

Refractance Window Dryer (RWD) for Food Products Using Solar Powered System: A Review

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Abstract: Traditional food drying approach caused significant nutritional, physical and chemical changes in the dried products, which caused less appetizing. As the market for foods with preserved nutrients and physicochemical properties grows, new drying processes are needed. Refractive window drying (RWD) technology has proven to be an effective method to minimize negative effects on food quality. RWD circulates hot water to generate heat energy during the drying process. In this process, surface evaporative cooling limits the temperature of the dry material to a range of 70°C to 85°C. This limited temperature range allows for preserving heat-sensitive food ingredients and maintaining material quality. RW drying's unique properties make it ideal for processing high-quality food products. This review study investigates the effects of RW drying on various quality attributes to explore potential applications in the food industry. This article reviews the operating philosophy of RWD and explains how it affects the retention and physicochemical properties of bioactive components in foods. Additionally, RW drying offers advantages over traditional drying methods, including improved retention of thermally labile compounds, compliance with quality standards, and increased energy efficiency due to reduced operating costs. This study focuses on the use of solar energy as an auxiliary heat source and also evaluates the effectiveness of his RWD using a solar auxiliary heating system for drying food. The system harnesses solar energy to increase energy efficiency and reduce dependence on traditional energy sources. The performance evaluation results provide important new information regarding the efficiency and long-term viability of combining RWD and solar-assisted heating systems in food drying processes.

Keywords: Refractance Window Dryer, Solar auxiliary heating system, Food drying, Solar collectors, Performance evaluation (Review)

1. Introduction

One of the most energy-intensive processes involved in large-scale food preservation is drying, which is also a vital phase in the process. However, it offers numerous advantages such as enhanced storage stability, reduced packaging requirements, and decreased bulk for transportation. The pursuit of numerous advantages, such as safer activities, bigger abilities, improved quality of the product, reduced impact on the environment, improved efficiency of energy, and cheaper prices, has resulted from the search for the optimum drying technique. Due to consumers' growing preference for wholesome and practical products with long shelf life, the market for dehydrated foods has been increasing significantly on a global scale [1].

Overall, drying is an indispensable technique for large-scale food preservation, offering advantages such as improved storage stability, reduced packaging requirements, and streamlined transportation. The search for the perfect drying technology strives to produce safer operations, greater capacities, better product quality, decreased environmental impact, increased energy efficiency, and cost savings. Food products are frequently dried in many different businesses around the world. Micro, Small, and Medium-Sized Enterprises (MSMEs) who rely on primitive drying technologies, producing inferior products that find it difficult to compete with imported alternatives, face a huge difficulty as a result. As a result, it is now of utmost national importance for the food industry to modernise its drying processes.

Advanced dehydration techniques like RWD are known for their gentle, straightforward operation and affordable price [2]. It has shown to be very efficient at drying fresh food that is sensitive to heat while maintaining its nutritive value, colour, flavour, fragrance, bioactive components, and sensory quality. RWD enables flexibility and can even be used in remote locations, such as on farms. Although the continuous belt-based setups used in the bigger capacity RWD systems are intended for industrial application, the fundamental operational concepts are the same [3]. Numerous studies have examined the effectiveness of RWD and consistently show that it is superior to conventional drying techniques in terms of maintaining good product quality, including colour, vitamins, and antioxidants. Surprisingly, RWD produces dried goods of equivalent quality as those produced by freeze drying, but at a much lesser cost to the environment. RWD has also shown promise in lowering *E. coli*, coliforms, and total aerobic counts in dried foods. Additionally, RWD has successfully handled a number of food items that are typically challenging to spray dry without the addition of non-sugar carriers. Due to its outstanding qualities, RWD is perfectly suited for processing high-value foods, nutraceuticals, and food supplements where tight criteria of quality and safety are necessary [4]. The technology provides a less expensive option to conventional drying techniques while producing products of equal or even higher quality.

2. RWD Methods

The fourth generation of drying techniques includes the RWD procedure. Hot water is used in the RWD process as the heat source, and the temperature of the water can be changed depending on the particular needs. The preservation of the product's sensory qualities and nutrient content, energy consumption, and environmental impact of the drying process are important considerations when evaluating and choosing the best drying method. Studies have shown that, when the drying capacity is held constant, the RW drying method provides significant cost reductions, needing between 50 and 70 percent less money and more than 50 percent less energy than freeze-drying procedures [4].

The RWD system's flowchart (Fig.1) demonstrates the step-by-step procedure for turning leftover waste into useable materials using a drying technique.

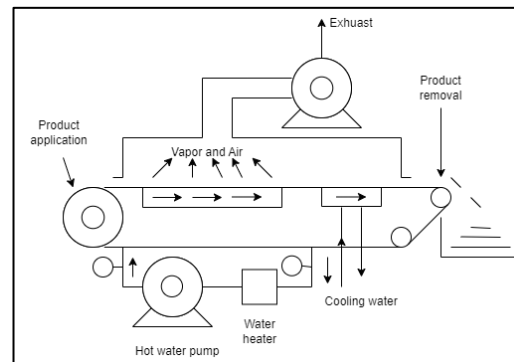


Figure 1: RW drying system's flow

Drying has long been a method used by humans to preserve food, ensuring its longevity by preventing the growth of bacteria and enzymatic activities. As a crucial process in the food industry, drying is incredibly important. Its main goal is to turn liquid or semi-liquid material into powdered, flaked, or solid forms so that they may be stored for a longer period of time and are easier to handle [5]. Maintaining their physicochemical qualities while attaining cost-effective production is a crucial need for dried end products [6]. Traditional drying techniques, on the other hand, frequently result in unfavourable nutritional, physical, and chemical changes that might make the food unpleasant for customers. Additionally, while choosing a drying procedure, energy usage is a key factor [7]. Conventional drying methods have a number of significant drawbacks, including a high energy need that accounts for 12–20% of the overall energy used in manufacture. Due to their energy-intensive nature, alternative drying technologies must be investigated in order to offer increased energy efficiency and lower operating costs.

Global attention on lowering energy use and greenhouse gas emissions has increased recently, driven by governmental organisations like the United Nations Framework Convention on Climate Change (UNFCCC). The need of researching novel drying equipment and procedures that can raise product quality, improve thermal and energy efficiency, and lower operating costs has been highlighted by the focus on sustainability [8].

Therefore, to increase product availability and open up new markets, the fresh produce and food

business has a critical need for enhanced drying procedures. Based on previous developments, drying technologies can be divided into several generations. Dryers from the first generation comprise cabinet and bed models, while innovations from the second generation include spray dryers (SD) and drum dryers (DD). Osmotic dehydration techniques and freeze dryers (FD) make up third-generation dryers.

The physical and chemical characteristics of food goods, as well as their nutritional worth, have been carefully preserved using these cutting-edge drying techniques. This emphasis has developed as a result of rising consumer demand for high-quality food that keeps its nutrient value while being dried [9]. Therefore, for attaining energy efficiency, lowering environmental impact, and maintaining the nutritional and physicochemical features of dried food items, the development of novel drying technologies is essential, especially within the fourth generation category. By concentrating on these developments, the food sector can meet consumer demand for high-quality, nutrient-rich food items while also advancing global sustainability goals [6].

The more nutrient-dense the human health, the greater the consumer interest. Various food products contain bioactive ingredients such vitamins, pigments, enzymes, phenolic compounds, and essential oils. The bulk of these bioactive chemicals, though, are vulnerable to oxidation by heat, light, and oxygen [10]. Food dryers have been created to address these issues by keeping product quality as a key consideration in dryer development. In this aspect, FD are quite effective at keeping end products' physico-chemical and nutritional qualities. However, the price of products that are freeze-dried (FD) is higher than the prices of alternatives that are spray-dried (SD) and air-dried. Additionally, freeze-dried foods have a tendency to rehydrate quickly in high humidity environments [11].

RW drying, a more recent drying technique, provides a reasonable approach to the drying process. The author of [12] released the first scientific study on this drying process and examined how well strawberries and carrots retained their flavour. Similar to DD (Direct Drying), RW drying involves drying a sample in a thin layer on a heated

surface. However, the main difference between RW drying and DD is that the latter uses a higher temperature range of 120–150°C while the former uses a smaller temperature range of 70–85°C. Many food products, including those that are thermally delicate, such purees and sliced fruits and vegetables, have shown to benefit from this unique drying technology, which has been effective in extending their shelf life. It has also been widely used in sectors such nutraceuticals, cosmetics, pigments, and pharmaceuticals [7]. To increase the value of fruits, vegetables, herbs, and other commodities in the food business, RW drying is used to turn them into powders and concentrates [11]. RW drying technology actually consumes 50% less energy and 50–70% less capital than freeze-drying technology to dry the same amount of material [11].

The commercial use of this technology has been greatly aided by MCD Technologies of Tacoma and Mount Capra, Washington [7]. In a review research, the impact of sample thickness and temperature on the RW drying process is examined by [13]. To learn more about how RW drying affects the bioactive ingredients and physicochemical characteristics of food products, more research is advised. RW drying has a lot of potential for preserving bioactive ingredients and maintaining overall product quality in the food business.

3. Process for Drying Dispersions of Fruit and Vegetables

The research study looked at four different dryer generations: hot air, drum and spray, osmotic, and freeze. Ahead-of-the-curve dryers from the most recent generation also include fluidized bed, microwave use and the infrared heating pump, radiofrequency, and RW dryers [9]. In this procedure, the meal is equally dispersed on a membrane made of a polymer, such as polyethylene, that is submerged in hot water. The hot water that is circulated is used for both heat transfer and moisture removal. The rapid thermal energy transfer properties of water cause moisture in food to swiftly evaporate, bringing about thermal equilibrium. The pharmaceutical, nutrition, cosmetic, and pigment industries all frequently utilise this drying technique [14]. RW drying has a number of benefits, including low operational costs, a longer shelf life for dried goods, consistent

product drying, and the preservation of vitamins, antioxidants, and flavours in dried goods [12]. While HA dryers have a thermal efficiency of less than 36%, RW drying systems often demonstrate high efficiency, ranging from 55% to 72%. RW dryers also guarantee the maintenance of dried product quality. Notably, RW dryers cost 30% to 50% less than freeze dryers while using just 50% as much energy.

A study looked into how drying aloe vera gel at temperatures between 50 and 90 °C affected its physicochemical characteristics and antioxidant capacity [15]. The results showed that the degradation of physicochemical qualities and reduction in antioxidant capacity were significantly influenced by drying temperatures of 80°C and 90°C [16]. The percentage of powder yield in a different study on drying aloe vera was 2.60, 2.60, 2.55, and 2.52% at 50, 60, 70, and 80 C, respectively [17]. By raising the temperature from 50 to 80 C 29, the aloin amount fell from 10.6 to 1.7 ppm, according to the HPLC chromatogram obtained for the dried samples. Another study [18] used a hot air (HA) dryer along with infrared (FIR) and high voltage electric field (HVEF) to dry aloe vera puree. The impact of several variables on drying kinetics, specific energy consumption (SEC), and dried product quality was examined in this study. These variables included air velocities, regulated surface temperatures, and high voltage electric field resistance (0, 1.88, and 3.75 kV). The drying kinetics were shown to be considerably influenced by the electric field strength, whereas the HVEF mostly had an impact on the drying kinetics at lower air speeds. Using HA, FIR, and HVEF dryers at an air velocity of 0.2 m/s, a temperature of 70 °C, and a high voltage electric field resistance of 0.1 m was the best combination for drying.

The RW dryer generated a high-quality dried product comparable to the freeze-drying process, according to a study testing the quality of dried goldenberries. In the study, dried golden berries produced by RW, HA, freeze, and infrared dryers were compared for quality. RW and freeze dryers produced substantially less total phenol than HA and infrared dryers did. Additionally, the RW dryer's flavonoid content was much lower than those of other dryers [19].

Another study [20] examined the impact of osmotic pretreatment on the RW dryer-dried sugar beets. The results showed that raising the drying temperature from 60 to 85 degrees Celsius resulted in a notable 150% reduction in drying time. The outcomes demonstrated that RW's dried product quality was superior to that of competing dryers. Furthermore, compared to spray and freeze dryers, the RW dryer showed energy savings of roughly 1.3 to 1.40 times. Four conductive dryers, including the vacuum drum dryer, drum dryer, agitated thin film dryer, and RW dryer, were used in a study on the drying of tomato powder. The different volatile components in dried tomatoes were successfully retained by the RW dryer thanks to its reduced working temperature [21].

A following study [2] used RW and HA dryers to investigate the drying of mango slices with thicknesses of 1 mm and 2 mm. The findings showed that the RW dryer dried items more quickly than the HA dryer [2]. In addition, compared to the HA dryer, the RW dryer produced products with less water activity and colour change. Another study [22] by the same author examined the drying of tomato powder at different temperatures (65°C, 75°C, 85°C, and 95°C) and two different thicknesses (1 mm and 2 mm) using a RW drier. According to the study, a thickness of 1 mm and a temperature of 95°C resulted in the quickest drying time. The dried samples' colour changes also became more pronounced as the drying temperature rose. Ortiz-Jerez [23] investigated the drying of pumpkin layers in RW dryers utilising both forced pump flow and natural convection water flow. According to the study's findings [24], forced flow drying had the maximum evaporation rate whereas natural convection drying had the lowest evaporation rate. Aça was dried using three different dryers in a different investigation by [25], including RW, freeze, and HA dryers. The data showed that compared to the other two drying methods, the RW dryer generated aça dried powder with a greater moisture content and water activity. Using the RW dryer, yoghurt puree was dried at three different temperatures (varying from 50°C to 70°C) and two distinct thicknesses (0.5 mm and 1 mm) in a different study by [26]. The outcomes showed that, with the exception of colour alterations, the RW dryer produced dried items with improved physical

attributes in comparison to the freeze dryer. Additionally, it was discovered that lowering the drying temperature decreased the bacteria in the yoghurt puree. Energy consumption is one of the key elements in fruit and vegetable drying, according to research [27]. The utilisation of sustainable, secure, and dependable energy sources, such as solar energy, might be particularly relevant given the high energy consumption and the associated environmental problems. Iran has the potential to be a region that is particularly vulnerable to the use of solar energy in agricultural product drying processes, with its annual solar radiation rate ranging from 1800 to 2200 kWh/m² (higher than the global average) and more than 280 sunny days per year [26].

4. Quality of Refractance Window 89 Drying

This section describes the qualitative knowledge of RWD. The RWD procedure was created by MCD Technologies. In RWD, hot water is heated and then delivered to a plastic conveyor belt that is in direct touch with the water. On the plastic conveyor belt, the material to be dried is thinly spread, and the belt and material travel constantly at a set speed. The huge refractive index mismatch between water and air in the absence of the product causes the majority of incident radiative energy to be reflected back and just a tiny amount to be transferred into the air [28]. However, the refractive index mismatch between the water and the food is lessened when the wet product, which is often a puree with a high water content, is put on the plastic conveyor belt. Increased radiative energy transfer into the meal is made possible by the reduction in refractive index mismatch [29].

When employed in RWD, the plastic material works well as a thermal radiation transmitter and is practically transparent to thermal radiation at relevant wavelengths. This characteristic of plastic allows thermal radiation to travel through it like a window that is open. The majority of the heat radiation is reflected back into the water, signalling the conclusion of the drying process, but as the wet material dries, its refractive index rises, creating a mismatch and slowing down the drying process [30].

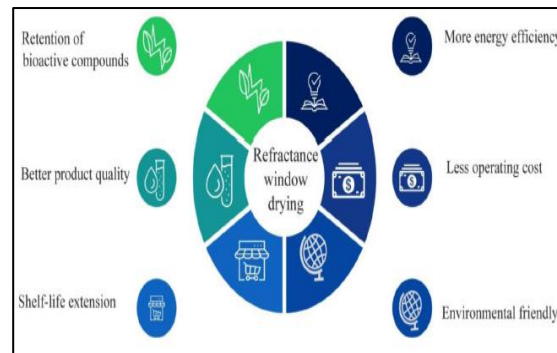


Figure 2: Applications of RW drying in the food industry [13]

The importance of refractive index mismatch and the idea of the refractive "window" in RWD, which allows thermal radiation to pass through plastic when in contact with wet material, are both emphasised by this knowledge. The "window" narrows as drying proceeds, and most of the heat radiation is reflected back into the water as a result of the growing refractive index mismatch.

5. Issues with the existing qualitative knowledge of RW 112 drying and the lack of a quantitative mode in RW 113

RWD's qualitative grasp of the drying process is deficient in specifics and in-depth study. Although other heat transfer mechanisms, such as conduction, convection, and radiation, have been taken into account in earlier research [31], neither actual measurements nor theoretical analyses have been done to determine the precise contributions and relative relevance of each mode. In comparison to thicker polymers, some claims have been made about the usage of thin plastic sheets that are transparent to important infrared radiation, implying more effective radiation transfer into the product. The ideal thickness of the plastic sheet for RWD, however, is not well understood. Additionally, it has been proposed that when a product dries, radiative heat transmission declines, favouring conduction heat transfer. According to [32], this slower rate of heating shields the product from overheating and prevents colour and flavour deterioration. These assertions lack precise measurements and analysis, nonetheless, at this time.

5.1 Absence of mathematical models

There is currently a paucity of quantitative knowledge on the precise contributions of various

energy modes and the specifics of moisture transport in the RWD drying process. The majority of previous research [4] have concentrated on experimentally assessing the moisture and temperature profiles of thin samples and contrasting them with other drying approaches. To determine if radiation plays a major role in heat transfer to the drying product, reports on the relative contributions of various heating modes are not yet available.

Studies on the thermal efficiency of RWD have been done, taking into account different heat transfer modes and contrasting them with other drying methods [33]. According to these investigations, quick drying of samples is made possible by radiant heat transfer from hot water in circulation and conduction heat transfer from the plastic film. The sole mathematical analysis of RWD that is currently accessible is a dimensional analysis-based model for drying strawberry juices on a heated glass plate employing all three modes of heat transfer, which links the drying coefficient and moisture ratio as functions of time [34]. The relative contributions of various heating modalities are not discussed in this work, nor is the significance of radiation heat transfer in accelerating sample drying confirmed.

5.2 Solar drying

One of the earliest types of renewable energy is solar drying, which uses solar radiation to dry food. A solar dryer typically comprises of a drying chamber, an air heater, and an airflow system, with the design varied depending on the drying chamber type, air flow, and heat transfer mechanism [35]. The two primary types of solar dryers are passive dryers, which rely on the movement of air naturally, and active dryers, which use forced air circulation. A setup that combines both passive and active drying techniques is also an option (Fig. 3) [36] [37]. In active dryers, the air is heated by a solar radiation collector and then transferred indirectly to the drying chamber. Conversely, passive dryers deliver heat directly to the drying process [38].

In dryers that operate in a mixed mode, a collector warms the air before it enters the drying chamber, and solar radiation also warms the items that are placed inside the drying chamber [35]. Food drying techniques using solar energy are inexpensive, practical, and energy-efficient in developing nations [39]. The solar photovoltaic system is integrated, a

fan is added, auxiliary heat pumps are added, and sun-tracking devices are integrated into the natural convection dryers [39]. These changes result in faster airflow, which quickens the drying process.

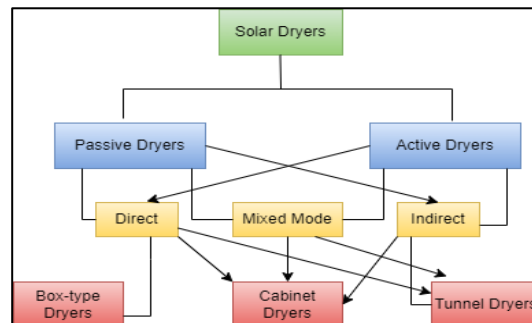


Figure 3: Types of Solar Dryer[36]

For instance, the solar tunnel dryer has a drying chamber that is square and shaped like a tunnel, as well as a fan to remove heat from the goods. Solar panels, which can be either monocrystalline, polycrystalline, or thin amorphous films, are used in the solar dryer. The electrical energy produced by the panels is used to recharge a built-in 12 V, 17 AH battery. The hot air produced by the panels is moved through the drying tunnel with the help of a blower, which makes it possible to control the air flow rate [37].

Despite the growing interest in food drying field there is a lack of comprehensive studies focusing on the optimization of RWD parameters in conjunction with solar auxiliary heating systems. While some studies have evaluated the performance of RWDs with solar collectors, there is a need for further investigations to determine the optimal configuration, design, and operation conditions for achieving maximum energy efficiency and drying performance.

6. Comparative Analysis

Table 1: Review of various agricultural goods dried using different sun drying technologies [40]

Materials with different drying technologies	Properties (Chemical and physical)					Reference
	Color	Essential oils	Aroma	Properties	Bioactive	

1. Sun drying						
Basil		√	√		√	[41]
Chamomile		√		√	√	[42]
Dates	√			√		[43]
Garlic	√	√			√	[44]
Ginger	√	√	√		√	[45]
Lemongrass		√		√	√	[46]
Onion slice	√	√			√	[47]
Peppermint	√	√			√	√ [47][48]
2. Shade drying						
Basil		√	√		√	[41]
Ginger	√	√	√		√	[45]
Origanum vulgare	√	√	√	√		[49]
3. Solar tunnel and greenhouse drying						
Chill	√				√	[50]
Peppermint	√	√			√	√ [48]
Dates	√			√		[51]
4. Solar-assisted drying						
Chamomile		√	√		√	[42]
Mushroom				√		[52]

Table 2: RW drying's impact on the physical and chemical characteristics of food goods

Physicochemical analysis	A drying test	Drying RW	Other methods of drying	Key discovery	References
Ascorbic acid	Apple slices	60, 70, 80, and 90°C hot water; 0.5–	Hot air drying: 60, 70, 80, and 90 °C; 0.5–0.02 m/s 1 FD:	Comparison of RWTM drying to hot air drying, the	[53]

		0.15 m/s air velocity.	5 Pa vacuum pressure; plate and condenser temperatures, respectively, were 20 and 80 °C.	maximal concentration was preserved. 80% RWTM drying retention at 90 °C	
	Pomegranate leather	Circulation water temperatures of 90, 95, and 98 °C; cooling water temperatures of 20 °C; 0.25 mm thick polyester film	50, 60, and 70 °C hot air drying temperatures; 1.5 m/s air speed; and 15–20% relative humidity.	RWTM drying has a higher retention rate than hot air drying.	[53]
Phenolic Compounds	strawberries, cranberries, tart cherries,	Mylar film that is thin (0.75 mm), samples that range in thickness from 50 to	Parallel airflow at 70 °C and 0.76 m/s for hot-air drying Freeze drying: condenser temperature of 64 °C, heating	the maximum amount was retained by freeze drying, followed by RWTM drying	[54]

	blueberries	80 microns, and drying times of 3 to 4 minutes.	plate temperature of 20 OC, and absolute pressure of 0.5mHg	and hot-air drying.	
Carotenoids	Guava pulp	90 OC water temperature	Tray dryer: 60 OC temperature; 0.6 m/s air speed FD: frozen at 35 OC	<ul style="list-style-type: none"> Greater retention in FD and RWTM drying. 	[55]
Texture	Slices of apple, meat, and salmon	A drying temperature range of 55 to 95 degrees Celsius. A 2 mm thick plastic film sheet.	Drying temperatures used traditionally range between 55 and 95 OC.	<ul style="list-style-type: none"> Compared to RWTM dried items, conventionally dehydrated products showed higher firmness values. 	[56]
Color	Sliced apples	95 °C temperature; 50 min. of drying time	Hot-air drying: 55 °C; 50 min. of drying time; 2.23 m/s air speed.	<ul style="list-style-type: none"> More discernible colour difference WWTM treatment significantly reduces 	[57]

				drying time when compared to hot-air drying.	
	slices of kiwifruit	Slice thicknesses of 0.8, 1.6, and 2.4 mm; temperature of 80, 90, and 100 OC	Slice thicknesses of 0.8, 1.6, and 2.4 mm; oven drying at 80, 90, and 100 OC	<ul style="list-style-type: none"> WWTM dried products show less colour variations than those dried using hot air. 	[58]

Numerous studies have been conducted and published reflecting the significance of food drying as a preservation technique and its impact on various aspects of food processing and product quality.

7. Strengths and Limitations

Lack of comprehensive performance evaluation: Previous studies have focused on the individual aspects of RWD or solar drying systems separately [59]. However, there is a research gap in conducting a comprehensive performance evaluation of the RWD system combined with a solar auxiliary heating system for food drying. This includes assessing parameters such as drying efficiency, energy consumption, product quality, and overall system effectiveness [60].

Evaluation of drying performance under variable conditions: The performance of drying systems, including RWD with a solar auxiliary heating system, can vary under different operating conditions, such as varying weather conditions and food product characteristics. The research gap exists in investigating the drying performance and efficiency of the integrated system under such variable conditions and identifying the optimal operating parameters.

Economic feasibility and scalability: While RWD and solar drying systems individually offer potential benefits in terms of energy efficiency and cost-effectiveness [61], the research gap lies in evaluating the economic feasibility and scalability of the combined system. This includes assessing the investment cost, payback period, and potential for large-scale implementation in the food industry.

8. Conclusion

The integration of solar collectors, specifically photovoltaic-thermal (PVT) systems, has demonstrated the feasibility and potential of utilizing solar energy in the drying process. The findings indicate that PV cells, commonly used in solar technologies, can effectively convert solar energy into heat, thereby enhancing the thermal efficiency of the drying system. The utilization of PVT technologies in transferring thermal energy from the PV panel surface to a fluid for low-temperature applications has shown benefits such as improved panel cooling and increased efficiency. This integration of solar auxiliary heating systems offers a sustainable and renewable energy solution for the drying process.

By harnessing solar energy through the use of PVT systems, the performance evaluation has shown improved energy efficiency, reduced operating costs, and enhanced product quality. This innovative approach addresses the global need for energy reduction and environmental sustainability in food processing industries. Overall, the findings highlight the potential of the RWD with a solar auxiliary heating system as an effective and eco-friendly solution for food drying. Further research and development in this field can contribute to the advancement of sustainable drying technologies and promote the adoption of renewable energy sources in the food industry.

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