Chapter

Assessment of Solar Dryer Performance for Drying Different Food Materials: A Comprehensive Review

Guna Muthuvairavan, Saranya Manikandan, Elavarasan Elangovan and Sendhil Kumar Natarajan

Abstract

Studying crucial drying parameters, such as activation energy and moisture diffusivity, offers valuable insights for optimizing food safety. Accurate predictions and simulations through mathematical thin-layer models aid in designing, controlling, and optimizing drying operations for various food items. Solar drying presents a viable and eco-friendly solution for food preservation. This chapter critically evaluates solar drying performance for various vegetables, fruits, marine products, and other commodities, providing comprehensive insights into its efficiency. According to the literature, the moisture diffusivity (m^2/s) for vegetables has been reported to be within the range of 2.01×10^{-10}–1.935×10^{-8}. For fruits, the moisture diffusivity varies between 1.33×10^{-10} and 6.98×10^{-9}. In the case of marine food products, the range is found to be 2.8×10^{-8}–3.408×10^{-7}, while for other commodities, it falls between 1.79×10^{-9} and 1.061×10^{-7}. The activation energy (kJ/mol) for vegetables has been observed to fall within the range of 24.81–47.19. Similarly, for fruits, the activation energy varies between 2.56 and 45.20. Notably, Ginger demonstrates an activation energy of 35.675 kJ/mol. Experimental results showed that lower activation energy and higher moisture diffusivity accelerate dehydration.

Keywords: solar drying, natural convection, forced convection, moisture diffusivity, activation energy, mathematical modeling

1. Introduction

Meeting the food demands of a rapidly rising global population is a significant concern for civilization. By 2050, the world's population is expected to reach 9.1 billion, demanding an additional 70% of the food supply. Most of this population expansion is likely attributed to emerging countries, with many currently suffering

Food substance	Post-harvest loss (%)
Cereals	20–40
Pulse and oil crops	10–20
Roots and tubers	10–20
Vegetables and fruit	40–50
Meat	20–30
Fish	20–30
Diary	10–20

Table 1.
Post-harvest loss of various food substances [1, 3, 4].

from hunger and food insecurity. Concerns about rising food consumption are exacerbated by increasing urbanization, climate change, and land use for non-food crop production. Most governments have focused their policies over the last few decades on improving agricultural production, land management, and population control to address rising food demand. However, despite being a critical issue, post-harvest loss does not receive the attention it needs, with fewer than 5% of research funds committed to it in previous years [1–3]. One-third of the world's food supply, or around 1.3 billion tons per year, is lost or wasted, as reported by the Food and Agriculture Organization of the United Nations (FAO). The post-harvest loss of various food substances are presented in the **Table 1**. These losses happen at every stage of the food system, from cultivation to processing to distribution to final consumption.

Principal causes of post-harvest losses include Insects, rodents, fungi, and bacteria that can damage or ruin food due to pests and diseases. Physical damage can occur when food is handled roughly, improperly stored, or transported. During storage and processing, nutrients can be lost from food. Food can be squandered due to spoilage, overproduction, or insufficient demand. Post-harvest losses have a substantial influence on food security. They decrease the quantity of available food, which can result in hunger and malnutrition. They also increase food costs, making it unaffordable for some people [1, 3, 4].

2. Drying-solution to post-harvest loss

Drying is a widely used solution to mitigate post-harvest losses in various agricultural products. The drying process involves reducing the moisture content of harvested crops, which helps prevent spoilage, inhibit microbial growth, and maintain the quality of the product for extended periods [5, 6]. However, it is essential to note that the effectiveness of drying as a solution for post-harvest losses can vary depending on various factors, such as the type of crop, climatic conditions, available drying methods, and storage facilities. Appropriate drying techniques must be selected and implemented to ensure that the quality and nutritional value of the crops are maintained during the drying process. The best drying method for a particular application will depend on several factors, including the type of food being dried, the desired quality of the dried product, and the available resources [7, 8].

3. Importance of solar drying

Solar energy is a renewable and clean source of power that harnesses sunlight to generate electricity or heat. Using solar panels made of semiconductors, photons from sunlight are absorbed, releasing electrons and creating an electric current. This energy is environmentally friendly, as it does not produce harmful emissions or deplete finite resources. Solar energy can be deployed at various scales, providing energy independence and resilience, particularly in remote areas. Although initial costs can be high, advancements in storage technologies are improving efficiency and overcoming limitations associated with weather conditions. Overall, solar energy offers a sustainable solution for our energy needs, contributing to a cleaner and more sustainable future [9, 10]. Solar drying methods offer several advantages compared to conventional drying techniques. Energy efficiency [8], cost-effectiveness [11], environmental sustainability [12], preservation of nutritional quality [13], and enhanced product quality [14] are the advantages of using solar dryers.

In this regard, Ekechukwu et al. conducted a comprehensive review of various solar energy drying system designs, construction details, and operational principles. Their findings indicated that properly designed forced convection (active) solar dryers are generally more effective and controllable than natural-circulation (passive) types. However, due to the need for electricity or fossil-fuel-driven fans and auxiliary heating sources, active solar dryers are unsuitable for remote rural village farm use in most developing countries, given their high capital, maintenance, and operational costs. On the other hand, for large-scale applications in rural areas, the “ventilated greenhouse dryer” offers the advantage of being cost-effective and simple to construct and operate on-site [15].

Fudholi et al. gave the technical directions for developing solar-assisted drying systems for agricultural produce [16]. Jairaj et al. reviewed solar dryers exclusively for grape drying on a normal scale. They included various pre-treatment and drying methods for good-quality grape drying [17]. For the Malaysia location, the air-based solar collectors integrated solar drying system was reviewed by Fudholi et al. They have included the energy, exergy, economic and environmental aspect of the various solar dryers [18]. Mustayenp et al. presented a study on various solar dryers' design, performance, and application. This review focused on solar dryer models suitable for producing high-quality dried products [19]. Hicham El Hage et al. extensively reviewed the economic and environmental aspects of the solar drying system. The critical parameters, such as payback period and CO_2 mitigation, were compared [20].

Om Prakash et al. reviewed the various modeling technics, including computational fluid dynamics (CFD), adaptive-network-based fuzzy inference system (ANFIS), artificial neural networking (ANN), FUZZY, thermal, mathematical, drying kinetic, and energy modeling [21]. Azwin Kamarulzaman et al. reviewed the global advancement of solar drying technologies and their prospects. They discussed various performance parameters, including energy assessment, payback period, and CO_2 mitigation [22]. Aprajeeta Jha et al. reviewed the recent advancements in design, application, and simulation Studies of hybrid solar drying technology. The review discussed the various software used for simulating the solar drying system, including PHOENICS, FLUENT (general purpose software with Multiphysics capabilities), FIDAP (modeling complex physics), ANSYS CFX, COMSOL Multiphysics, TRNSYS [23]. Nukulwar et al. focused on various materials used to construct solar dryers and their performance evaluation for agricultural products [24].

The literature shows that various authors reviewed the performance evaluation of some specific food commodities, the use of simulation software, various modeling, and economic and environmental aspects of solar drying systems. However, the performance evaluation of various ranges of fruits, vegetables, marine food products, and other commodities was not reported exclusively. This chapter mainly focused on the review of the performance of solar drying techniques for a range of food substances which is widely used in India, including vegetables (bottle gourd, carrot, potato, ivy gourd, and onion), fruits (banana, cucumber, Tomato, and grapes), marine food products (Fish, shrimp, and prawn), and other commodities (Ginger, Chili, and Jaggery). The drying parameters such as moisture diffusivity, activation energy, drying rate, operating temperature, size, and shape of the drying product were compared for mentioned food substances. A suitable mathematical thin-layer model for food substances was also presented.

4. Types of solar drying

Solar drying is an age-old technique that utilizes the sun's power to remove moisture from various substances, including food. This preservation method has been practiced for centuries and continues to be widely used in many regions worldwide. By harnessing solar energy, solar drying offers a natural and cost-effective way to extend the shelf life of perishable items while preserving their nutritional value. Different solar drying methods, each with its unique approach and design, are presented in **Figure 1**. The description, suitability, advantage, and disadvantages of each significant solar drying technique are presented in **Table 2**. These methods are often tailored to suit specific needs, environmental conditions, and the type of dried material.

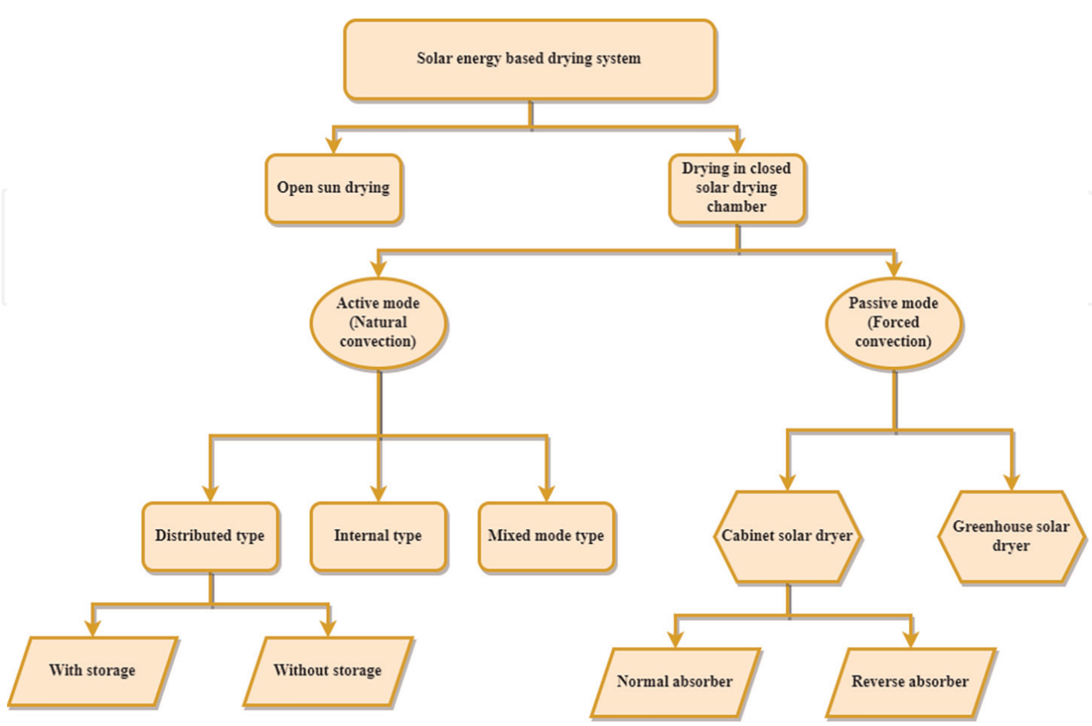

Figure 1.
Types of solar energy-based drying methods [7].

Type	Description	Suitability	Advantages	Disadvantages	Reference
Open sun drying	The product to be dried is simply placed in the sun, as shown in **Figure 2**.	Various drying needs	Simple and affordable.	Highly dependent on weather conditions.	[7, 11]
Direct solar dryers	The product to be dried is exposed to the sun directly, as illustrated in **Figure 3**.	Low-scale drying needs	Low cost, simple to build and operate.	It can only be used during the day when the sun is shining and exposure to environmental elements.	[5, 25]
Indirect solar dryers	The product to be dried is not exposed to the sun directly. The air that is used to dry the product is heated by the sun and then circulated around the product as represented in **Figure 4**.	Delicate/ valuable items	Controlled drying environment and Can be used at night or on cloudy days.	Slightly higher cost than direct solar dryers and is more complex to build and operate.	[11, 14, 26]
Mixed-mode solar dryers	A combination of direct and indirect solar drying **Figure 5**.	Improved efficiency	Combines the advantages of both direct and indirect solar dryers.	More complex to build and operate.	[14, 27]
Hybrid solar dryers	A solar dryer that uses an auxiliary energy source, such as a fan or a heater, to supplement the solar energy **Figure 6**.	Variable drying needs	It can be used in areas with low solar irradiance or on cloudy days.	More complex to build and operate.	[12, 23, 28, 29]

Table 2.
Comparison of different solar dryers.

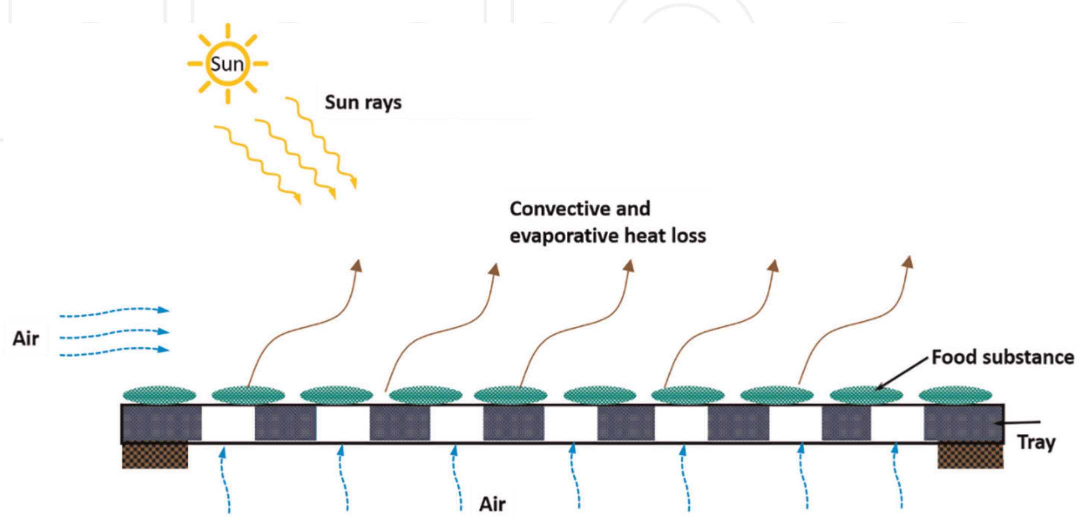

Figure 2.
Schematic of open sun drying [8].

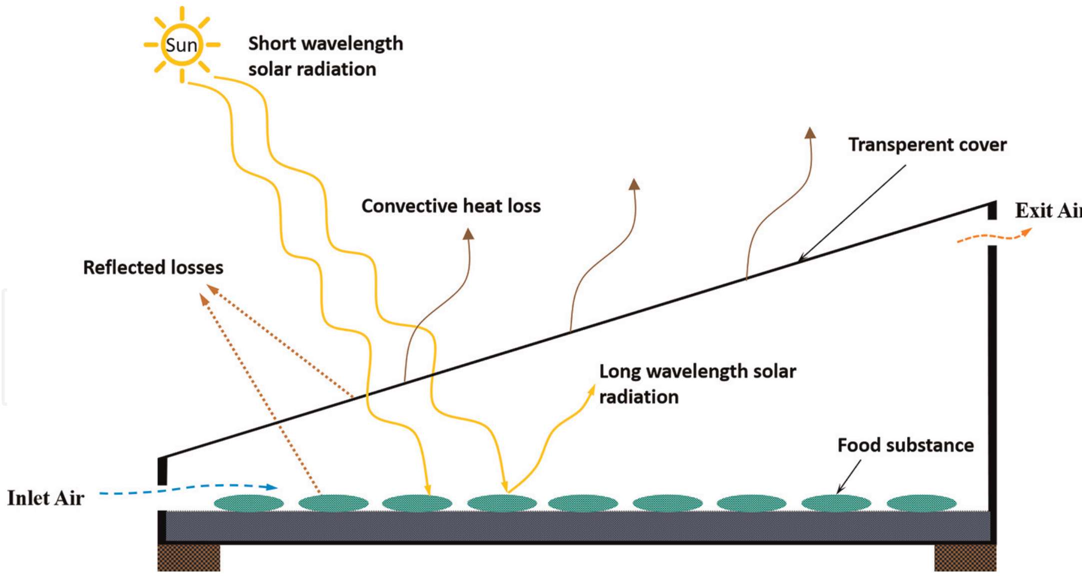

Figure 3.
Schematic of the direct solar dryer [7].

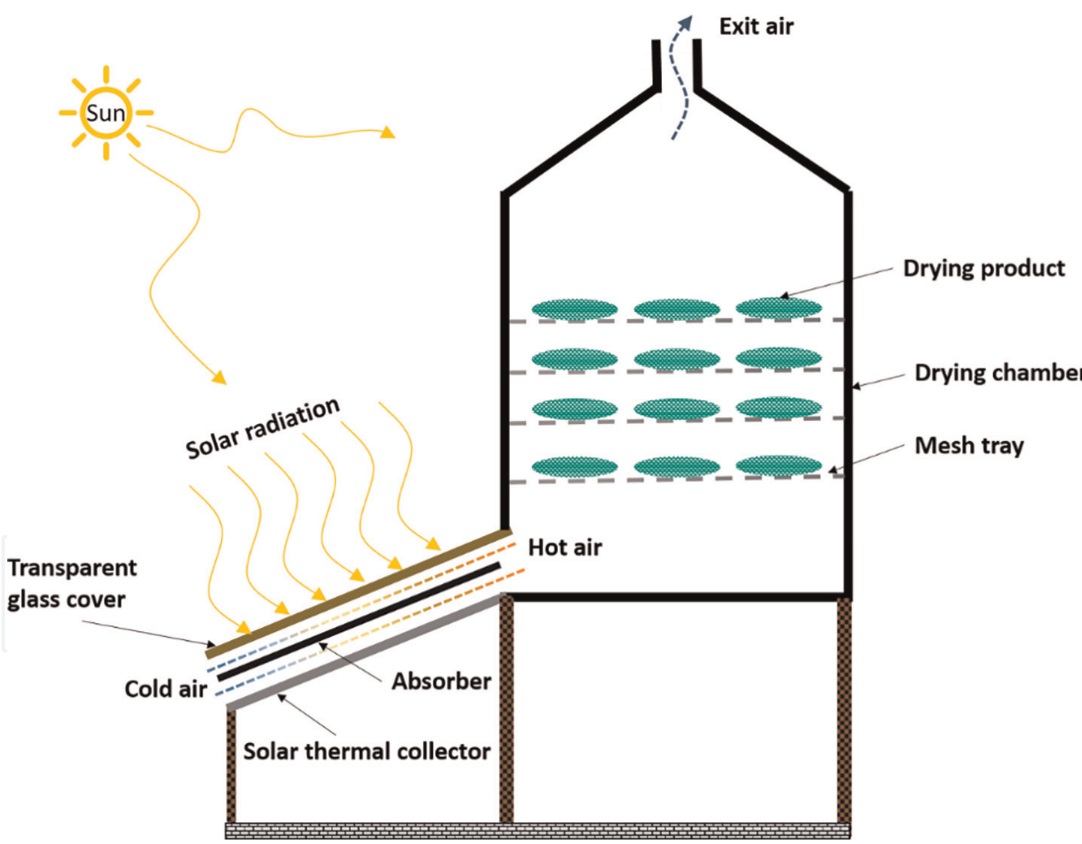

Figure 4.
Schematic of the indirect solar dryer [14].

5. Drying kinetics

This section presents the mathematical formulation of important drying parameters including moisture content, moisture ratio, moisture diffusivity, activation energy, and various thin-layer mathematical model.

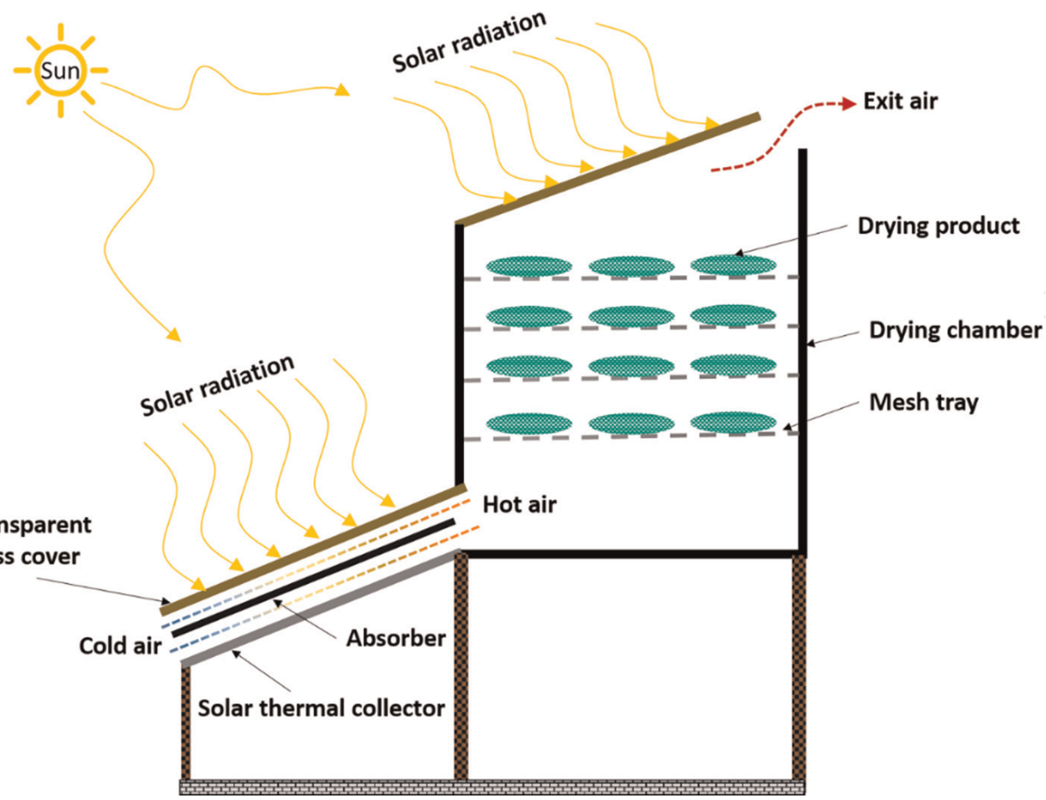

Figure 5.
Schematic of the mixed-mode solar dryer [14].

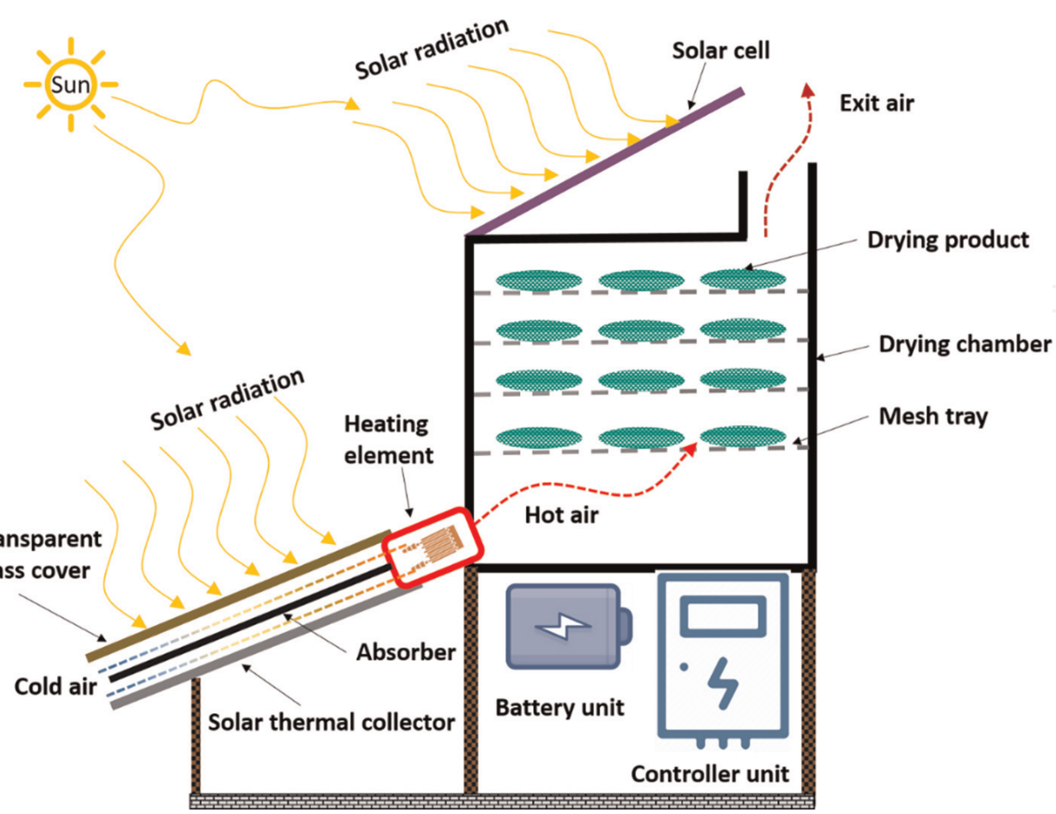

Figure 6.
Schematic of the hybrid-mode solar dryer [12].

The moisture content (MC) of a drying product refers to the amount of moisture or water present in the product, expressed as a percentage of its total weight, as presented in Eq. (1), [30].

$$MC = \frac{m_w - m_d}{m_w} \tag{1}$$

Where, m_w is the mass of the drying product before drying and m_d is the mass of the dried product.

Activation energy is a crucial concept in the realm of drying products, denoting the energy required to initiate and propel the drying process [31]. This context refers explicitly to the energy necessary to surmount the molecular forces that bind water molecules to the product's surface, thus enabling their evaporation. This activation energy measures the minimum energy essential for the drying process to occur at a noteworthy rate. It is important to note that the activation energy is unique to the material undergoing drying and the specific drying conditions applied. Different materials and various drying methods may exhibit distinct activation energies. Empirical investigations are typically carried out to ascertain this value, involving the study of drying kinetics for the material at different temperatures.

Another fundamental property relevant to drying processes is moisture diffusivity. This parameter describes the rate at which moisture traverses a drying product during the drying procedure [31]. Understanding moisture diffusivity is paramount in modeling and comprehending the drying kinetics of diverse materials. The moisture diffusivity factor represents the capability of water molecules to move through the product's microstructure, and its value is influenced by several factors, including temperature, humidity, and the inherent nature of the material being dried. To determine the moisture diffusivity experimentally, the moisture content is measured at various locations within the drying product over time. The acquired data is then fitted into appropriate mathematical models, such as Fick's second law of diffusion, enabling the calculation of the diffusivity coefficient [13].

The diffusion mechanism governs the drying process of food substances at the rate of falling period. Fick's second law of diffusion governs effective moisture diffusion [30].

$$\ln MR = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{L^2} \tag{2}$$

MR is a moisture ratio, and it represents the ratio of the current moisture content of the product to its initial moisture content. D_{eff} is an effective moisture diffusivity (m^2/s), t is the corresponding drying time (hrs), and L is the thickness of the drying sample (m). The slope of the $\ln MR$ with respect to time can be written as Eq. (3),

$$slope = \frac{\pi^2 D_{eff}}{L^2} \tag{3}$$

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

Where M_t, M_e, and M_0 are the instantaneous, equilibrium, and initial moisture content, respectively.

The diffusion of moisture during drying can be described as Eq. (5) by Fick's second law of diffusion as equation [13],

$$D_{eff} = D_0 e^{\left(-E_a/RT\right)} \tag{5}$$

Where D_0 is the diffusion factor (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 kJ/mol.K), and T is the temperature (K). The plot of $\ln D_{eff}$ against 1/T gives a straight line of slope k where the relation between E_a and diffusivity coefficients can be defined through linear regression analysis and activation energy E_a is evaluated by Eq. (6),

$$k = \frac{E_a}{R} \tag{6}$$

The thin-layer drying model is a mathematical representation that describes the drying kinetics of a material during the drying process [30]. It assumes that the drying occurs within a thin-layer on the material's surface and considers the moisture transfer from this layer to the surrounding drying medium (usually air) [32]. Several thin-layer models have been proposed over the years. The important thin-layer model is presented in **Table 3**.

6. Solar drying of various food substances

In this section, solar drying of various food substances such as vegetables, fruits, marine products, and others, as shown in **Figure 7**, was elaborately discussed.

6.1 Vegetables

This section discusses the performance of different solar dryers for drying various vegetables, including Bottle gourd, Carrot, Potato, Ivy gourd, and Onion. The summary of the same is presented in **Table 4**.

Name	Model	Reference
Newton	$MR = e^{-kt}$	[30]
Page	$MR = e^{-kt^n}$	[32]
Modified page	$MR = e^{[-(kt)^n]}$	[30]
Henderson and Pabis	$MR = ae^{(-kt)}$	[32]
Logarithmic	$MR = ae^{(-kt)} + c$	[30]
Midilli-Kucuk	$MR = ae^{(-kt^n)} + bt$	[32]
Wang and Singh	$MR = 1 + at + bt^2$	[32]

Table 3.
Different thin-layer models for drying.

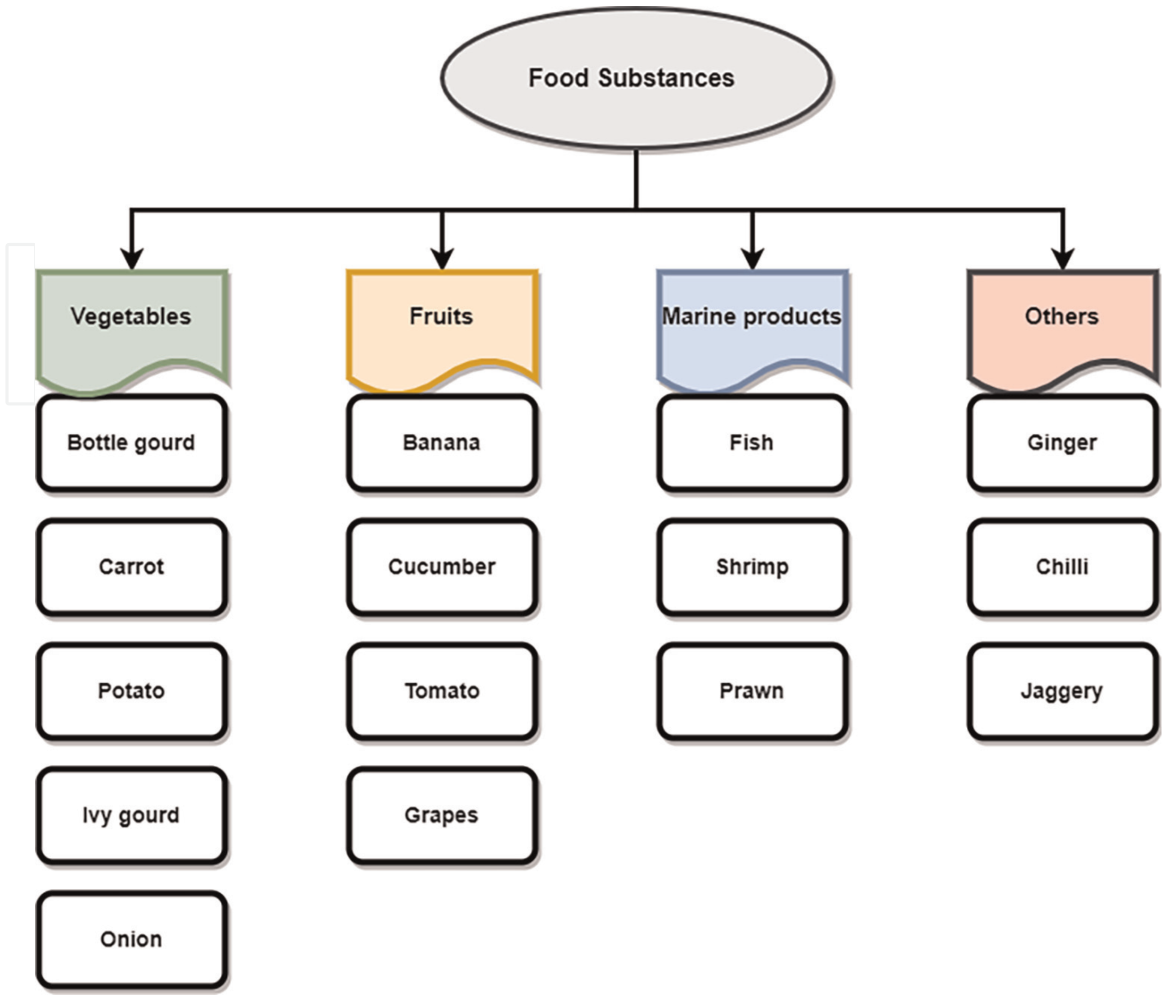

Figure 7.
List of various food substances.

6.1.1 Bottle gourd

K.A. Shinde et al. evaluated the drying characteristics of steam-blanched and non-blanched bottle gourd samples. A tray dryer with forced convection and hot air was used to carry out the drying process. The samples were pulverized for analysis, and their initial moisture content was 0.04 kg water per kg dry matter. The study aimed to determine the effect of blanching on the drying efficiency and qualitative parameters of bottle gourd. The samples are pulverized for examination, and the research intends to determine the effect of blanching on the drying efficiency and qualitative features of bottle gourd [33].

Kukadiya Vishal et al. investigated using a fluidized bed dryer with forced convection for drying samples of various forms; specifically slab shapes 10 × 10 × 3 mm, 10 × 10 × 5 mm, and 10 × 10 × 7 mm. The study compared the effects of various temperatures on quality measures, including water activity and color. According to the data, the sample with dimensions of 10 × 10 × 3 mm and a temperature of 70°C has the optimum quality in terms of water activity. Furthermore, the sample with dimensions of 10 × 10 × 5 mm at 60°C exhibits outstanding color quality. The importance of shape and temperature selection in optimizing the quality features of dried items using a fluidized bed dryer was underlined in this study [34].

Sample	Type of dryer	Mode of heat transfer	Air velocity (m/s)	Kinetic model	Pre-treatment	Sample shape / size	Initial M.C	Final M.C	Drying time	Temp. (°C)	Moisture diffusivity (m^2/s)	Activation energy (kJ/mol)	Ref
Bottle gourd	Tray Dryer	Forced convection	1.5	_	Steam blanch	Powdered	0.04 kg water/ kg d.m.	_	345–660 mins	50–80	_	_	[33]
	Fluidized bed	Forced convection	10	Page model	_	Slab	_	_	80–140 mins	50–70	1.03×10^{-9}–6.18×10^{-9}	_	[34]
Carrot	Hybrid infrared power and hot air technique	Forced convection	1	Midilli-Kucuk model	_	Slices	13.38 ± 0.67 (d.b.)	0.12–0.14 (d.b.)	_	45–75	2.01×10^{-10}–12.10×10^{-10}		[35]
	Indirect solar dryer without a heat storage unit	Natural convection	_	_	_	Slices	9.13 (d.b.)	0.478 (d.b.)	16 h	_	6.7×10^{-9}	_	[36]
	Indirect solar dryer with heat storage unit	Natural convection	_	_	_	Slices	9.13 (d.b.)	0.478 (d.b.)	15 h	_	7.24×10^{-9}	_	[36]
Potato	Waste heat-based convective dryer	Forced convection	1.4 ± 0.5	Midilli-Kucuk model	_	Slices	_	_	_	50–70	4.22×10^{-10}–11.67×10^{-10}	47.19	[37]
Ivy gourd	Indirect-type solar dryers	Natural convection	_	_	_	Slices	_	_	16 h	31–66	2.286×10^{-9}–1.271×10^{-9}	39.85	[38]
		Forced convection	NA	_	_	Slices	_	_	13 h	32–62	2.286×10^{-9}–1.935×10^{-8}	35.54	[38]
	Single slope single basin solar dryer	Forced convection	1	_	Lemon juice	Slices	_	_	7 h	56.2	5.27×10^{-9}–1.32×10^{-10}	26.06	[13]

Sample	Type of dryer	Mode of heat transfer	Air velocity (m/s)	Kinetic model	Pre-treatment	Sample shape / size	Initial M.C	Final M.C	Drying time	Temp. (°C)	Moisture diffusivity (m^2/s)	Activation energy (kJ/mol)	Ref
					Honey	Slices	_	_	8 h	56.2	4.01×10^{-10}0–2.13×10^{-10}	27.79	[13]
					Ascorbic acid	Slices	_	_	7 h	56.2	5.85×10^{-9}–4.47×10^{-9}	24.81	[13]
					Sugar solution	Slices	_	_	7 h	56.2	5.26×10^{-9}–2.71×10^{-10}	27.05	[13]
Green onion	Solar dryer assisted by a photovoltaic module	Natural convection	_	Page and Overhults model	_	Small circles	91.01 ± 0.15% (w.b.)	1.64 ± 0.15 g (w.b.)	_	_	5.15×10^{-9}	_	[39]
		Forced convection	NA	Page and Overhults model	_	Small circles	91.46 ± 0.16% (w.b.)	1.94 ± 0.23 (w.b.)	_	_	1.15×10^{-8}	_	[39]
Onion	Thin-layer infrared radiation drying	Forced convection	1–1.5	Third order polynomial	_	Slices	_	_	7–9 h	35–45	0.21×10^{-1}–1.57×10^{-10}	_	[40]

Table 4.
Summary of performance of different dryer for drying various vegetables.

6.1.2 Carrot

The researchers investigated drying sliced carrots utilizing hybrid infrared power, hot air drying techniques, and thermal energy storage. The carrots' diffusivity ranged from 2.01×10^{-10} to 12.10×10^{-10} m^2/s, while the specific energy used during drying ranged from 30.20 to 87.51 MJ/kg. Carrot shrinkage was measured to be between 23.49 and 51.25%. The Midilli-Kucuk model was discovered to be the best fit for the drying kinetics. The study indicated that the thermal energy storage arrangement produced promising results for future large-scale applications. These findings emphasized the possibility of adding thermal energy storage into the drying process of carrots, which would increase efficiency and quality in industrial-scale drying processes [35].

Whereas sliced carrots were dried using a passive indirect solar dryer, compared setups without (configuration 1) and with thermal energy storage (configuration 2). Configuration 1 had a drying rate of 0.5, while Configuration 2 had a greater drying rate of 0.59. In configuration 2, the sample dried faster, with the moisture content dropping from 9.13 to 0.478 on a dry basis. The average effective diffusivity for Configuration 1 was determined to be 6.7×10^{-9} m^2/s and 7.24×10^{-9} m^2/s for configuration 2. The two settings' specific energy consumption and moisture extraction rates were 3.5 and 0.28 kg/kWh for configuration 1 and 0.29 and 3.62 kg/kWh for configuration 2. Configuration 2 had a higher drying efficiency with an average of 10.25% compared to configuration 1. Based on the study's findings, it is considered that configuration 2, with the passive indirect sun dryer and thermal energy storage, is an acceptable recommendation for future large-scale applications. These findings showed the benefits of drying sliced carrots with a passive, indirect sun drier with thermal energy storage. Configuration 2 indicated higher drying efficiency, energy utilization, and a faster drying rate. This study gave valuable insights for optimizing the drying process of carrots using renewable energy sources, and it can guide future large-scale industrial applications [36].

6.1.3 Potato

A waste heat-based convection dryer was used to dry potato samples. The study evaluated the drying kinetics of potato samples and found the best model to describe the process. The drying process's activation energy was 47.19 kJ/mol. This parameter gives information about the drying process's temperature sensitivity by indicating the energy required to remove moisture from potato samples. According to the study results, the Midilli et al. model offered the best fit to characterize the drying kinetics of the potato samples. This model is often used to depict removing moisture during drying. Furthermore, the effective moisture diffusivity of the potato samples was determined to be 4.22×10^{-10}–11.67×10^{-10} m^2/s at temperatures ranging from 50 to 70°C. The effective moisture diffusivity measures moisture's ability to travel within potato samples during drying [37].

Siyabonga Gasa et al. used a solar-venturi dryer to model the drying process of sweet potato slices in naturally ventilated warm air. The drying characteristics were studied using a non-linear regression approach. The naturally ventilated solar-venturi dryer and a lemon juice pre-drying treatment were suitable for small to medium-scale drying of sweet potato slices in the study. The dryer arrangement allows for efficient drying in warm air while utilizing solar energy. The naturally-ventilated solar-venturi dryer's effective diffusivity (D_{eff}) values ranged from 3.32×10^{-9} to 6.31×10^{-9} m^2/s.

On the other hand, the D_{eff} values for the hot air oven dryer ranged from 1.02×10^{-8} to 2.19×10^{-8} m^2/s. According to these findings, the naturally ventilated solar-venturi dryer had lower effective diffusivity values than the hot air oven drier. This implied that the solar-venturi dryer setup provides a more regulated drying environment, enhancing drying efficiency and preserving sweet potato slices [41].

6.1.4 Ivy gourd

While drying ivy gourd, the researchers compared natural and forced convection indirect-type solar dryers. Various metrics were used to compare the performance of the two types of dryers. The natural convection solar dryer had an average collector efficiency of 62.56%, whereas the forced convection solar dryer had a higher average collector efficiency of 77.2%. The researchers also calculated the average values of activation energy, mass transfer coefficient, heat transfer coefficient, and diffusion coefficient for ivy gourd drying. The activation energy values of 39.85 and 35.54 kJ/mol were obtained, demonstrating the energy required for moisture elimination during drying. According to the evaluation results, the forced convection configuration produced the most significant results for drying ivy gourd. The increased drying performance was aided by better collector efficiency and favorable activation energy, mass transfer coefficient, heat transfer coefficient, and diffusion coefficient values [38].

Another study examined how various pre-treatments affected the qualitative characteristics, moisture diffusivity, and activation energy of solar-dried ivy gourd. Ascorbic acid, lemon juice, sugar solution, honey dip, and a control group were used as pre-treatments. The effective moisture diffusivity of dried ivy gourd samples varied depending on the pre-treatment. According to the findings, pre-treatments substantially impact solar-dried ivy gourd's moisture content and quality features. The findings show that pre-treatments can efficiently decrease moisture content and contribute to extended preservation periods. The lemon juice samples were found to be the best regarding moisture diffusivity and activation energy among the pre-treatments tested, demonstrating their effectiveness in the drying process [13].

Elavarasan Elangovan et al. investigated the drying kinetics of ivy gourd using a solar dryer, explicitly contrasting passive and active mode solar dryers with traditional sun drying. The results revealed that for the passive mode solar drier, the safe moisture content, indicating the necessary moisture level for storage, was obtained in 9 hours, for the active mode solar dryer in 7 hours, and for sun drying in 11 hours. This suggests that, compared to typical sun drying, both solar dryers were more efficient in drying time. The rate of moisture evaporation from the ivy gourd is affected by air temperature, whereas relative humidity influences the moisture content of the surrounding air. Airspeed, or air movement, aids in the removal of moisture-laden air from the drying environment, allowing for faster drying. The study suggested optimizing and managing certain drying parameters might improve the drying process, resulting in improved drying kinetics. Altering and regulating the solar drier's air temperature, relative humidity, global radiation, and airspeed might produce more efficient and faster ivy gourd drying [42].

Elavarasan Elangovan et al. conducted an experimental investigation to determine the investigated convective and evaporative heat transfer coefficients during the drying process of ivy gourd using natural and forced convection solar dryers and open sun drying. For ivy gourd, the average evaporative heat transfer coefficient, representing the efficiency of moisture evaporation, ranged from 181.89 to 421.84 W/

m^2 °C. The rate at which heat is delivered to the product and utilized for evaporation is indicated by this coefficient. Higher air velocity, as achieved by forced convection, resulted in a faster drying rate for the ivy gourd samples. Increased air velocity accelerates heat and mass transmission, resulting in faster drying. Furthermore, as drying air velocity rose, the mass transfer coefficient, representing the moisture transfer rate from the ivy gourd to the drying air, increased. This suggests that higher air velocity improves more efficient moisture removal from ivy gourd samples [25].

6.1.5 Onion

G.P. Sharma et al. dried onion slices using a thin-layer infrared radiation drying technique. The effective moisture diffusivity, which represents the rate of moisture movement within onion slices, ranged from 0.21×10^{-10} to 1.57×10^{-10} m^2/s. The drying process used forced convection, which involves the utilization of air circulation to improve heat and moisture transfer. This method allows for faster drying and increases the drying system's efficiency. Furthermore, the drying time was calculated concerning the amount of infrared power used during drying. The drying time was shortened by nearly 2.25 times when the infrared power was increased from 300 to 500 W. This suggests that the drying of the onion slices was expedited by increasing infrared power. A third-order polynomial relationship was discovered to correlate several elements influencing the specified drying process. This relationship aided in predicting drying behavior based on variables, including infrared power, drying duration, and moisture content [40].

Hidalgo et al. dried green onions using a direct sun drier aided by a photovoltaic module, focusing on natural and forced air convection operation. The effective diffusivity values for natural convection were 5.15×10^{-9} m^2/s and 1.15×10^{-8} m^2/s for forced convection. These values indicate the rate of moisture diffusion within the green onions during drying. The Page and Overhults models were selected as the best-fit models during the slower drying periods [39].

6.2 Fruits

This section discusses the performance of different solar dryers for drying various fruits, including Banana, Cucumber, Tomato, and Grapes. The summary of the same is presented in **Table 5**.

6.2.1 Grapes

Traditional grape drying methods have several disadvantages, such as mass losses and low quality. A joint German-Greek research program developed low-cost solar grape dryers to address these challenges. Solar dryers use the sun's energy to heat air, which is then circulated through the dryer to dry the grapes. This drying method has several advantages over traditional methods, including reduced drying time, improved quality, and prevention of mass losses [47].

The drying kinetics of two varieties of grapes grown on both shores of the Mediterranean Sea was the subject of another study. The drying kinetics were evaluated as a function of drying conditions, and the diffusion coefficient was determined. Two diffusion models were employed to determine the effective diffusivity: a simplified model based on Fick's law and a more complex model that accounted for the grapes' shrinkage. The study revealed that the drying kinetics of the two grape varieties were

Sample	Type of dryer	Mode of heat transfer	Air velocity (m/s)	Kinetic model	Sample shape/size	Initial M.C	Final M.C	Drying time	Temp. (°C)	Moisture diffusivity (m2/s)	Activation energy (kJ/mol)	Ref
Red Banana	Direct solar dryer	Natural convection	_	Newly developed model	Slices	76% (w.b.)	18% (w.b.)	10 h	71.3	$0.87–1.56 \times 10^{-9}$	22.56–35.49	[42]
	Direct solar dryer	Forced convection	NA	Newly developed model	Slices	76% (w.b.)	18% (w.b.)	8 h	83	$0.87–1.56 \times 10^{-9}$	24.58–45.20	
	Open sun drying	Natural convection	_	Newly developed model	Slices	76% (w.b.)	18% (w.b.)	13 h	_	_	_	
Poovan Banana	Direct-type solar dryer	Natural convection	_	Newly developed model	Slices	74% (w.b.)	20% (w.b.)	7 h	51	$1.6–2.5 \times 10^{-10}$	23–30	[43]
	Open sun drying	Natural convection	_	Newly developed model	Slices	74% (w.b.)	20% (w.b.)	12 h	66	$1.6–2.5 \times 10^{-10}$	24–30	
Cucumber	Double slope solar dryer	Natural convection	_	_	Slices	93.93% (w.b.)	11.96% (w.b.)	3.5 days	35–55	_	_	[44]
Tomato	Hot air solar dryer	Forced convection	0.5–2	Page model	Slices	93.6% (w.b.)	_	_	_	1.58×10^{-9}–6.98×10^{-9}	_	[45]
	Hybrid dryer	Natural convection	_	Page model	Slices	94.22% (w.b.)	10% (w.b.)	300 min	_	2.00×10^{-1}–5.84×10^{-10}	_	[46]
	Solar dryer	Natural convection	_	Page model	Slices	94.22% (w.b.)	10% (w.b.)	360 min	_	1.37×10^{-10}–4.40×10^{-10}	_	
	Open sun dryer	Natural convection	_	Page model	Slices	94.22% (w.b.)	10% (w. b.)	420 min	_	1.33×10^{-10}–4.01×10^{-10}	_	

Table 5.
Summary of performance of different dryers for drying various fruits.

comparable, but the grapes cultivated on the southern side of the Mediterranean Sea had a higher effective diffusivity. The study also demonstrated that the drying conditions influenced the drying kinetics, with a faster drying rate at higher temperatures and reduced relative humidities [48].

Fadhel et al. compared the three solar processes to dry Sultanine grapes: natural convection solar drier, tunnel greenhouse, and open sun. The results showed that the solar tunnel greenhouse drying was the most efficient, followed by the natural convection solar drier and open sun. The solar tunnel greenhouse drying was also the most consistent, with the drying rate being relatively unaffected by changes in weather conditions [49].

6.2.2 Tomato

J. B. Hussein et al. dried tomato slices in thin-layers using hybrid, solar, and open sun drying methods. The effective moisture diffusivity values, which represent the moisture transfer rate within the tomato slices, were determined for each drying process. The effective moisture diffusivity values in the hybrid drying method ranged from 2.00×10^{-10} to 5.84×10^{-10} m^2/s, according to the results. The values for solar drying ranged from 1.37×10^{-10} to 4.40×10^{-10} m^2/s, whereas open sun drying ranged from 1.33×10^{-10} to 4.01×10^{-10} m^2/s. On a wet basis, the moisture content of the tomato slices was reduced by 94.22–10% following drying. The Page model was used to simulate the drying kinetics. The declining rate stage of drying is described by this model, in which the moisture removal rate lowers as the moisture content falls. The Page model was used to forecast drying behavior and estimate drying time for tomato slices [46].

H. Samimi, Akhijani et al. concentrated on hot air solar drying of tomato slices using forced convection. The moisture diffusivity, representing the moisture transfer rate within tomato slices, was examined at various air velocities and slice thicknesses. At an air velocity of 2 m/s and a slice thickness of 7 mm, the most significant moisture diffusivity value achieved was 6.98×10^{-9} m^2/s. Higher air velocity and thicker slices facilitate faster moisture transfer during drying. At an air velocity of 0.5 m/s and a slice thickness of 3 mm, the minimum moisture diffusivity value achieved was 1.58×10^{-9} m^2/s. This shows that slower moisture transfer is caused by decreased air velocity and thinner slices. The Page model was used to analyze the drying kinetics, and it provided the best fit for the experimental data [45]. P. Rajkumar et al. examined vacuum-assisted solar drying of tomato slices using a vacuum-assisted solar drier. Compared to open sun drying, the vacuum-assisted solar drying approach required less drying time for the slices. The Page model, which best fits the experimental data, was used to analyze the drying kinetics [50].

6.3 Marine products

This section discusses different solar dryers' performance for drying marine food products, including Fish, Shrimp, and Prawn. The summary of the same is presented in **Table 6**.

6.3.1 Fish

Pranav Mehta et al. dried fish using a mixed-mode tent-type solar drier. The Fish's moisture content was reduced from an initial value of 89% to a final value of 10%.

Sample	Type of dryer	Mode of heat transfer	Air velocity (m/s)	Kinetic model	Initial M.C	Final M.C	Drying time	Average temperature (°C)	Moisture diffusivity (m^2/s)	Ref
Fish	Microwave heating	Forced convection	1	Midilli model	2.76 (d.b.)	0.01 (d.b.)	_	_	7.158×10^{-8}–3.408×10^{-7}	[51]
	Tent-type solar dryer	Forced convection	0.28	Lewis model	89% (w.b.)	10% (w.b.)	18 h	60–65	1.53×10^{-7}	[52]
Shrimp	Electric Dryer	Forced convection	0.8 ± 0.04	Midilli model	73–79% (w.b.)	8–10% (w.b.)	8 h	55	_	[53]
	Oven	Forced convection	NA	Alibas model	4.8824 kg of water/kg of dry matter	0.35 ± 0.143 kg of water/kg of dry matter	210–330 min	60–80	2.8×10^{-8}	[54]
	Vacuum	Forced convection	NA	Midilli & Kucuk	4.8824 kg of water/kg of dry matter	0.35 ± 0.143 kg of water/kg of dry matter	110–190 min	60–80	5.49×10^{-8}	
Prawn	Direct-type solar dryer	Natural convection	_	Newly developed model	3.621 (d.b.)	0.081 (d.b.)	14 h	35.91	_	[55]
Chelwa fish	Direct-type solar dryer	Natural convection	_	Newly developed model	2.676 (d.b.)	0.138 (d.b.)	21 h	39.65	_	
Silver jewfish	Hybrid solar dryer	Forced convection	NA	_	64% (w.b.)	10% (w.b.)	8 h	50	_	[56]

Table 6.
Summary of performance of different dryers for drying various marine food products.

During the drying process, the effective moisture diffusivity was 1.53×10^{-7} m^2/s. The drying kinetics were described using the Lewis model of drying. The Lewis model is widely used to study moisture transfer in porous materials during drying.

Furthermore, the study concluded that, under loaded conditions, recirculating the outlet's hot air after absorbing moisture is the most efficient energy utilization [52]. The researchers used the Page equation to predict the drying process of Fish. The drying rate of the fish samples was found to be fastest in the beginning and gradually decreased over time. The average effective diffusivity ranged from 7.158×10^8 to 3.408×10^7 m^2/s, demonstrating that moisture could diffuse throughout the Fish at different rates during the drying process. The moisture content of the fish samples was reduced significantly in the study, from 2.76 to 0.01 on a dry basis, suggesting the efficiency of microwave heating in drying the Fish. The Page equation was used to simulate the drying process using non-linear regression analysis, which offered a good fit for defining the drying characteristics of the fish samples [51].

6.3.2 Shrimp and prawn

D.S. Aniesrani Delefiya et al.'s studies provided valuable insights into the drying process of shrimp in an electric dryer. The initial moisture level of the shrimp samples ranged from 73 to 79% (wb) in the study on the drying characteristics of shrimp in an electric dryer, and the drying process aimed to reduce it to a final moisture content of 8–10% (wb). Many mathematical models were explored to understand and model the drying behavior of the shrimp. The Midilli model was chosen as the best-fit model for understanding the drying kinetics of shrimp [53]. The effect of several drying processes on the physical and qualitative parameters of dried shrimps was examined. The prawns were dried in an oven at 60, 70, and 80°C for 330–210 minutes and in a vacuum oven for 190–110 minutes. The usage of a vacuum pump decreased the drying time. The drying kinetics of prawns were investigated, and both techniques' appropriate moisture diffusion and activation energy were estimated.

The Alibas and Midilli and Kucuk models offered the best experimental data with a high coefficient of determination (R^2) for the oven and vacuum oven approaches. The final dried goods' color features, heavy metal levels, and protein analyzes were investigated. The rehydration ratio of dehydrated shrimps was also established. The study's findings revealed that the drying conditions influenced the color characteristics of the shrimps. Shrimp dried in ovens and Hoover ovens had higher brightness and yellowness scores but lower redness levels. The Pb, As, Cd, Hg, Cu, Zn, and Fe concentrations in dried prawns were below permissible levels [54].

6.4 Other food substances

In addition to the above-mentioned vegetables, fruits, and marine food products, the other food substances are also undergoing post-harvest loss predominantly. This section discusses the performance of different solar dryers for drying various essential food products, including Chili, Ginger, and Jaggery. The summary of the same is presented in **Table** 7.

6.4.1 Chili

Zakaria Hossain et al. developed a solar dryer for drying chilies. The initial moisture level of the chilies placed in the drier was 73%, which decreased to 14% during

Sample	Type of dryer	Mode of heat transfer	Air flow rate	Kinetics model	Initial M.C	Final M.C	Drying time	Average temperature (°C)	Moisture diffusivity (m^2/s)	Activation energy (kJ/mol)	Ref
Ginger	Solar drying	Natural convection	_	Page model	621.5 (d.b.)	12.19 (d.b.)	8 h	57 ± 8.5	1.789×10^{-9}	_	[57]
Cassumunar ginger	Solar greenhouse dryer	Natural convection	_	System of partial differential equations	90% (w.b.)	10% (w.b.)	24 h	30–55	_	_	[58]
Ginger	Thin-Layer Vacuum Dryer	Natural convection	_	Two-term model	_	_	_	40–65	1.859×10^{-8}–4.777×10^{-8}	35.675	[59]
Chili	Solar cabinet dryer coupled with gravel bed he	Forced convection	58 m^3/h	_	88.5% (w.b.)	7.3% (w.b.)	56 h	25–55	_	_	[60]
	Chimney solar dryer with sea pebbles	Natural convection	_	Simple linear regression	73.12%	7.15% (w.b.)	36 h	_	1.061×10^{-7}	_	[61]
	Chimney solar dryer without sea pebbles	Natural convection	_	Simple linear regression	73.12%	9.67% (w.b.)	37 h	_	8.93×10^{-8}	_	
	Solar Dryer	Forced convection	0.11 m^3/s	_	73% (w.b.)	14% (w.b.)	41–46 h	44.28	_	_	[62]
	Open sun drying	Natural convection	_	_	73% (w.b.)	18% (w.b.)	91 h	34.34	_	_	

Table 7.
Summary of performance of different dryers for drying various other food products.

drying. One interesting observation was that the drying rate of the chiles on the upper tray was faster than on the lower tray. This disparity in drying rates can be attributable to various factors, including heat distribution, air circulation, and direct solar exposure. The dryer uses forced convection technology, which uses a fan or blower to increase movement and speed up drying. Forced convection improves heat transfer and moisture elimination from the chilies, resulting in faster drying [62]. Francis Kumi and Bram Parbi used an innovative approach to improve the heating system and drying performance in their study on a solar chimney dryer for chili peppers. They increased the efficiency of the solar drier by including sea pebbles in the collection base.

Using a basic regression analysis model, the researchers tested the solar chimney drier's drying performance. The chili peppers had an initial moisture content of 73.12% (w.b.) that decreased to 7.15% (w.b.) after drying. The inclusion of sea pebbles in the collection base was critical in improving the solar dryer's heating mechanism. The sea pebbles absorbed and held the sun's heat, contributing to higher temperatures within the drying chamber. As a result, the drying performance improved, and the moisture removal from the chili peppers was hastened [61]. A.K. Kamble et al. used a solar cabinet drier with a gravel bed and forced convection for drying chiles. The solar cabinet drier used forced convection to improve heat and moisture transfer by boosting airflow within the drying chamber. This forced convection technique helped the chiles dry more quickly.

Furthermore, a heat storage system was added to the drying process. This technique made heat available even after sunset, allowing the drying process to continue for an additional 4 hours. The heat storage system assisted in maintaining the required temperature within the dryer, ensuring successful drying even when solar radiation was limited [60].

6.4.2 Ginger

The performance of the solar greenhouse drier for drying Ginger was examined by Nimnuan et al. The purpose of the drying method was to bring the moisture content of the Ginger down from its initial value of 90% (wb) to a final value of 10% (wb). A thin-layer drying model was used to characterize drying kinetics. The effectiveness of the solar greenhouse drier in facilitating the drying process and attaining the target moisture content was evaluated in this study. The results provide insight into the solar greenhouse dryer's capability and efficacy for drying ginger [58]. Another study on the solar drying of Ginger reported an effective moisture diffusivity of 1.789×10^9 m^2/s, which quantifies the rate at which moisture flows within the Ginger during drying. Various mathematical models were tested to understand the drying kinetics and model the drying process. The Page model was determined to be the best fit for characterizing the drying kinetics of Ginger in the solar dryer using natural convection among the models tested. It estimates the material's drying characteristics by considering the moisture content, drying duration, and drying rate [57].

6.4.3 Jaggery

Om Prakash et al. investigated the use of fuzzy logic to predict the rate of Jaggery's moisture evaporation in a controlled environment. MATLAB software generated the fuzzy logic model, which was then validated using experimental data. The results demonstrated that the fuzzy logic model could predict the moisture evaporation rate with no more than 0.27% error. The model can be extended to various locations under varying weather conditions: ambient temperature, solar radiation, and relative humidity [63]. The objective of another study was to construct an adaptive-network-based fuzzy inference system (ANFIS) model to predict the jaggery temperature, greenhouse air temperature, and moisture evaporation during the natural convection drying of jaggery within a greenhouse. For complete drying, distinct experiments were conducted for 0.75 kg and 2.0 kg jaggery pieces measuring $0.03 \times 0.03 \times 0.01\ m^3$. The jaggery was desiccated in a roofed, even-span greenhouse with a $1.20 \times 0.78\ m^2$ floor area. MATLAB software was used to construct the ANFIS model for calculating jaggery temperature, greenhouse air temperature, and moisture evaporation. The model was also utilized to predict the greenhouse's thermal performance based on solar intensity and ambient temperature. Analytical and experimental results for jaggery drying were in excellent agreement following experimental validation of the model [64].

Using an artificial neural network (ANN), Om Prakash et al. predicted the hourly mass of jaggery during drying in a greenhouse dehydrator with natural convection. Jaggery was dehydrated until its mass fluctuated constantly. The input parameters for the ANN model were solar radiation, ambient temperature, and relative humidity. The outcomes of the ANN model were validated using experimental data on the dehydration of jaggery mass. The statistical parameters root mean square error (RMSE) and correlation coefficient (R^2) was utilized to determine the difference between the values predicted by the ANN model and those observed in the experimental investigation [65].

Kumar et al. developed a thermal model that could forecast the jaggery temperature, greenhouse air temperature, and moisture evaporated (jaggery mass during drying) during natural convection drying of jaggery. The jaggery was dried in a roof-type even-span greenhouse with a $1.20 \times 0.78\ m^2$ floor area. In MATLAB software, a computer program was developed to calculate the jaggery temperature, greenhouse air temperature, and moisture evaporated. The program was also utilized to forecast the greenhouse's thermal performance based on sun intensity and ambient temperature. The program was experimentally evaluated, and the findings revealed that the analytical and experimental results for jaggery drying agreed well [66].

7. Conclusions and prospects

In conclusion, drying is a valuable approach to reducing post-harvest losses in agriculture, offering numerous benefits such as lower moisture content, extended shelf life, and inhibition of microbial growth. By choosing appropriate drying techniques tailored to specific crops, quality objectives, and available resources, successful post-harvest preservation can be achieved, supporting sustainable agricultural practices. Based on the literature review, the following conclusions can be drawn:

- Among the various drying methods, solar drying is a sustainable and cost-effective solution for preserving agricultural products while maintaining their nutritional quality and enhancing market value. Solar dryers, including open sun drying, direct and indirect solar dryers, and mixed-mode and hybrid-mode solar dryers, harness the sun's energy efficiently, reducing reliance on non-renewable energy sources and contributing to environmental sustainability.

- Solar drying has been extensively studied for different food substances, including vegetables, fruits, marine products, and other essential items like chili, Ginger, and Jaggery. Researchers have evaluated various parameters, such as effective moisture diffusivity, activation energy, collector efficiency, and drying kinetics, to optimize the drying process and improve quality. Pre-treatments have been explored to enhance moisture removal and preservation periods for some food products.

- Studies on solar drying of vegetables revealed the benefits of forced convection, fluidized bed, and passive indirect sun dryers with thermal energy storage, highlighting improved drying efficiency and reduced drying time. For fruits, solar tunnel greenhouse, hybrid, and vacuum-assisted solar drying demonstrated advantages such as reduced drying time and improved quality. Solar drying also proved effective for marine products, achieving improved drying performance using solar chimney dryers and electric dryers.

- The moisture diffusivity values for the studied vegetables range from 0.21×10^{-10} to 1.15×10^{-8} (m^2/s), and the activation energy varies from 24.81 to 47.19 (kJ/mol).

- The moisture diffusivity values for the studied fruits range from 1.6×10^{-10} to 6.98×10^{-9} (m^2/s), and the activation energy varies from 22 to 58 (kJ/mol).

- The moisture diffusivity values for the studied marine food products range from 2.8×10^{-8} to 1.53×10^{-7} (m^2/s).

- The moisture diffusivity values for the studied other food products range from 1.789×10^{-9} to 1.061×10^{-7} (m^2/s).

- Higher moisture diffusivity and lower activation energy accelerates the dehydration process.

Solar drying presents a diverse range of methods to efficiently remove moisture from various substances while harnessing the sun's energy. It offers a sustainable and effective solution to preserve agricultural products, minimize post-harvest losses, and reduce food waste. By incorporating solar drying into agricultural practices, we can promote greener and more resilient food processing, supporting a cleaner and sustainable future for food preservation worldwide.

Future research directions should focus on further optimizing solar drying techniques, exploring innovative designs and materials, and integrating advanced control systems to enhance the performance and versatility of solar dryers. Additionally, investigations into solar drying technologies' economic feasibility and scalability are warranted to facilitate widespread adoption in both small-scale and large-scale food processing operations. Future research on modeling drying kinetics of food substances could focus on developing novel mathematical models, incorporating multi-scale modeling approaches, applying artificial intelligence and machine learning techniques, studying non-conventional drying methods, investigating coupled phenomena, analyzing quality attributes, and integrating sustainability considerations. These efforts aim to improve the accuracy and efficiency of drying models, account for complex interactions during drying, predict drying behavior under different conditions, optimize energy consumption, and minimize environmental impact. Such research will contribute to advancements in drying technologies and enhance the understanding of drying processes in the food industry.

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Conflict of interest

The authors declare no conflict of interest.

Nomenclature

Symbol	
MR	moisture ratio
MC	moisture content
m_w	mass of the drying product before drying (kg)
m_d	mass of the dried product (kg)
M_t	moisture content at any time ‘t’ (kg)
M_e	equilibrium moisture content (kg)
M_0	initial moisture content (kg)
k	drying constant (min^{-1})
t	drying time (min)
n	empirical exponent
$a\&b$	empirical parameter
D_{eff}	effective moisture diffusivity (m^2/s)
L	thickness of the drying sample (m)
D_0	diffusion factor (m^2/s)
E_a	activation energy (kJ/mol)
R	Universal gas constant (8.314 kJ/mol.K)
T	temperature (K)
k	slope of $\ln D_{eff}$ against 1/T

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