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Refractive window drying a novel drying technique for fruits and vegetables: A review

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Abstract

Insufficient postharvest handling, storage, and processing technologies can result in a major issue of postharvest losses in agricultural and horticultural crops. Drying has been a typical food preservation approach to mitigate these losses and increase product shelf life. Traditional drying procedures, on the other hand, might have a detrimental influence on product flavour, colour, and nutritional characteristics due to high temperatures. As a result, there is a need for alternate drying technologies that can preserve product quality and nutritional value. Refractance window drying (RWD) is a thin-film drying process that employs high rates of heat and mass transfer to remove moisture from materials. RWD creates a drying "window" by spreading the product over a transparent plastic film, resulting in lower product temperatures and faster drying through all modes of heat transmission. Compared to traditional drying methods such as drum, hot air, freeze, and spray drying, RWD requires lower drying temperatures, shorter drying times, and lower costs and energy usage. This review paper explores recent RWD trends and their impact on food quality attributes, highlighting the differences between RWD and other drying technologies.

Keywords: RWD, phenols, antioxidant, energy efficiency

Introduction

In light of contemporary consumer demand for more nutritious and health-promoting bioactive food products, development efforts In the engineering of food dehumidifiers now prioritize product quality as a significant criterion of dryer performance, despite the fact that the fundamental objectives of drying as a unit operation, specifically to offer microbiological stability, lessen deteriorating chemical reactions, make storage easier, and cut down on shipping expenses, remain important and relevant (Nguyen *et al*., 2022) [35]. This is noteworthy given that the dehydration processes involved in drying necessitate a significant amount of energy. Furthermore, it should be noted that drying as a process is distinct from evaporation, which involves producing a liquid with a high concentration of dissolved solids as the final product. (Karate, M *et al*., 2022) [15]

Drying, a traditional and widely used method of food preservation, is primarily Aspired at reducing the moisture content of highly perishable food items such as fruits, vegetables, and spices, which typically have a moisture content of over 80%. This technique offers numerous advantages, including increased shelf-life of products, decreased costs associated with packaging, storage, handling, and transportation, as well as the ability to provide a diversified product offering for buyers even out-of-season. (Moses, J *et al*., (2014) [20].

Drying technologies are classified into four generations based on their suitability for different types of raw materials and their ability to retain the quality attributes of the final product. The first-generation dryers, such as kiln, tray, and tunnel dryers, utilize hot air as the medium for heat transfer and are most suitable for solid materials like food grains and horticultural commodities. Second-generation technologies, such as spray and drum dryers, are better suited for slurries and pastes that need to be dried in the form of flakes and powders. Third-generation drying technologies include freeze dehydration and osmotic dehydration. Finally, fourth-generation drying technologies, such as microwave, infrared, heat pump, fluidized bed, radio frequency, and refractance window drying, are distinguished by their ability to handle different types of raw materials and preserve the quality attributes of the intended products. (Raghavi, L *et al*., (2018) [28].

The refractance window (RW) drying method is a promising technique for preserving heat-sensitive vitamins and phytochemicals, while maintaining low temperatures and shorter process times.

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Compared to freeze-drying, RW equipment is more cost-effective and energy-efficient, with an evaporation capacity of up to 10 kg m−2 h−1. Moreover, the absence of direct contact between the product and the heat transfer medium eliminates the risk of cross-contamination during drying. Notably, RW drying has demonstrated the ability to retain the color and nutritional content of food products, which makes it an attractive option for food processing applications. (Baeghbali, V., & Niakousari, M. (2018) [6].

This review paper aims to provide a comprehensive overview of the refractive window drying system, which is a novel drying technology that requires further exploration. The article covers the fundamental principles of refractive window drying, including the heat and mass transfer processes involved, the energy efficiency of the drying process, and the potential impact on the nutritional and sensory quality of the final product. Additionally, the paper discusses the future prospects of refractive window drying.

Working of refractive window drying

The drying equipment developed by RW operates based on the principle of infrared radiation emitted by hot circulating water. The process involves spreading the wet pulpy material uniformly on an infrared transparent plastic sheet made of Mylar, which floats on the surface of the heated water. The thickness of the Mylar film is crucial, as thinner films allow more transmission of infrared radiation but have less mechanical strength. Therefore, an optimum thickness of 0.25 mm was determined. The heated water, at a temperature between 95 to 97 °C, efficiently transfers thermal energy to the wet material through a combination of conduction, convection, and radiation of heat, resulting in less drying times and superior quality products.

The thickness and moisture content of the pulpy material influence its absorptivity for infrared thermal energy. The contact point between the material and the Mylar film over the hot water surface forms a window for infrared heat to pass directly from the surface of the hot water to the material to be dehydrated. As the drying progresses, the infrared window gradually closes, reducing the passage of infrared heat as the moisture content decreases (Zotarelli, *et al.,* 2015) [34]. To facilitate the easy separation of the dried product from the plastic conveyor belt, a scraper device is used to remove the product after it has been moved over a cold-water trough. Finally, the cooling section helps to reduce the temperature of the product below the glass transition point, making it easier to remove the final product. (Shende. *et al.,* 2019) [29].

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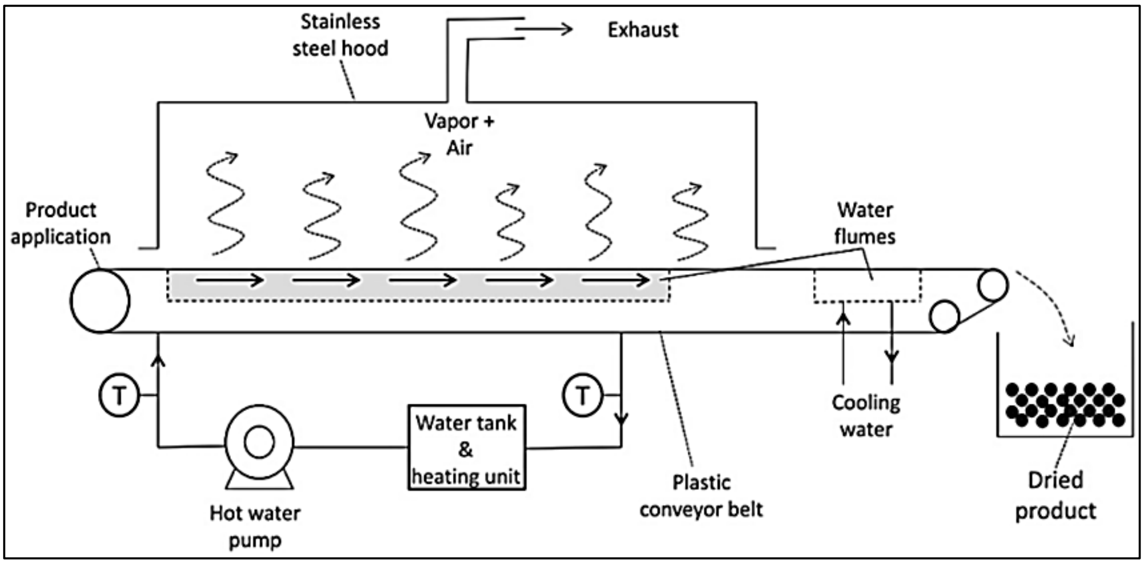

Fig 1: A diagram illustrating the process of refractance window drying can be found in a study by Raghavi *et al*. (2018) [28].

MYLAR SHEET transparent substrate for heat transfer

Mahanti *et al*. (2021) [18] mentioned the use of Mylar film in refractance window drying. Mylar film is a transparent polyester film that is commonly used as a window material in the refractance window drying process. It is used to separate the food product from the heating medium while allowing infrared radiation to pass through and heat the food. The authors discussed the importance of selecting appropriate Mylar film thickness, which affects the heat transfer rate and ultimately the quality of the dried product.

Physical Properties

Colour

Colour is an important aspect of high-quality food that has a direct impact on consumer acceptance. There are several colour coordinate systems, with RGB (red, green, blue) being the most common, including the Lab* system from the Commission Internationale de l'Eclairage (CIE) and Hunter Lab. L* represents luminosity, while a* is positive for reddish colours and negative for greenish hues, and b* is positive for yellowish colours and negative for bluish ones (Chauhan, *et al*., 2011) [10]. Thermal processing can induce colour changes owing to a variety of reactions, and the drying technique and circumstances can also have an impact on the colour characteristics. Another aspect influencing food colour is pigment concentration. RWD, being a mild drying procedure, can result in less pigment production and less alterations in colour characteristics (Zalpouri *et al*., 2022) [32].

In a study conducted by Caparino *et al*., various drying methods including RWD, freeze drying, drum drying, and spray drying were employed to produce mango powder, and the color properties of the resulting powders were investigated. Results showed no significant difference in color between the RW- and freeze-dried powders, while the spray-dried powder had a lighter color compared to the drum-dried powder. Meanwhile, Puente-Díaz *et al*. (2020) [26, 27] evaluated the color retention of golden berry pulp using RWD and freeze-drying methods, and found that RWD was equally effective in preserving the color of the dried product, maintaining it similar to both the fresh sample and the freeze-dried product.

Textural Properties

Texture is the sensory experience of the composition of the food and its reaction to applied pressures that incorporates vision, kinesthetics, and hearing (Martynenko *et al*. 2014) [19]. The texture of the food influences the physical and touchable sensations during mastication, making it an important quality indicator for customers to judge the acceptance of a product. The drying temperature and pace have a large influence on the textural attributes of food items (Guiné, R. 2018) [11]. While the RWD method is excellent for Desiccating fluid or semi-fluid comestibles, it is ineffective for drying fruit or vegetable slices or cubes (Waghmare, R. 2021) [31].

In an assessment (Jafari *et al*., 2016) [13] comparing oven-dried and RW-dried kiwifruit samples, it was discovered that RW-dried samples exhibited lower textural hardness than oven-dried samples, which were dried at temperatures ranging from 80 to 100 °C. Jalgaonkar *et al*. (2020) [14] discovered that raising RWD temperature and pectin content enhanced the hardness of sapota bar. The interplay of the two elements, however, resulted in a reduction in hardness. Sucrose, citric acid (0.6% w/w), and pectin were mixed with sapota pulp to make sapota fruit bars for the study.

Effects of RW drying on nutrient content

Phytochemicals, phenolic compounds, flavors, pigments, essential oils, and nutraceuticals are types of bioactive compounds that are secondary metabolites found in plant tissues (Zia *et al.*, 2022). [33] So, preserving the bio active components in the dried plants and fruits play a important role in attracting the consumers and to meet the RDA in foods. New studies have expanded on this concept and demonstrated that a significant amount of heat energy is transferred through conduction, resulting in the creation of a thermal-resistant film at the base or the formation of air gaps among the product and plastic sheet. This process helps to minimize thermal damage and maintain the integrity of the product (Mahanti, N. K *et al*., 2021) [18]. And another advantage is that it operates at low temperature and high moisture rate transfer adds another advantage to this method and compared to spray dryer and drum dryer refractive window drying is cost effective and cost half of the money as another dryers and its energy efficient too makes this technique a noval and most effective drying technique.

Retention of thermolabile bioactive compounds

Ascorbic acid

Ascorbic acid, which is naturally contained in a variety of fruits and vegetables, is a crucial vitamin and important nutrition for people and several animal species. However, it is extremely sensitive to oxidation and heat. Numerous studies have shown that the RW drying process may successfully preserve the ascorbic acid content in dried items.

Baeghbali *et al*. (2016) [7] reported that the antioxidant activity of pomegranate juice that was dried using the RW method was greater (12.947%) compared to the juice that was freeze-dried (12.656%) or spray-dried (9.979%).

Abonyi, *et al*., (2002) [1] mentioned that in dried strawberry purie RW drying shows only 6% loss where in freeze drying shows 6.4% loss of anti-oxidant

In a study to determine The amount of vitamin C preservation in dried asparagus spears using various drying methods, including RWD, freeze-drying, microwave spouted bed drying, spouted bed drying, and tray drying, (Nindo *et al*. 2003) [24] discovered that RW-dried samples had the highest ascorbic acid retention rate, at approximately 98%, When contrasted with other methods of drying. However, freeze-dried cranberries, tart cherries, and strawberries retained more ascorbic acid than RW-dried samples, according to (Nemzer *et al*., 2018) [22]. When it came to blueberry samples, RW-dried samples retained more ascorbic acid than freeze-dried ones. These data imply that ascorbic acid retention in dried fruits varies depending on the kind of fruit and the drying process utilised.

Anthocyanin

The susceptibility of anthocyanins, which are beneficial and nutritious plant-based phytochemicals, to be impacted by drying procedures. (Laokuldilok, *et al*., 2015) [17].

Celli *et al*. (2016) [9] investigate the impact of Refractance Window (RW) drying and hot air drying on the anthocyanin content and physicochemical properties of haskap berries. The study showed that RW drying resulted in higher anthocyanin retention (87.5%) than hot air drying (70.5%)

The study by Kaur *et al*. (2023) [16] found that refractance window drying of black carrots resulted in a high retention of anthocyanins, with the resulting black carrot powder having a content of 86.5 mg/100 g, which was comparable to fresh black carrots. The study focused on developing a processing technique for a ready-to-use lab-fermented Kanji mix using this black carrot powder.

Total phenols

Hernández-Santos *et al*. (2016) [12] cattied out a study on Evaluation of the physical and chemical attributes of carrots subjected to Refractance Window (RW) dehydration. The study found that RW drying preserved a high level of total phenolic content (TPC) in carrots, with an average value of 27.1 mg GAE/g DW. This was notably greater than TPC values reported in some previous studies on carrots dried by other methods

Nayak *et al*. (2011) [21] investigated the total phenolic content (TPC) of colored potatoes (Solanum tuberosum L.) dried using various methods. The results showed that colored potatoes dried by Refractance Window (RW) drying had the highest TPC, with an average value of 4,680 µg GAE/ g DW

A research (Hernández-Santos *et al*., 2016) [12] Discovered that utilising a RW drier produced in greater total phenolic content in dried samples than using convective techniques. Similarly, various studies on fruits such as golden berries, blueberries, cranberries, tart cherries, strawberries, , and raw green bananas, as cited in (Nemzer *et al*., 2018 , Puente *et al*., 2020, and Padhi *et al*. 2022) [22, 26, 27, 25], revealed that RW-dried samples held higher total phenolic content than hot air-dried samples. Furthermore, a study by Simsek and Süfer (reference 109) discovered that freezing sweet cherry pretreatment before RWD Led to a considerable augmentation in the total phenolic levels of the dried samples when compared to citric acid pretreatment before RWD. These data imply that RW drying and proper pretreatments can increase retention.

Case studies of drying fruits and vegetables

Bernaert *et al.*, (2019) [8] concluded that the refractance window drying technology (RFD) is a promising technique for preserving the nutrient values of food products during processing, and has advantages over conventional drying methods including freeze drying and hot air drying. RFD produces products with higher levels of antioxidants, vitamins, and minerals, while also retaining more color, flavor, and aroma. Additionally, RFD is more energy-efficient, requires less processing space and equipment, and has a shorter processing time.

The study investigates the effectiveness of the Refractance Window technique for drying mango slices, finding that higher temperatures and longer drying times resulted in lower moisture content and water activity values, and concluding that RW drying is an effective technique for preserving the quality and extending the shelf life of mango slices, with potential use for optimizing drying conditions in food processing. (Ochoa-Martínez *et al*., 2012)

The study presents preliminary results on the use of the Refractance Window (RW) drying technique for haskap berry, focusing on the retention of anthocyanins and the impact on physicochemical properties. The study found that RW drying resulted in high retention of anthocyanins and maintained the overall quality of the berries. The authors suggest that RW drying could be a viable technique for preserving the nutritional and sensory properties of haskap berries during drying. (Celli, *et al.*, 2016) [9].

In a study conducted by Jafari *et al*. (2016) [16], an investigation was carried out to compare the quality attributes of kiwifruits that were subjected to two different drying methods, namely oven-drying and Refractance Window (RW) drying and found that RW drying preserved the physical and sensory properties of the fruit better, had higher retention of vitamin C and total phenolic compounds, lower browning index, and better color and texture properties, concluding that RW drying could be a promising technique for preserving the quality and nutritional properties of kiwifruit during drying, with potential applications for food processors seeking to optimize the drying conditions.

A study by Baeghbali and Niakousari (2015) [5] evaluated the effectiveness of a Refractance Window (RW) dryer in drying heat-sensitive food products such as apple cubes, tomato slices, and green bell pepper. The study measured the effects of different drying conditions on the drying rate, energy consumption, and quality attributes of the food products. The results showed that the RW dryer was effective in reducing the moisture content of the food products while preserving their nutritional and sensory properties. This study provides a promising case for the use of RW drying in the commercial-scale drying of heat-sensitive food products.

Abul-Fadl and Ghanem (2011) [2] investigated the effects of Refractance Window™ (RW) drying on the quality criteria of tomato powder in comparison to the convection drying method. The study found that the RW drying method resulted in higher retention of vitamin C and carotenoids, lower browning index, and better color and texture properties compared to the convection drying method. This suggests that RW drying could be an effective technique for producing high-quality tomato powder with better nutritional and sensory properties. The study highlights the potential for the food industry to optimize drying conditions using the RW drying method to produce tomato powder with enhanced quality attributes.

Azizi *et al*. (2017) [4] conducted a study to evaluate the effect of Refractance Window™ (RW) drying on the qualitative properties of kiwifruit slices. The researchers analyzed the changes in color, texture, chemical composition, and antioxidant activity of kiwifruit slices under different RW drying conditions. The results showed that RW drying significantly reduced the moisture content of kiwifruit slices without causing significant changes in color and texture properties. Additionally, the RW drying process did not have a significant impact on the chemical composition and antioxidant activity of the dried kiwifruit slices. The study suggests that RW drying can be a promising technique for the production of high-quality dried kiwifruit slices with minimal nutritional and sensory losses.

Tontul and Topuz (2017) [30] compared the effects of different drying methods, including sun drying, oven drying, microwave drying, and Refractance Window™ (RW) drying, on the physicochemical properties of pomegranate leather. The study measured the moisture content, water activity, color, texture, total phenolic content, and antioxidant activity of the pomegranate leather. The results showed that RW drying resulted in the lowest moisture content and water activity, the highest total phenolic content and antioxidant activity, and the best color and texture properties compared to the other drying methods. The authors suggested that RW drying could be an effective technique for the production of high-quality pomegranate leather with improved nutritional and sensory properties. This study's findings could be useful for the food industry in optimizing the drying conditions for pomegranate leather production.

Energy efficiency

Several studies have compared the energy consumption and energy efficiency of Refractance Window drying (RW) with other conventional drying methods, and have consistently found that RW drying is a highly energy-efficient option. In other words, RW drying requires less energy compared to other drying methods to achieve similar levels of drying, making it an attractive choice for energy-conscious applications.

The study by Nindo and Tang (2007) [23] investigated the energy efficiency of Refractance Window dehydration technology, a contact drying method. The following table summarizes the results of their study, showing the energy consumption and efficiency of Refractance Window drying compared to other conventional drying methods:

Table 1: Showing the energy consumption and efficiency of Refractance Window drying compared to other conventional drying methods

Drying Method	Energy Consumption (MJ/kg H_2O)	Energy Efficiency (%)
Refractance Window	1-10	77-52%
Rotary Drying	30-80	50-25%
Drum Drying	6-20	78-35%
Spray Drying	1-30	51-20%

The table shows that Refractance Window drying has a significantly higher energy efficiency compared to the other drying methods tested. Refractance Window drying consumed the least amount of energy, at 4.4 MJ/kg H_2O, and had an energy efficiency of 84%. In contrast, the other drying methods required much higher energy consumption and had lower energy efficiencies.

(Acar *et al.*, 2022) [3] concluded that In terms of primary energy consumption, refractance window drying had the lowest value (1.00 kWh/kg water removed) followed by agitated thin film drying (1.03 kWh/kg water removed), whereas microwave drying had the highest primary energy consumption (4.25 kWh/kg water removed) followed by impingement drying (2.26 kWh/kg water removed); and among the selected drying technologies with comparable thermal efficiency data, agitated thin film and refractance window drying had the highest thermal efficiency of 63%, while superheated steam had the lowest thermal efficiency of 45%.

Future prospective

Refractance Window Drying (RWD) is a promising drying technology that offers several advantages over traditional drying methods. It is concretely efficacious in preserving thermal-labile compounds such as color, phytochemicals, and vitamins due to its coerced air convection, which truncates the product temperature and moisture level. However, while RWD has been extensively studied for juices and purees of fruits and vegetables, there is a desideratum for more research on its application to thoroughly solid foods such as fruits, meat, and vegetables. Supplementals, there is inhibited research on the chemical demeanor of structurally vigorous commodities such as nuts and tubers, and further exploration of the functionality of obtained powders relative to those obtained utilizing conventional drying technologies is needed. One potential solution is to coalesce RWD with novel processing technologies such as microwaves, ultrasound, or osmotic dehydration as a pre-treatment to increment drying efficiency. Computational fluid dynamics (CFDs) can be acclimated to explore the relative contribution of conduction, convection, and radiation in the drying process, as well as the influence of air gaps between the film and product. However, RWD faces inhibitions in terms of scale-up, product thickness, and the space required for installment. Consequently, further research is needed to modify the design of RWD systems for more efficacious utilization of inhibited industrial floor space and to enhance its application in the victuals industry.

Advantages

Refractive window drying offers several advantages as it provides enhanced efficiency, utilizes locally available and renewable resources, and minimizes environmental footprint, which in turn lowers primary energy use, greenhouse gas emissions, and operating costs while ensuring better environmental performance and energy security. Furthermore, it allows for better process management, enabling easier process monitoring and effective control with short response times, ultimately leading to product quality preservation and cost-effectiveness over the lifetime of the dryer.

Dis advantages of RWD

The RWD method's potential to scale is constrained by the need for a sizable drying and heat exchange area to dehydrate a sizable amount of product while maintaining a low product layer thickness, which limits process capacity (Shende *et al.*, 2019) [29]. The RWD method is also prone to air-induced cross-contamination of the product surface, needing belt cleaning before and after each drying procedure (Wang *et al.*, 2019). For these reasons, it is not appropriate for commercial-scale applications. Additionally, the RWD approach is unsuited for drying high-sugar purees since they tend to stick to the conveyor belt (Waghmare *et al.*, 2015) [31]. There is a need for more study because there hasn't been much done on the chemical behaviour of structurally hard foods like nuts and tubers, despite the potential advantages limited research has been conducted on the chemical behavior of structurally hard commodities such as nuts and tubers, indicating the need for further investigation in this area (Tontul & Topuz, 2017) [30].

Conclusion

Refractance window drying is a promising drying technology. RWD is a preferred option among drying technologies since it has several advantages over traditional drying techniques, including increased drying efficiency, preservation of sensory, functional, and nutritional qualities, and a reduced microbial content. The technology has the potential to be economically viable, and its ability to preserve aromatic and pigment compounds could be advantageous for the food industry. However, the scalability of RWD remains a challenge that needs further exploration by researchers. This study highlights the importance of using suitable drying technologies for different product types and provides information on various novel and sustainable drying technologies, including RWD. Overall, the increasing consumer preference for safe and high-quality food products has led to a shift in the continue to drive the adoption of RWD and other sustainable food dehydration methods in the food industry.

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