square sum error (SSE), which are the statistical parameters taken into account for the selection of the model. The Ea values were 12.46 kJ/mol for oven drying and 1.54 W/g for microwave pineapple drying. These E_a values are in the general range of 12.7 to 110 kJ/ mol for foodstuffs. Patil and Gawande [1] presented some solar dryer modeling techniques using mathematical modeling, computational fluid dynamics (CFD), and artificial neural networking techniques (ANN). In its results, it emphasizes that for better organization of drying processes during modeling, parameters such as pressure, product shape, retention time, flow configuration, shelf geometry, and drying support condition need to be taken into account more specifically. They indicated that the most suitable model should have higher R2 (determination coefficient) values and lower $\chi2$ (square chi), MBE (bias error) and RMSE (average quadratic error). The author hopes that this revision effort can be valuable and conducive to future improvements in the work. Onwude et al. [80] illustrated a detailed overview of thin film drying theories, expressions, implications, activation energy, and effective moisture diffusivity with the results of thin film drying modeling of foodstuffs. The study revealed that temperature and product thickness are mainly responsible for modifying the thin-film drying behavior of vegetables as well as fruits.

A comprehensive study of thin-film drying modeling for selected Nigerian products was recently proposed by Chukwunonye et al. [81] who reported that Page and Midilli et al. are the dominant models. They suggest that the statistical approach is the most appropriate method of investigation for evaluating the performance of all the thin-film drying models available in the literature. Wang et al. [6] presented the mathematical modeling of an indirect forced convection solar dryer with an auxiliary heater for mango drying. The results reveal that the performance parameters measured were air temperatures at the collector inlet and outlet, air temperature inside the dryer, air mass flow rate, ambient temperature, relative humidity (RH), and solar radiation.

Page's model: MR = exp (-ktn) (9)

This model gave comparatively higher R2 values (0.9913-0.9991), as did the $\chi2$ (0.0001-0.0006). Page's model was the most appropriate to describe the drying kinetics of mango slices. This mathematical model can predict the moisture content of mango slices during solar drying, irrespective of drying time and temperature. The results show the thermal efficiency of the collector (22%) and the drying efficiency (19%). Here, the average thermal efficiency of the collector varies from 52.3% to 53.6%; the average thermal efficiency of the dryer varies from 30.9% to 33.8%. Consequently, this result shows that the solar dryer with auxiliary heating has a high performance compared to previous literature. Hamdi et al., [82] did the numerical modeling and experimental study of a mixed-mode, forced convection solar greenhouse dryer for grapes. The results show that the best model is that of two-term [21], [23], [40]:

$$MR = a \exp(k0t) + (1-a) \exp(k1t) \tag{10}$$

It is solved by the simulation software TRNSYS which gives R2= 0.986 and χ2= 0.0296. In addition, several terms vary in the model developed such as temperature, water content of the product (M), ambient temperature, airspeed, solar radiation, humidity rate, and drying time. The ambient air temperature varied from 34.5 to 42.93 °C, and the temperature at the output of the solar sensor ranged from 40.47 to 66.51 °C. The absorber temperature varied between 47.33 and 70.46 °C per second. The average effectiveness was 54.23. The maximum recorded solar radiation was approximately 1,040 W/m2 during the maximum sunshine hours. The yield of the collector with a flow rate of 0.05 kg/s varied between 29.63 % and 19.88,52 % for drying days. The moisture content of the grape was reduced to 0.22 (g of water/g of dry matter) from its initial humidity content of 5.5 (g water/G of dry material) in 128 hours. The efficiency of the solar air sensor reached 88.52%. Thus, the developed model is more realistic compared to other conventional models and can be used in the field of solar drying. As prospects, the present study will focus on the variation of certain parameters of the model, such as the change in airflow and weather conditions, in order to improve the model. Adeleye et al [83] carried out mathematical modeling of shredded carrot drying data for carrot samples of sizes 2 mm and 5 mm using an oven dryer. The results show that the model Midilli and Kucuk:

$$MR = a \exp(-ktn) + bt \tag{11}$$

This model was selected as best describing the grated core samples (R2 = 0.997, 2χ2 = 0.00055, RMSE = 0.02044, FE = 0.99699). The 5 mm thick sample has the highest value of effective moisture diffusivity; 3.4544 × 10^{-6} m^2/s and the 2 mm thick sample has the lowest value; 0.5680 × 10^{-6} m^2/s. This indicates that sample size has a pronounced influence on effective moisture diffusivity values. Das et al. [84] modeled an indirect solar dryer with forced convection for mass transfer using four different methods: numerical analysis (CFD), machine learning algorithms (ANN, SVM), and mathematical models of drying kinetics.

Table 10 shows the Four thin-film mass transfer models Adeleye et al [83] carried out mathematical modeling of shredded carrot drying data for carrot samples of sizes 2 mm and 5 mm using an oven dryer. The results show that the model Midilli and Kucuk can be written as follows:

$$MR = a \exp(-ktn) + bt \tag{12}$$

This model was selected as best describing the grated core samples (R2=0.997, χ2=0.00055, RMSE=0.02044, FE=0.99699). The 5 mm thick sample has the highest value of effective moisture diffusivity; 3.4544 × 10^{-6} m^2/s and the 2 mm thick sample has the lowest value; 0.5680 × 10^{-6} m^2/s. This indicates that sample size has a pronounced influence on effective moisture diffusivity values. Das et al. [84] modeled an indirect solar dryer with forced convection for mass transfer using four different methods: numerical analysis (CFD), machine learning algorithms (ANN, SVM), and mathematical models of drying kinetics.

Mass transfer, an important parameter for drying system design and product selection, is expressed using mathematical empirical equations, artificial intelligence methods and numerical analysis methods. The results show that the mathematical model closest to experimental values for expressing drying kinetics is Page's using the root mean square error (RMSE) analysis method. To this end, numerous parameters such as product moisture, ratio (MR), product convective heat transfer coefficient, product surface temperature, product dry-base moisture content, and drying air velocity were modeled with CFD. Deff, Ea, and drying efficiency values calculated from experimental data were found to vary between 0.15×10-10 and 0.1×10-10 m2/s, between 21.6 and 15.9 kJ/mol, and between 51.8% and 15.9%, respectively. Following the experiments, the average drying efficiency was calculated at 24%.

Table 10. Four thin-film mass transfer models

Model name	Models
Newton	MR = exp (-kt)
Page	MR= exp (-kt^n)
Midilli et Küçük	MR = a exp (-kt^n) + bt
Thompson	T=a ln(MR)+b[ln(MR)]^2

4.4. Discussion summary

Through the analysis of various research works, we have discussed direct, indirect, mixed, and hybrid solar dryers. Among these dryers, we have opted for indirect solar dryers because of their performance, and they are the most widely used in the preservation of agri-food products. In addition, based on various studies, the performance of each type of dryer, and their return on investment considers fruits with a high-water content (mango, lemon, Ananas comosus). The best models obtained for these fruits are shown in Table 11.

Table 11. Three best thin-film models selected (mango, lemon, Ananas comosus).

Model name	Models
Page	MR= exp (-kt^n)
Wang & Singh	MR =1 + at + bt^2
Hasibuan & Daud	MR =1-at^{n}exp (-kt ^{m})

The model that best describes pineapple drying kinetics in an indirect forced convection solar dryer with an auxiliary heating device for drying through mathematical and numerical modeling is then deduced. The parameters considered are solar air collector inlet and outlet temperatures, air temperature inside the dryer, air mass flow rate, ambient temperature, relative humidity, solar radiation, drying speed, product mass, and meteorological data from Cotonou (Benin). In addition, these authors have used various simulation software packages, with ANSYS FLUENT and OriginPro being the most widely used in the literature for solar fruit dryers, and this will be our simulation software.

4.5. Weaknesses of the approaches and the authors' perspective

Studying the performance of solar dryers is a challenging and intricate task. This study provides a comprehensive overview of the significant advancements made by numerous researchers in the development of diverse dryers and models tailored to different drying methods and specific types of fruits. However, the existence of research limitations and gaps has impeded the investigation into the effectiveness of solar dryers. Researchers in the majority of the reviewed studies developed their models by following controlled or predefined parameters. While the majority of the studies that were reviewed provided accurate identification of the performance of each system, Armel et al. [85] highlighted the necessity of enhancing prediction models for heat and mass transfer in convection drying. Specifically, the mean relative error should be limited to 3% or less of the product. Laskar et al. [19] suggested that future research should prioritize the development of effective drying techniques and the optimization of the cost of dried products. This will enable the production of high-quality products that are affordable to invest in. Saini et al. [86] demonstrated that there are several potential areas for future research and development in solar dryers. These include exploring alternative methods for improving design and enhancing performance, such as employing computational fluid dynamics (CFD) and numerical simulation tools to analyze heat and mass transfer processes in solar dryers. Additionally, optimizing solar dryer control and operation can be achieved through the application of artificial intelligence (AI) and machine learning (ML) techniques. Gilago et al. [86] noted the absence of any studies in the literature that provide a comprehensive performance evaluation of a domestic solar dryer. Castro et al. [62] examine upcoming developments in the mathematical modeling of fruit convection drying, which include novel techniques like multiscale modeling and drying in three-dimensional geometries. Advanced methodologies that integrate three-dimensional (3D) and temporal variations can accurately calculate the convective coefficients. Conducting comparative studies among various approaches would be beneficial. As an illustration, Hamdi et al. [82] have proposed to manipulate specific model parameters in order to enhance the model, thereby facilitating more precise intervention. Based on the mentioned factors, there is a substantial requirement for additional research in this area to create more effective, economical, and energy-efficient models for agricultural and food products.

5. Conclusions

This study has presented comprehensive information on solar dryers, their merits and drawbacks, and the specific models employed for each type of dryer and product. This study has examined various research studies, focusing specifically on modeling solar dryers for the agro-food sector pineapple. In addition, heat balance models for each type of solar dryer indicated in the literature have been listed. The methodology used was adapted from an existing one. From the existing models, two best models for the product were selected. And among these two models selected, the best uses a statistical regression method. From the analysis done, indirect solar dryers are appropriated to study pineapple drying. Hence, the indirect solar dryer model with cabinets as they dry fruits with high humidity levels, such as bananas and grapes. The literature reveals three appropriate models widely used in the agri-food sector such as Page, Wang and Singh, two terms models respectively. These models will be used in future research to develop a heat balance model for drying pineapple, which does not currently exist in the literature. Furthermore, the review highlighted the need to adopt a comprehensive methodology to simulate solar fruit dryers, with particular emphasis on developing a model that is both economically efficient and accurately reflects the city's weather conditions of Cotonou (Benin). This study not only contributes to the advancement of research on solar dryer modeling in the agro-food sector but also provides crucial information to researchers and helps mitigate post-harvest losses in the agri-food sector, particularly for pineapples. In perspective, the modeling and optimization of an indirect solar dryer with a new heat balance model for the drying of pineapple will be performed to its design.

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The authors would like to thank the editor and the anonymous reviewers who will spend their time on the present manuscript.

Abbreviations

$\dot{m}_a$	Air flow rate	(kg/s)
h_1	Absorbent fluid convective heat transfer coefficient	(W/m² K)
h_2	Coefficient of heat transfer by convection of covering fluid	(W/m² K)
h_V	Volume coefficient of heat transfer between air and gravel	(W/m³ K)
h_{af}	Convective heat transfer coefficients between cover and air inside collector	(W/(m²·K))
h_{ca}	Convective heat transfer coefficients between cover and air outside the collector	(W/(m²·K))
h_e	Overall loss coefficient	(W/m² K)
h_{fg}	Latent heat of vaporization	(kJ/kg)
h_{los}	Conductance through insulation	(W/K)
$h_{r,p-g}$	Absorber-cover radiative heat transfer coefficient	(W/m² K)
h_{re}	Radiative heat transfer coefficient between cover and outside air	(W/(m²·K⁴))

h_{rp}	Radiative heat transfer coefficient between absorber plate and cover	$(W/(m^2 \cdot K^4))$
h_w	Coefficient of heat transfer by cover-ambient convection	$(W/m^2\ K)$
$\dot{Q}_{PCM\ i:i+1}$	Heat transferred to lower layer	(kWh)
$\dot{Q}_{PCM\ i-1:i}$	Heat transfer from upper layer	(W/m^2)
$\dot{Q}_{PCM\ L}$	Heat transfer from PCM to ambient air (through insulation)	(kWh)
η_c	Collector efficiency	(%)
η_{cov}	Convection dryer efficiency	(%)
η_{ins}	Instantaneous system energy efficiency	(%)
Φ_{sa}	Absorbing solar radiation	(W/m^2)
A_C	Collection area	
A_c	Collector surface area	(m^2)
A_{c1}	Collector surface	(m^2)
C_p	Specific heat	(J/kg K)
C_p	Specific heat	$(J/(kg \cdot K))$
E_c	Energy consumption	(kWh)
F'	Collector efficiency factor	(%)
F_R	Collector heat removal factor	(%)
$I1_T$	Irradiance to collector plane	$(W\ /m^2)$
I_c	Solar irradiation	(kW/m^2).
L_w	Latent heat at medium temperature	(J/kg)
M_0	Initial moisture content,	(%)
M_e	Equilibrium moisture content	(%)
M_i	Initial sample mass	(kg)
P_f	Fan power	(W)
P_t	Total energy input	(kWh)
$\dot{Q}_g$	Absorbed solar radiation	(kW/m^2)
$\dot{Q}_{PCM,u}$	PCM charging or discharging heat transfer	(W)
Q_d	Energy required for drying	(J)
R_e	Reynolds number	
T_a	Average ambient air	(°C)
T_{amb}	Ambient temperature	(°C)
T_{amb}	Ambient temperature	(°C)
T_{co}	Air temperature at collector outlet	(°C)
$T_f(i,t)$	Air temperature	(°C)
T_{fs}	Collector outlet temperature	(°C)
T_i	Air temperature at collector inlet	(°C)
$T_{in\ c}$	Collector inlet temperature	(°C)
T_{in}	Inlet temperature	(°C)
T_{out}	Outlet temperature	(°C)
T_p	Average absorber temperature	(°C)
T_{pa}	Absorber plate	
$T_s(i,t)$	Gravel temperature	(°C)
$T_{tout\ c}$	Collector outlet temperature	(°C)
T_v	Lid	
U_L	Total collector loss coefficient	(W/m^2K)

U_b	Collector return loss coefficient	(W/m²K)
U_t	Collector top loss coefficient	(W/m²K)
V_a	Air velocity in the solar dryer	(m/s)
V_{amb}	Wind speed	(km/h)
m_{air}	Air mass flow	(kg/s)
m_f	Final moisture content	(kg)
m_i	Initial moisture content	(kg)
m_w :	Mass of water removed from sample during drying process	(g)
q'	Thermal power required to heat the air in the absorber plate	(W)
q_u	Useful energy gain per unit collector area	(W/ m²)
t_{on}	Microwave drying exposure time at applied power	(s)
α_p	Absorbance of absorber plate	
α_v	Absorption of glass cover	
ε_v	Cover emissivity	
η_{D1}	Dryer efficiency	(%)
η_{E1}	Dryer efficiency	(%)
η_{O1}	Overall efficiency	(%)
η_{c1}	Collector efficiency	(%)
$\lambda_{PCM.i}$	Liquid fraction of layer i	(%)
ν_a	Air kinematic viscosity	(m²/s)
τ_{C1}	Collector cover transmission	(%)
τ_{G1}	Transmission of polycarbonate cabinet	(%)
τ_v	Transmissivity of glass cover	(%)
ϱ_u	Useful energy gain	(W)
A	Surfaces	(m²)
B	Half-height of groove	(m),
D	Diameter	(m)
DE	Drying efficiency of continuous vacuum and microwave drying	(%)
E	Thickness	(m)
Er	Energy required to dry foodstuffs	
Es	Energy supplied	(J)
H	Enthalpy	kJ/kg
I	Incident solar radiation	(W/m²)
ISD	Indirect solar dryer	
L	Manifold flow length	(m)
M	Product moisture content at time t	(%)
MSD	Mixed solar drying	
N	Number of sensors connected in series	
Nu	Nusselt number	
SER	Specific energy requirement	(kWh /g)
SMER	Specific Moisture extraction rate	(kg/kWh).
T	Time	(s)
T	Temperature	(°C)
TES	Thermal energy storage	
W	Specific humidity in kg of water vapor per kg of dry air	

H	Overall dryer efficiency	(%)
T	Glass cover transmission	(%)
I	Global radiation	(W/m^2)
MC_f	Moisture content, dry base	(%)
MC_i	Moisture content, wet base	(%)
α	Absorber absorption	(%)
λ	Thermal conductivity	(W/m K)
ν	Air flow rate	(m^3 /s)
σ	Stefan-Boltzmann constant	(W/(m^2·K^4))

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript£.

Author Contribution Statement

Aigbe, Ahouansou, Semassou, Fopah-Lele: proposed the research problem.

Aigbe, Tossa, Vodonou, Amoussou: developed the theory and performed the computations.

Aigbe, Amoussou, Vodonou, Tossa: verified the analytical methods and investigated the validity of the model selected.

Fopah-Lele, Ahouansou, Semassou: supervised the findings of this work.

All authors discussed the results and contributed to the final manuscript.

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I. APPENDIX – A (LIST OF EQUATIONS EXPRESSING THE THERMAL PERFORMANCES OF THE SOLAR DRYER)

$$\eta=\frac{E_r}{E_S} \quad (A1)$$

$$\eta_{cov}=\frac{T_{in}-T_{out}}{T_{in}-T_{amb}} \quad (A2)$$

$$\eta_{ins}=\frac{\text{énergie utilisée pour l'évaporation au temps } t}{\text{énergie d'entréeau temps } t} \quad (A3)$$

$$DE=\frac{t_{on}\,p(1-m_f)10^{-6}}{M_i(m_i-m_f)} \quad (A4)$$

$$SMER=\frac{\text{quantité d'eau évaporée}}{\text{L'énergieutilisée}} \quad (A5)$$

$$SER=\frac{E_c}{m_s} \quad (kWh/g) \quad (A6)$$

$$SER=\frac{E_c}{m_w} \quad (kWh/g) \quad (A7)$$

$$h_{rcs}=\varepsilon_c\times\sigma\times(T_c^2+T_s^2)\,(T_c+T_s) \quad (A11)$$

$$T_s=0.552(T_a)^{1.5} \quad (A12)$$

$$h_{rbc}=\frac{\sigma(T_b^2+T_c^2)\,(T_b+T_c)}{\frac{1}{\varepsilon_b}+\frac{1}{\varepsilon_c}-1} \quad (A13)$$

$$h_{rbc}=[5.37+(3.8\times V)] \quad (A14)$$

$$N_u=0.0158\times(R_e)^{0.8}=0.0158\times\frac{D_h\times V\times\rho_f}{\nu}:=\frac{h_{cbf}\times D_h}{K}=0.0158\times\frac{D_h\times V\times\rho_f}{\nu} \quad (A15)$$

$$D_h=\frac{4\times w_c\times D_c}{2\times(w_c+D_c)} \quad (A16)$$

$$\eta_{c1}=\frac{\dot{m}1C1_p(T_{tout\,c}-T_{in\,c})}{A_{c1}I1_T} \quad (A30)$$

$$\eta_{E1}=\frac{m_w h_{fg1}}{(A_{c1}+A_{G1})I1_T} \quad (A31)$$

$$\eta_{D1}=\frac{m_{p1}Cp_p(T_{p,t+dt}-T_{p,t})+m_w h_{fg1}}{I1_T(A_{c1}\eta_{C1}+A_{G1}\tau_{G1})} \quad (A32)$$

$$\eta_{O1}=\frac{m_{p1}Cp_p(T_{p,t+dt}-T_{p,t})+m_w h_{fg1}}{(A_{c1}+A_{G1})+m_{a1}(H_{out}-H_{in})} \quad (A33)$$

$$\dot{Q}_{p\text{-}v,rad}+\dot{Q}_{a\text{-}v,conv}+\dot{Q}_s-\dot{Q}_{v\text{-}amb,rad}-\dot{Q}_{v\text{-}amb,conv}=m_v C_{p,v}\frac{\Delta T_v}{\Delta t} \quad (A35)$$

$$\dot{Q}s = \alpha_v A_C I_c \quad \text{(A36)}$$

$$\dot{Q}_{v\text{-}amb,\,rad} = h_{v-amb,rad}\, A_C(T_v - T_{amb}) \quad \text{(A37)}$$

$$\dot{Q}_{p-v,rad} = h_{p-v,rad} A_C(T_{pa} - T_v) \quad \text{(A38)}$$

$$\dot{Q}_{a-v,conv} = h_{a-v,conv} A_C(T_a - T_v) \quad \text{(A39)}$$

$$\dot{Q}_{p\text{-}a,conv} - \dot{Q}_{a\text{-}v,\,conv} - \dot{Q}_U = m_a C_{p,a} \frac{\Delta T_a}{\Delta t} \quad \text{(A40)}$$

$$\dot{Q}_{p\text{-}a,conv} = h_{pa-a,conv}\, A_C(T_{pa} - T_a) \quad \text{(A41)}$$

$$\dot{Q}_U = \dot{m}_a C_{p,a}(T_{tout} - T_{amb}) \quad \text{(A42)}$$

$$\dot{Q}_g - \dot{Q}_{p\text{-}v,\,rad} - \dot{Q}_{p\text{-}a,conv} - \dot{Q}_{PCM,u} = m_p C_{p,u} \frac{\Delta T_p}{\Delta t} \quad \text{(A43)}$$

$$m_c C_{pc} \frac{dT_c}{dt} = A_c h_{c,c-a}(T_a - T_c) + A_c h_{r,c-s}(T_s - T_c) + A_c h_w(T_{am} - T_c) + A_c \alpha_c I_t \quad \text{(A50)}$$

$$m_a C_{pa} \frac{dT_a}{dt} = A_p h_{c,p-a}\left(T_p - T_a\right) + A_{fl} h_{c,fl-a}\left(T_{fl} - T_a\right) + D_p A_P C_{pv} \rho_P \left(T_p - T_a\right) \frac{dM_p}{dt} + (\rho_a V_{out} C_{pa} T_{tout} - \rho_a V_{in} C_{pa} T_{in}) + U_c A_c (T_{am} - T_a) + [(1\text{-}F_p)\left(1 - \alpha_f\right) - (1 - \alpha_p) F_p]\, I_t A_c \tau_c \quad \text{(A51)}$$

$$m_p(C_{pp} + C_{pl} M_p) \frac{dT_p}{dt} = A_p h_{c,p-a}\left(T_a - T_p\right) + A_p h_{r,p-a}\left(T_c - T_p\right) + D_p A_P \rho_P [L_P + C_{pv}\left(T_p - T_a\right)] \frac{dM_p}{dt} + F_p \alpha_p I_t A_c \tau_c \quad \text{(A52)}$$

$$m_{fl} C_{pfl} \frac{dT_{fl}}{dt} = A_{fl} h_{c,fl-a}\left(T_a - T_{fl}\right) + A_{fl} h_{d,fl-g}\left(T_g - T_{fl}\right) + (1 - F_P)\alpha_f I_t A_f \tau_c \quad \text{(A53)}$$

$$\rho_a V \frac{dH}{dt} = A_{in} \rho_a H_{in} v_{in} - A_{out} \rho_a H_{out} v_{out} + D_p A_p \rho_p \frac{dM_p}{dt} \quad \text{(A54)}$$

$$\frac{M - M_e}{M_0 - M_e} = \exp(-kt^d) \quad \text{(A55)}$$

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