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REVIEW ARTICLE

A review on refractance window drying process of fruits and vegetables: its integration with renewable energies

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Abstract

Drying is a fundamental process in the food industry, especially for highly perishable foods, such as fruits and vegetables, because they tend to have short durability post-harvest, resulting in economic and environmental losses. The Refractance Window (RW) is a suitable technique for fruits and vegetables as it maintains the nutritional quality of the raw material in the dry product. Although RW is more energy-efficient than hot air-based techniques, the equipment traditionally consumes electricity, largely obtained from fossil fuels, emitting polluting gases. As a solution to this problem, hybridization of the heating system can be adopted in the drying process. Hybridization is when two or more heat transfer techniques are used in food dehydration. Renewable alternatives, such as solar energy, represents a clean and abundant energy source. The integration of these technologies (RW with solar energy) represents a technological improvement for the food industry, especially regarding environmental concerns. The present study analyzed the current progress in the integration of renewable energies into traditional RW for the drying of fruits and vegetables, as well as highlighted the existing knowledge gaps.

Keywords: Cast-tape drying; Food quality; Hybrid drying; Conventional drying; Renewable energy; Non-renewable energy.

Highlights

- The RW is a suitable technique for drying fruits and vegetables
- The use of solar energy in a hybrid form with electricity reduces costs and possible environmental impacts
- Compared to conventional techniques, the RW is more energy efficient
- Bioactive retention is more effective compared to freeze-dried material

1 Introduction

Fresh foods, such as fruits and vegetables, have between 80 and 95% of moisture content; a factor that contributes to their rapid degradation, generating a high volume of losses and food waste (Prosapio & Norton, 2018; Waghmare, 2021). To avoid this issue an alternative solution is the use of drying, which is the oldest conservation method developed by mankind (Acar et al., 2020). Water removal from the food achieved through the drying process limits microbial growth and decreases chemical reaction rates meanwhile still maintaining the food's nutritional quality (Onwude et al., 2022; Qiu et al., 2019). Currently, a large variety of drying technologies are available such as sun drying with direct exposure to outdoor solar radiation (Deng et al., 2021), hot air drying (convection), high-tech drying equipment (Zhang et al., 2017), hybrid dryers and alternative technologies that are more environmentally friendly (Acar et al., 2020).

Now, the intensive focus has been directed on developing energy-efficient technologies that leverage environmental capabilities. Industrial drying equipment is responsible for up to 25% of energy consumption in the food processing industries. Traditionally, the energy required in these systems is obtained directly and indirectly from fossil fuels, which are the major responsibility for greenhouse gas (GHG) emissions (Mourshed et al., 2017). On the other hand, countries like Brazil have been investing in renewable energy sources, relying on its potential to explore alternative sources (such as solar and wind power) in combination with drying techniques to help reduce the carbon footprint of their operations (Empresa de Pesquisa Energética, 2021).

In this sense, among the available technologies, Refractance Window (RW) is a relatively new technique and presents some advantages such as a short drying period, conservation of bioactive, thermal and energy efficiency, and mechanical simplicity (Raghavi et al., 2018). In a previous study carried out analyzing asparagus dehydration, plant moisture reduction from 90% to 4% was obtained in only 5 minutes (Nindo & Tang, 2007). This short processing period contributes to the maintenance of quality parameters such as color and aroma (Nindo et al., 2003; Raghavi et al., 2018). Researchers have also shown that considering milk dehydration, a 61% reduction in processing time was obtained when compared to a traditional concentrator (Al-Hilphy et al., 2020). In addition, the RW dryer has been proven to present good energy efficiency when compared to conventional dryers (between 28% and 38%) (Acar et al., 2020; Nindo & Tang, 2007; Ortiz-Jerez et al., 2015). Finally, when focusing on the preservation of bioactive compounds such as vitamin C, antioxidants, and phenolic compounds, RW has proven to yield higher final concentrations when compared to traditional techniques such as freeze-drying (Celli et al., 2016).

Overall, the RW technique has a promising future as a drying solution. However, there are still potential areas of improvement which would ease its ample industrial application such as reducing the use of conventional energies sources for operation. The main objective of this work is to present a compilation of some potential improvements for the RW technique bringing to light the current state of the art, the potential for hybridization with renewable technologies, or other more recently developed solutions (e.g. ultrasound and infrared). Finally, a brief discussion on the future trends regarding the use of renewable energy in drying models will be presented.

2 Drying process of fruits and vegetables

The consumption of fruits and vegetables, especially fruits in nature is highly encouraged due to the several health benefits associated with adding regular portions of them to your daily diet (Silva & Claro, 2019). However, because they are highly perishable (moisture content > 80%) they are commonly the reason for product losses in the food industry. Thus, the dehydration of foods with high water content is applied as a practical solution to the problem presented (Mat Desa et al., 2019). Consumptions of dried fruits present several health benefits including control of satiety and improvements in lipid profile (Chang et al., 2016). Improvements in bone health (Wallace, 2017) have also been reported, since many phytochemicals remain in the product even after dehydration (Alasalvar et al., 2020; Hernández-Alonso et al., 2017; Onwude et al., 2022; Senadeera et al., 2020). Table 1 shows previous research analyzing the dehydration of fruits and vegetables.

Table 1. Fruits and vegetables found in the literature are dehydrated by different drying methodologies.

Materials	Techniques	Motivations	Conclusions	References
Sweet potatoes	Direct solar dryer with coupled solar collector	Analysis of drying kinetics	Reduction in drying time with increasing temperature due to solar collector	Rodrigues et al. (2021)
Mushroom	Convective drying, freeze-drying, vacuum microwave, and convective combination + microwave	Study the effects of drying on chemical and sensory composition	Convective combination + microwave proved to be the best alternative for dehydration	Politowicz et al. (2018)
Pumpkin	Microwave (with different associations), freeze-drying, and convective greenhouse	Drying kinetics, kinetics and rehydration indexes, quality.	Microwave drying methods are suitable for pumpkin dehydration	Monteiro et al. (2018)
Peach	Hot air, infrared, hot air combinations + microwave and radiofrequency + hot air	Evaluate texture, rehydration ratio, moisture, color, and microstructure	Hot air + microwave = shorter drying time, infrared produced dried peach om better flavor and odor	Azam et al. (2019)
Chinese cabbage	In a greenhouse, solar cabinet, sun drying, and freeze-drying	Study color and antioxidant components	Lyophilization showed the best results, while sun drying and microwaves had a negative impact	Managa et al. (2020)
Fruits and vegetables - review	-	Application of Artificial Intelligence (AI) in quality control in the drying of fruits and vegetables	AI can contribute to the maintenance of dry product quality indirectly, without the intervention of invasive monitoring techniques.	Chen et al. (2020)

Fruits and vegetables are potentially suited for dehydration; however, it is important to note that the quality of the final material varies according to the drying technology applied. Fruits and vegetables are thermally sensitive, and the inadequate choice of drying technology can induce nutritional value loss, product oxidation, color change, and the development of unpleasant texture and flavors (Zhang et al., 2017). Factors such as physiological properties, characteristics of the materials to be dried, desired initial and final moisture content, temperature, and drying time are important characteristics to be considered when determining drying procedures (Sehrawat et al., 2018). Additionally, minimal repair and maintenance, low energy consumption, material versatility, ease of operation, and reduced cost are some of the relevant operational criteria considered for drying equipment selection (Chua & Chou, 2003).

3 Drying technologies

The food industry relies on high-performance equipment to reach drying processes that yield high-quality dried foods. This equipment requires a high implementation cost which is only found in companies that present large investment capacity (Chua & Chou, 2003). Among the technologies applied, 85% of dryers used in the industry are conventional dryers that use hot air as a drying medium (Kluczek & Olszewski, 2017). These dryers account for 20% of energy consumption in the food production process, have low energy efficiency (about 30%) and contribute to 90% of the total costs in the production process. Figure 1 highlights some of the major issues that can be addressed with new drying technologies.

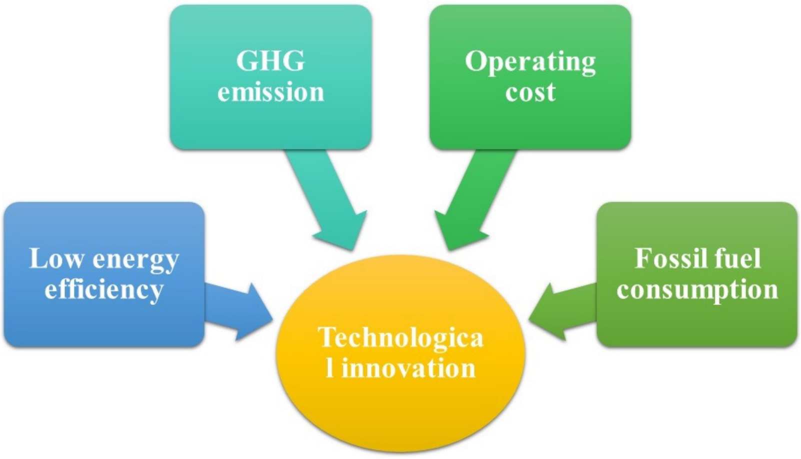

Figure 1. List of problems to be overcome by new drying technologies.

Consequently, new techniques are currently under development to improve drying efficiency, reduce costs and curb the use of fossil fuels in the process. Acar et al. (2020), conducted a broad study on the advances made in drying technologies. Among the techniques studied are adsorption-mediated drying, agitated thin film, electrotechnology, heat pump, microwave, ohmic-heating, RW, hybrid systems, impingement, rotating drum, superheated steam, and vacuum. With this analysis, the authors concluded that the selection of the best drying method was not a straightforward process with electricity consumption and cost varying immensely between processes. Moreover, inclinations to lower electricity consumption were found for processes that did not necessarily present the lower operational cost, bringing to light the need for the development of more efficient solutions that can combine advantageous conditions for all the operational requirements necessary.

Additionally, previous studies analyzing the RW, have demonstrated that the technique is a good alternative to more conventional technologies since it is overall cheaper, can be combined with renewable energy, and is energy efficient (Acar et al., 2020; Shende & Datta, 2019).

3.1 Refractance Window (RW)

The RW is a relatively new process, considered a 4th generation technique (Vega-Mercado et al., 2001) which has been gaining relevance in the latest years (Acar et al., 2020; Calderón-Chiu et al., 2020; Shende & Datta, 2020). RW is also referred to as conductive hydro-drying and is considered a form of Cast-Tape Dryer (CTD). CTD is applied to suspensions or viscous materials to transform them into flakes, films, or powders (Baeghbali et al., 2019; Frabetti et al., 2018; Ortiz-Jerez & Ochoa-Martínez, 2015). For the process, the material to be dried is arranged in thin layers on a transparent infrared conveyor belt (polyester film or fiberglass coated with Teflon^{TM}) floating in overheated water or steam (heated to 98 °C) (Raghavi et al., 2018). RW dryers keep the water in circulation being reheated so that the temperature is maintained throughout the process.

The thermal energy of the water is transferred through the plastic film (or fiberglass coated with Teflon$^{TM)}$ and radiated through the film to the material arranged on the conveyor. The vaporized water of the product is removed by an extractor present in the dryer. In this technique, there are three processes of heat transfer occurring simultaneously: conduction (between the plastic sheet and material), radiation (through the material), and convection (between material and air; and between the treadmill and water) (Bernaert et al., 2019; Durigon et al., 2016). Although three heat transfer mechanisms are occurring simultaneously, the thermal radiation emitted by the heating medium (hot water or water vapor) is responsible for only 5% of the amount of energy supplied to the material and can be neglected (Frabetti et al., 2018; Zotarelli et al., 2015). Figure 2 shows an industrial RW dryer scheme.

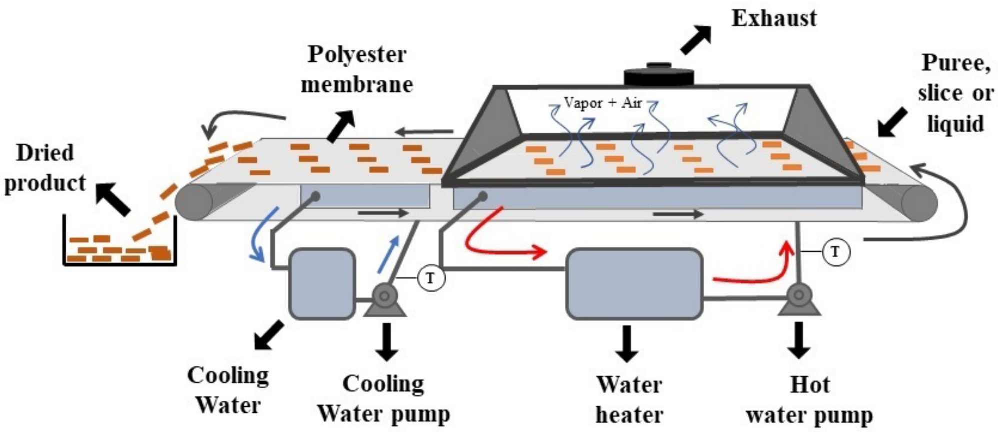

Figure 2. Working diagram of industrial equipment by RW.

Literature shows variations of the industrial equipment, that work under the same principle. The drying of pumpkin puree was investigated by commercial equipment and pilot equipment aiming to reduce microbial activity and energy efficiency of the process. In both, Mylar^{TM} plastic film was used with 0.2 mm thickness and water temperature of around 95 °C. In the pilot-scale equipment, the film was placed on hot water with dimensions 3 m × 0.6 m × 0.2 mm. On the industrial scale, the film had 12.9 m × 1.41 m × 0.2 mm in size. It was possible to reduce the moisture content from 80% to about 5% in less than 5 min. The energy efficiency of the commercial equipment varied between 50% and 70%. The analysis of the microbiological activity in the product obtained in pilot-scale equipment was satisfactory, with a reduction in detectable levels of *coliforms, Escherichia coli, and Listeria innocua* (Nindo et al., 2003).

Studies on the energy efficiency of different dryer technologies have already been carried out. Baeghbali et al. (2016) studied quality and energy efficiency in the dehydration of pomegranate juice by different techniques (RW, freeze-dryer, and spray dryer). For the RW drying, the following configurations were followed: the water temperature was 91 °C; track speed 3.9 mm/s; and material thickness on the mat was 0.5 mm. For spray-drying: dryer with an internal diameter of 115 cm and height of 165 cm; and the pressure of 1 bar. The feed rate was 0.75 L/h and the feed temperature was 40 °C. The air inlet and outlet temperatures were around 140 °C and 75 °C, respectively. In the freeze-dryer, the operational conditions were the pressure of 3.0 kPa, the temperature of the heating plate at 20 °C, and the condenser temperature of -40 °C. The drying experiments were performed until moisture content in a wet base (wb) of 5.3%, 2.9%, and 8.5% was reached, for RW, spray dryer, and freeze-dryer, respectively. RW drying presented better results in energy consumption, energy efficiency, and lower CO_2 emissions. Although the freeze-dryer is usually used as a standard technique for high-quality dry products, its energy efficiency is low, besides being an expensive process (Nindo & Tang, 2007). While the drying by RW obtained 31.56% efficiency, for the freeze-dryer it was only 1.12%.

Leiton-Ramírez et al. (2020a) evaluated moisture content, color, porosity, volume variation, water activity, carotenoids content, and vitamin C content after drying guava pulp by three different methods (freeze-drying, convection, and RW). As a result, RW required the shortest drying time (from 80% db to 4% db in 76 min) to reduce moisture contributing to greater overall color retention of the final product obtained. The freeze-drying and RW methods showed the highest retention of physical and nutritional characteristics compared to convection. Based on these results, the authors conclude that RW is a suitable technique for the development of guava snacks.

Regarding the drying of fruits and vegetables with RW, only 26 studies were found by the Web of Science tool in the last 10 years, studying: apple (Hernández et al., 2020; Nascimento et al, 2020; Rajoriya et al., 2019, 2020); mango (Shende & Datta, 2020; Zotarelli et al., 2015); papaya (Minuye et al., 2021); yam (Santos et al., 2020); beetroot (Preethi et al., 2020); physalis (Puente-Díaz et al., 2020); sapota (Jalgaonkar et al., 2020); pomegranate (Baeghbali et al., 2016; Tontul & Topuz, 2019); pupunha, tucupi and mango (Costa et al., 2019); cherry, blueberry and strawberry (Nemzer et al., 2018; Tontul et al., 2018); guava (Frabetti et al., 2018; Leiton-Ramírez et al., 2020b), and pumpkin (Ortiz & Ochoa-Martínez, 2018).

The application of RW in fruits and vegetable drying has several advantages such as low or zero cross-contamination, lower operating cost, lower temperatures requirements and energy consumption, conservation of bioactive contents (color, vitamins, and antioxidants), faster process, thermal efficiency, and mechanical simplicity (Acar et al., 2020; Baeghbali et al., 2016; Moses et al., 2014; Nindo & Tang, 2007).

Nevertheless, some disadvantages of RW are worthwhile noting among which are: low production capacity; and required cleaning of the treadmill before or after a new process. Also, when compared to drum drying and spray dryer the RW is more expensive, however, when compared to freeze-drying the cost reduction is significant (Acar et al., 2020). In addition, drying cannot be performed at higher temperatures (above 98 °C) and is not recommended for materials with a high sugar content (fructose and glucose) due to the adhesive behavior of the pulp resulting from the material's low glass transition temperature. In this case, it is necessary to choose the appropriate material to be dried or change the Mylar™ film (usually used in RW) for another material with a low glass transition (T_g) temperature (such as fiberglass coated with Teflon™) to ease the removal of the material from the belt. (Durigon et al., 2018; Waghmare, 2021).

3.1.1 Product quality obtained by RW

Fruits and vegetables are heat-sensitive foods and their quality properties (e.g. color, antioxidants content, and microbiological activity) are affected by dryers. Although the RW operates at temperatures above 90 °C, the heating is not applied directly to the food, in this case, the temperature reached by the food is lower than the temperature of the bath (70-85 °C) preventing the product from becoming brittle or losing the quality of the product. (Mat Desa et al., 2019; Sehrawat et al., 2018; Waghmare, 2021).

Regarding quality determining parameters (e.g. bioactive content and physicochemical properties) of the material dried by RW (Waghmare, 2021), concluded that although there are studies on these impacts, there is still much to be explored. According to Celli et al. (2016), products dried by RW showed good retention of bioactive content, with above 90% of anthocyanins and vitamin C preserved. The ascorbic acid (vitamin C) is especially relevant because it is an unstable compound and it indicates the degradation of the remaining vitamins in the food, thus being directly correlated with the high quality of the dry product (Rajoriya et al., 2021). In the study carried out by Tontul et al. (2018), it was possible to observe a higher concentration of vitamin C in the cherry pulp when drying by RW compared to convective drying (90% and 80%, respectively), thus confirming the positive effect on the conservation of the bioactive of the RW technique.

Literature has also presented a detailed analysis of the physicochemical properties obtained from RW drying. Particle size distribution, bulk density, particle density, porosity, moisture, morphology, color, total carotenoids content, glass transition temperature, and water sorption were analyzed by Zotarelli et al. (2017) in the production of mango powder with and without the addition of maltodextrin (viscosity reducing agent) by spray-drying and RW drying. According to the authors, due to the sticky characteristics of the mango pulp, it is important to add maltodextrin in the spray-dryer process, which was not required for RW. However, to produce the final powder it is necessary to adopt a grinding after the RW process when an irregular structure is obtained. The RW drying process resulted in powders with an apparent density of 0.8 g cm^{-3} and 0.7 g cm^{-3} (with and without maltodextrin, respectively) higher than those presented by the spray dryer (0.45 g cm^{-3}, 0.5 g cm^{-3}). The concentration of carotenoids was higher in the powder produced by spray-drying (113 µm of carotenoid g^{-1} of dry mass). As for stability, the powder obtained by RW presented better conditions than the powder obtained by spray-drying. After all the analyzes the authors considered RW or CTD a suitable process in the production of mango powder. Table 2 summarizes the conditions and main quality results.

Table 2. Authors who used RW for fruit and vegetable dehydration.

Materials	Motivations	Conditions	Answers	References
Potatoes	Retention of total oxidants to produce snacks	Freeze Drying: potato puree 2mm thick, frozen at -35 °C for 1 h and dehydrated for 24 h at 3.33 Pa. Drum Drying: Pressurized steam at 413 kPa, saturation temperature of water at 145 °C and the surface temperature of the drums was 135-138 °C. RW: conveyor belt speed 1.04 m/min in contact with hot water circulated at 95 °C	The analysis of antioxidant activity, total phenols, and total antioxidants varied according to the analyzed potato species. In dehydrated potatoes, there was no significant difference in antioxidant activity and total phenols between the methods studied. RW showed lower losses in anthocyanin content	Nayak et al. (2011)
Mango	Comparison between RW and tray dryer	In both techniques, 1 and 2 mm thick slices were used. RW: thermostatic bath at 92.5 °C and static mat (Mylar^{TM} 0,26 mm thick). Tray dryer: air temperature 62 °C and airspeed 0.52 m/s	Reduction in the time required to obtain moisture to 5% at 1 and 2 mm thicknesses for RW (30 and 60 min, respectively) compared to tray drying (240 min). Water activity was reduced to 0.6 in 30 min by RW and 240 min for tray drying. Lower impacts on color, higher values of effective diffusivity with fewer signs of deterioration of the product by RW.	Ochoa-Martínez et al. (2012)
Kiwifruit	Dry product quality	Analyzes performed only by RW. Drying temperatures of 80-100 °C, slice thickness of 0.8-2, .4 mm and Mylar^{TM} thickness of 100-300 µm	Increasing the temperature and decreasing the thickness of the drying time were reduced (between 25 and 60 min). The film thickness showed no influence on the drying parameters.	Azizi et al. (2017)
Apple	Study of effective diffusivity through fick model and anomalous model	Conventional drying: convection oven at 55 °C and 95 °C. RW: thermostatic bath at 55 °C and 95 °C, with static belt (Mylar^{TM} 2 mm thick)	Reduction in time required for dehydration from 12.5 h (55 °C) to 3 h (95 °C) by conventional drying and 5 h (55 °C) and 1 h (95 °C) by RW. The anomalous diffusional model was the one that best represented the drying curves	Franco et al. (2019)
Banana	Effects of drying temperature	Analyzes performed only by RW. Heating water temperature (70, 80, and 90°C) and banana puree thickness (2 and 3 mm) and Mylar^{TM} film 25 mm thickness	The higher temperatures and lower thicknesses reduced the drying of the pulp, the consequent increase in the time of energy consumption. The color was between 70 and 90 °C, however, there was no significant difference between 70 and 80 °C. At 90 °C, it showed the best retention in bioactives such as ascorbic acid (76-78%), phenolics (84%), flavonoids (64%), and antioxidant activity (80%).	Rajoriya et al. (2021)

3.2 Hybrid technologies

The term “hybrid technology” is relatively new and is used in processes that use two or more drying methods or multiple heat transfer modes, to improve the efficiency of the system and ensure product quality, minimizing costs and possible environmental impacts (Menon et al., 2020). The ideal concept of this combination of technologies is to minimize the negative effects of an isolated method. For example, although widely studied, convective dryers present several problems, such as prolonged process time, high energy consumption, and reduction in product quality (Politowicz et al., 2018). Often, infrared is used to minimize such negative aspects in convective methods, to reverse the problems presented (Taghinezhad et al., 2021).

Andrade et al. (2019) studied the effects of the combination of infrared and convective drying on the drying kinetics of orange residue. Tests were performed with and without air heating. With heating, an incandescent lamp (60 W) at full power was used. In the experiments, the heated air reached 49 and 42 °C, for velocities of 0.4 and 1.0 m/s, respectively. The infrared source temperatures were 80 and 100 °C. The authors showed that at 80 °C and 4 m/s it was possible to reduce the time needed to reach equilibrium moisture from 140 to 100 min. With the increase in speed to 1 m/s, there was a reduction in the drying time of 100 and 80 min without heated air and with heated air, respectively. The authors show that the heated air contributed to a higher temperature in the material during drying, increasing the rate of dehydration, and thus reducing the drying time. Additional studies developed by Taghinezhad et al. (2021), used the combination of infrared convective drying for turnip dehydration. The authors concluded that adding the infrared drying to the process brought some improvements to the results obtained, mainly, in energy efficiency where an increase from 0.9 to 15.23% was noted.

Hybrid dryers allow you to increase efficiency and overcome disadvantages related to conventional hot air systems, such as lower product quality, low thermal/energy efficiency, and slow drying kinetics. (Fan et al., 2017; Menon et al., 2020; Mohammed et al., 2020). A compilation of studies on hybrid methodologies can be seen in Table 3.

Table 3. Hybrid drying techniques are found in the literature.

Drying types	Materials	Conditions	Answers	References
Convective + infrared	Turnip	Variables: drying temperature (50, 60, and 70 °C) and thickness (2, 4, and 6 mm). Pretreatments: bleaching (at 90 °C for 2 min), ultrasonic (at 30 °C for 10 min), and microwave (360 W per 2.5 minutes). There are in the dryer two Infrared (IR) lamps (500 W each)	70 °C and 2 mm proved to be the optimal condition in drying parameters such as time (20 min, specific energy consumption (21.57 MJ/kg), energy efficiency (15.23%), and dryer efficiency (21.2%). The use of different pretreatments exerts different influences on the samples.	Taghinezhad et al. (2021)
Gas, Solar, and Gas + solar	Green chilies	Hybrid heating (water-air) consists of a tubular photovoltaic system and gas burner with a heating capacity of 60 kW. Initial temperature 60 °C	Higher gas and hybrid drying rates. Specific energy consumption for hybrid heating is 22.28 MJ/kg, gas 24.90 MJ/kg, and solar 19.19 MJ/kg. Although the energy consumption is lower with solar heating alone, a longer dehydration time is required, so hybrid heating is a viable option in this system.	Amjad et al. (2021)
Open sun, Tunnel + Solar Photovoltaic	Mint	The system consists of a solar tunnel dryer (STD), photovoltaic system, and flat	Time to reach equilibrium moisture thickness I 210 min, thickness II 270 min and	Eltawil et al. (2018)

Table 3. Continued…

Drying types	Materials	Conditions	Answers	References
		solar collector. Hot airflow 3.12 m 3 /min. Thickness I (1 cm), II (2 cm) III (3 cm). Initial humidity 76%.	thickness III 360 min (hybrid system) and 270 min, 360 min and 420 min (outdoors). The highest drying efficiency of 30.71% and overall efficiency of 16.32% were recorded in the layer thickness of mint II.	
Open sun, Solar + thermal shelf	Black turmeric	The hybrid system consists of a solar heater and thermal energy storage system. Mint leaves are cut into a cylindrical shape (around 30 to 35 mm thick × 5 to 6 mm). Initial moisture 73.4% (wb)	It took 1110 min (hybrid dryer) to 2790 min (open sun) to obtain a final moisture content of 8.5% (wb). The best models to describe the drying curves were two terms and Page (hybrid dryer and solar drying, respectively). Hybrid dryer energy efficiency is superior to solar (25.6% and 12.0%, respectively)	Lakshmi et al. (2018)
Conventional, microwave+ convectionaltional	Sour cherries	Drying temperatures are 50, 60, and 70 °C. Airspeed 0.5 m/s (conventional drying). Hybrid operations were performed at three levels of microwave power and air temperature: 120, 150, 180 W, and 50, 60, and 70 °C, respectively.	Reduced humidity from 80,75% to 25% at times 720, 1200, and 2940 min in hot air temperatures of 70, 60, and 50 °C, respectively. In the hybrid drying, the time varied between 266 and 1645 min. The energy efficiency of the hybrid technique proved to be superior to the conventional one, as well as the rehydration capacity of the dry product.	Horuz et al. (2017)

Calderón-Chiu et al. (2020) analyzed the color, texture, total polyphenol content, total flavonoid content, and antioxidant capacity of beet dried by RW and Osmotic Dehydration (OD). OD was performed with 35, 50, and 65% of sucrose concentrations and temperatures of 30, 40, and 60 °C. The polyester film temperatures were maintained between 60 and 85 °C and beetroot was sliced into chips of 1 and 5 mm. RW-DO hybridization partially reduced moisture, reducing drying time for RW at 85 °C (100 and 40 min at 60 and 85 °C, respectively). According to the authors, hybridization provided a stable product while maintaining chemical and physical properties.

Another widely studied technique is the hybridization of solar dryers. Solar drying reduces operating costs and reduces greenhouse gas emissions (Roratto et al., 2021). Hybrid solar dryers use sun-radiated thermal energy, along with energy sources such as electricity, fossil fuels, or biomass to complete the supply of energy during periods where there is no solar incidence (Amjad et al., 2021; Lakshmi et al., 2018).

Roratto et al. (2021) developed equipment that uses solar energy and operates under a vacuum. Vacuum drying reduces the temperature of the food and increases the drying rate, contributing to higher quality products compared to hot air drying. With this equipment, it is possible to dry 4 kg of food in 3-4 h. Slices of banana, persimmon, and carrot were dried as test samples for this study. The solar hybrid system contributed to supplying the necessary thermal energy for the drying process, as long as drying conditions are similar to those presented in this study are followed.

An Ultrasound and Infrared Assisted Conducted Hydro-Drying (UIACHD) was developed by Baeghbali et al. (2019) aiming to increase the drying rate, reduce the hot water temperature and increase the thickness of the drying material. The quality of the product (flavonoid content, total phenolic compounds, antioxidant activity, vitamin C content, and color), energy consumption, and energy efficiency were compared to freeze-dryer and cabinet dryers in the drying of apple slices (1, 2, and 3 mm). An ultrasound unit (1680 W) and two incandescent infrared lamps (250 W) were installed in the UIACHD on a pilot scale (2.65 m in length). The circulating water temperature was set at 85 °C. Studies carried out in these conditions show the positive effects of drying by UIACHD. In addition to physical-chemical parameters similar to the freeze-dryer and superior to the cabinet dryer. In this way, UIACHD proves to be good equipment to maintain product quality, in addition to reducing the use of energy in the drying process.

4 Future perspectives in RW drying

New technologies are currently being developed and they are expected to be cost-efficient, energy-efficient, and environmentally effective. Considering these expectations, renewable energies are seen as a viable solution to help reach such requirements. In this sense, alternatives for technological development in the drying field using processes integrated with renewable energies are still scarce. For example, there is only one paper in the literature that explores this integration. Seyfi et al. (2021) showed that it was possible to combine a photovoltaic-thermal system that allows drying process improvements, such as zero GHG emissions. In the study, three methods were compared: Conventional RW (CRW); Solar RW (SRW); and a Hot Air dryer (HA). Four temperatures (60, 70, 80, and 90°C) and three thicknesses (1, 2, and 3 mm) were used for the dehydration of Aloe Vera pulp. According to the authors, there were no social costs due to the non-emission of pollutants in the SRW system. The results showed that the content of phenols in SRW/CRW dryers increased from 1.30 to 2.73 folds when compared to HA. Similar behavior was also noted for glucose (1.07 to 1.37 folds increase). In the SRW and CRW methods, energy efficiency and Drying Efficiency (DE) were increased with higher temperatures and lower thickness (the DE and EE in the SRW/CRW dryer increased by 1.50 to 2.54 and 1.59 to 2.65 folds compared to the HA dryer).

From this analysis, it was possible to conclude that there is a knowledge gap that needs to be addressed for studies of RW drying with the use of solar thermal energy as the heat source for the water heating in the RW process, or even hybrid, solar-electric heating. Waghmare (2021) could explain that more research is required for further understanding of RW drying, for example, a hybrid solar-RW dryer can be analyzed, to produce an even more efficient dryer, with better quality parameters and that is more environmentally friendly. The use of renewable energies in hybrid systems is considered beneficial due to their continuous supply. Moreover, solar energy can be used in various ways and has significant participation in moisture removal when used in combination with other technologies (Anum et al., 2017; Roratto et al., 2021).

5 Final considerations

Drying is an extremely important unit operation of the food industry. Through it, it is possible to keep quality products out of the harvest season, especially in the case of fruits, vegetables, and greens, as they are highly perishable and cause great waste. However, unfortunately, the consumption of electricity by dryers in the food industry is excessive, making the process expensive, energy inefficient, and environmentally damaging. New technologies are being developed and/or improved to overcome the presented problems. In this sense, RW has proven to be an important part of the possible solutions being analyzed. It is a cheap technique compared to traditional techniques such as spray-drying, hot air, and freeze-drying (Acar et al., 2020; Celli et al., 2016), which is used as a quality standard in dehydrated products. Moreover, it is energy efficient and, if combined with renewable energy, such as solar, can be environmentally friendly. In short, the exchange of fossil fuels for renewable sources in industries still needs to be more thoroughly studied and this important knowledge gap should be addressed to improve drying processes and enable a net-zero transition in this industrial sector.

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