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Evaluating the Potential of Refractance Window™ Drying Technology in Food Preservation: A Review of Current Research and Future Directions

A. A. Akinola[1*], I. O. Nwaze[2], R. U. Owolabi[2]
[1,2]Department of Chemical Engineering, University of Lagos, Nigeria
Email: aaakinola@unilag.edu.ng

Abstract

One significant issue facing developing nations is the preservation of agricultural products, especially during harvesting. Dehydration remains critical in food preservation as dried products are cost-effective, lightweight, and have an extended storage duration. However, traditional drying techniques are either time-consuming, energy-intensive, or degrading the product. In the quest for efficient and sustainable technologies to preserve and enhance the quality of agricultural produce, Refractance Window Drying (RWD) has emerged as a promising technique with vast potential that remains largely unexplored. This review introduces this novel technique, including its principles, unique advantages, efficacy compared to traditional drying methods, and potential application in dehydrating agro-products. By discussing the current challenges and future research directions of this innovative drying technique, this review contributes to the growing knowledge of advanced dehydration technologies and empowers the audience with practical insights for their adoption in the food industry.

Keywords: Food preservation, Dehydration, Refractance Window Drying

1.0 INTRODUCTION

The preservation of agro-products remains a critical challenge in the global food industry. According to the Food and Agriculture Organization of the United Nations (FAO), approximately one-third of all food produced for human consumption is lost or wasted annually, amounting to nearly 1.3 billion tons worldwide (Losses & Waste—Extent, 2011). Food preservation enhances food security by ensuring a more reliable and consistent yearly food supply. In many regions, agricultural production is seasonal, with peaks and troughs in harvest yields depending on weather conditions, soil fertility, and pest infestations. Without proper preservation methods, surplus harvests during peak seasons may go to waste, leading to scarcity and food insecurity during lean periods. By employing efficient techniques such as dehydration, food products can be preserved for extended periods, enabling a steady flow of food supply and reducing the vulnerability of communities to hunger and malnutrition (Mercer, 2014). Furthermore, this maintains product quality during transportation and distribution, ensuring consumers access to safe, healthy, nutritious food.

Drying technologies offer a viable solution for food preservation, particularly in Africa where agricultural challenges are prevalent. Drying removes moisture from produce, inhibiting microbial growth and enzymatic activity while preserving nutritional value (Amit *et al.*, 2017). Compared to other methods, drying requires minimal energy inputs and can be adapted to local conditions, making it suitable for small-scale farmers in rural areas. Additionally, dried products have a longer shelf life and are easier to transport and store, reducing post-harvest losses and improving market access (Kumar *et al.*, 2015). In terms of effectiveness, drying has also been shown to produce high-quality dried products with minimal loss of nutrients and sensory attributes.

Traditional drying methods such as sun drying, hot-air drying, and freezing drying have been widely used to extend the shelf life of perishable goods. However, many of these techniques come with significant drawbacks, including long drying times, high energy consumption, and degradation of nutritional and sensory qualities. As a result, there is a pressing need for innovative drying technologies that can overcome these limitations and enhance the efficiency and quality of food preservation processes (Vega-Mercado *et al.*, 2001).

A novel dehydration technique that promises to address many of the shortcomings of conventional methods is the Refractance Window drying (RWD) technology. The RW Dryer has emerged as a gentle drying method that accelerates the drying process and helps retain the nutritional and sensory attributes of the dried products. It operates on conductive, convective, and radiative heat transfer principles, utilizing a thin film surface to transfer heat from a hot water medium to the product being dried (Nindo and Tang, 2007). The potential of RWD to revolutionize food dehydration makes it a subject of significant interest and research within the food technology sector.

Although RWD shows considerable promise, extensive studies on its use across various agricultural products still need to be conducted. This review aims to investigate the feasibility and efficacy of RWD for dehydrating food products. This paper evaluates previous studies to understand the drying kinetics, energy efficiency, and quality attributes of products dried using RWD compared to those processed through traditional drying methods. Furthermore, existing studies were analyzed to explore the effects of critical process parameters such as temperature and product thickness to provide a comprehensive understanding of how RWD can be optimized for different types of produce.

The significance of this review extends beyond academic interest, as it has the potential to impact food security and sustainability. Effective dehydration methods can reduce post-harvest losses and extend the shelf life of produce, thus improving food availability and reducing waste. By addressing a critical need in the food industry for improved drying technologies, this paper aims to contribute valuable insights that can guide farmers and food industry professionals in adopting RWD to enhance their food preservation strategies.

This review aspires to advance the field of food dehydration and to provide practical solutions for efficient and high-quality preservation of agro-products.

2.0 MATERIALS AND METHOD

Refractance Window Drying (RWD) is a method that relies on the principles of conduction, convection, and radiation to efficiently dry various food products. The core of RWD involves a water-filled, transparent belt, typically made of Polyethylene terephthalate (PET). This belt allows for selective transmission of infrared radiation while effectively blocking the passage of water vapor, thereby creating a highly controlled drying environment (Raghavi *et al.*, 2018). The RWD is illustrated in Figure 1.

This heating surface, maintained at a specific temperature, facilitates heat transfer to the food items via the water layer, effectively creating a "Refractance Window" through which infrared energy is transmitted. As the material dries out, this "window" gradually closes, blocking thermal radiation and preventing the sample from reaching hot water temperature. When the product reaches the almost-dry stage of RW drying, conduction heat transfer takes over, and the rate of heat transmission to the product decreases as it dries further (Nindo and Tang, 2007).

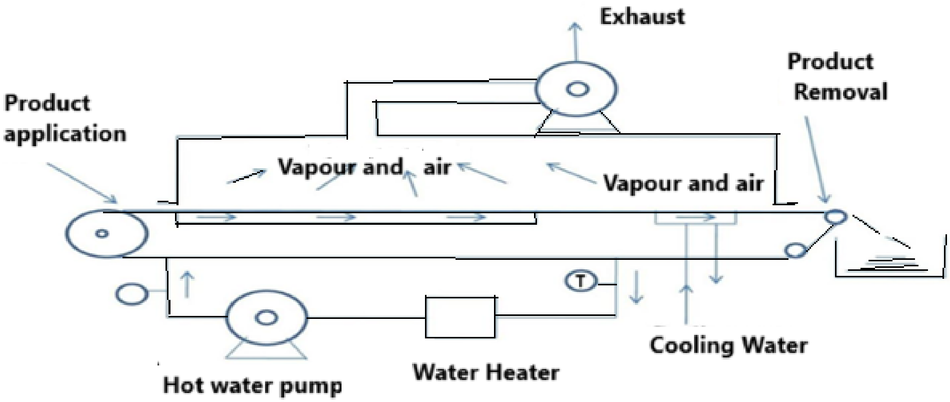

Figure 1: Schematic diagram of a Refractance Window^{TM} drying system (Abonyi *et al*., 2002)

This simultaneous use of the three modes of heat transfer results in rapid and uniform heating, significantly reducing the drying time compared to conventional methods like hot-air drying or freeze-drying (Nindo *et al*., 2006). Additionally, the process operates at relatively low temperatures, which helps preserve the nutritional and sensory qualities of the food, such as vitamins, flavour, and colour.

As the food items are heated through direct contact with the heated surface and radiative heat transfer, air is blown over the surface, removing the evaporated moisture from the food. This convective cooling mechanism not only enhances the drying rate but also prevents the overheating of food items, which can occur in methods that rely solely on high-temperature air (Abonyi *et al*., 2002). By maintaining an optimal balance between conduction, convection and radiation, RWD ensures that the dried products retain their structural integrity and nutritional value.

The RWD process is also notable for its energy efficiency. Water as a medium for heat transfer is significantly more effective than air due to water's higher specific heat capacity and thermal conductivity. This efficiency translates into lower energy consumption for the same degree of dehydration, making RWD an economically and environmentally advantageous option for small-scale farmers with limited resources and large-scale food processing operations (Nindo and Tang, 2007). Furthermore, the ability to control the drying parameters precisely allows for customization based on the specific requirements of different food products, further enhancing the versatility and applicability of RWD in the food industry.

In a study on pineapple slices and mango pulp drying, Namayengo *et al*. (2021) compared RWD, solar dryers, and box dryers. It was observed that, with the RWD's ability to self-regulate, product temperature and heat damage were kept at a minimum. The study demonstrated that the RWD could keep the dried fruits original color, and for every batch of pineapple flakes, the box dryer took 48 hours to dry, while the RWD took 2 hours, and the solar dryer took 10 hours. For a 10-hour production cycle, the throughput for the various dryers was determined to be 6 kg, 7.5 kg, and 0.5 kg for the solar, RWD, and box dryers, respectively. The RWD’s advantage over other dryers facilitates the creation of products with higher nutritional attributes. In addition, its capacity to regulate temperature enables it to achieve moisture content levels as low as 3–7%, which is not achievable with solar drying.

RWD emerges as a promising alternative to traditional drying methods, offering a good balance of efficiency, quality retention, and energy consumption. This method is particularly suitable for various foods due to its effectiveness with thin product layers and rapid drying capabilities. Sun drying, while inexpensive, is highly dependent on weather and is prone to product contamination. Hot-air drying is less efficient in time and energy and is more likely to degrade nutrients. Freeze-drying, although providing the highest quality dried products, is not economically feasible for large-scale operations due to its high energy consumption and prolonged processing times.

2.1 Preservation of Product Quality and Nutrients, Consistency and Uniformity

One of the most critical benefits of RWD is its ability to preserve the quality and nutritional content of dried products. The gentle drying conditions provided by the RWD helps retain the agricultural produce's natural colour, texture, and flavour, resulting in higher-quality dried products than traditional drying methods. Moreover, RWD minimizes nutrient loss by preserving heat-sensitive vitamins, antioxidants, and other bioactive compounds in fruits, vegetables, and herbs (Mandale *et al*., 2023). This preservation of product quality and nutrients increases the market value of dried products and significantly enhances their economic potential, fostering consumer acceptance and driving market growth.

In a notable study by Nemzer *et al.* (2021), the effects of Freeze drying, RWD, and hot air drying techniques on the preservation of the phytochemical and physical properties of blueberries, tart cherries, strawberries, and cranberries were investigated. It was observed that, in comparison to FD and hot air-dried products, RW-dried cranberry and strawberry samples exhibited higher overall vitamin B retention.

Another comparison between Refractance Window^{TM} drying and conventional methods, such as tray and oven drying at 95 °C and 2.5 mm mango pulp thickness, was conducted by Shende in 2020. As a result, the Refractance Window-dried mango leather produced was of higher quality and retained more nutrients. Furthermore, the mango powder's SEM microstructure examination revealed that RW drying results in powder particles with a consistent thickness, smooth surface, and regular shape, while mango powder produced via tray and oven drying resulted in particles with an uneven thickness and form as well as a corrugated, irregular, and crinkled surface (Shende and Datta, 2020).

Furthermore, Caparino *et al.* (2012) examined the impact of drum drying, spray drying, RW, and freeze-drying methods on the microstructures and physical characteristics of mango powders. The study's findings were clear: RWD can produce mango powder of a quality that surpasses that of spray drying and drum drying, and is on par with freeze-drying, demonstrating RWD's versatility and effectiveness in different food preservation applications.

2.2 Lower Energy Consumption

One significant advantage of RWD is its reduced energy consumption compared to conventional drying methods. RWD operates at lower temperatures, typically between 40°C and 80°C, significantly reducing the energy required for the drying process (Da Costa *et al*., 2019), unlike hot air drying, which relies on high temperatures to facilitate moisture removal. This results in energy savings and lower operating costs. In a study by Baeghbali *et al*., (2010), tomato juice, tomato ketchup, aloe vera gel, and carrot puree were dehydrated by RWD system and freeze-drying methods. The total energy consumption for dehydrating a 150 g batch required only 375-525 W by RWD system, which was considerably lower than 70-84 kW for freeze drying. This indicates that the RWD is an efficient choice.

Acar *et al*. (2022) also reported that Refractance window drying had the lowest primary energy consumption in drying various foods (1.00 kWh/kg water removed), followed by agitated thin film drying, while Microwave drying had the highest primary energy consumption (4.25 kWh/kg water removed).

2.3 Rapid Drying

Despite operating at lower temperatures, RWD offers rapid drying rates, ensuring efficient moisture removal while minimizing processing time. The unique design of the RWD system, with its polymeric film window and controlled infrared radiation, facilitates uniform heat distribution. This means that the heat is evenly spread across the drying surface, accelerating the drying process and ensuring that all parts of the material dry at the same rate (Padhi *et al*., 2022). RWD's rapid drying capability benefits small-scale farmers in rural areas who must preserve their harvest quickly to prevent spoilage and minimize post-harvest losses.

A comparative study of the drying kinetics of asparagus purée using tray and RW drying techniques was published by Nindo *et al*. (2006). For tray drying and RWD, residence periods of 3.5 and 0.074 hours were needed, respectively, to achieve a moisture content of less than 0.1 (DB). Similar outcomes were reported by Nindo *et al*., (2006) for drying pumpkin purée and Abonyi *et al*., (2002) for drying carrot and strawberry purées. These outcomes show that the RW approach may effectively dry fruit and vegetable slices by minimizing the time. Furthermore, the rapid drying rates offered by RWD enable manufacturers to increase production throughput and meet market demands more efficiently, making them feel more competitive and successful in their industry.

Another research study by Nindo and Tang examined the Refractance window drying of strawberry puree and discovered that the product dried in 5 minutes instead of several hours for other drying methods, such as tray drying and freeze-drying of the same material. The water was maintained at 95 °C, and the puree had a thickness of around 1 mm. The product interacts with oxygen less because of the quick mass transfer procedure, which preserves the product's quality (Nindo and Tang, 2007). This emphasis on quality preservation through RWD should reassure manufacturers and farmers about the reliability of this technique, instilling a sense of confidence in its effectiveness.

In an assessment of the impact of various drying techniques, including refractance window drying (RWD), hot air drying (HD), freeze-drying (FD), and vacuum drying (VD), on qualitative attributes like crude fibre, ash content, and color, of a banana variety known as Malbhog by Dadhaneeya *et al*., (2023), the average drying time in RWD, HD, FD, and VD was 760 minutes, 930 minutes, 1125 minutes, and 975 minutes at drying temperatures of 60 °C, 60 °C, 40 °C, and 60 °C, respectively. Compared to hot air-dried and vacuum-dried samples, RWD-dried samples obtained a higher quality product and significant colour retention.

3.0 EFFECT OF PROCESS PARAMETERS IN REFRACTANCE WINDOW DRYING

In Refractance Window Drying (RWD), several process parameters play crucial roles in determining the efficiency and effectiveness of the drying process. Studies have reported that the significant process parameters include water temperature, product thickness, and residence time, which have been shown to influence the drying rate.

3.1 Water Temperature

The water temperature in an RWD refers to the water circulating beneath the polymeric film. Usually, the water's temperature is between 70-90°C, enabling rapid drying while preserving nutritional and sensory qualities. This temperature range is optimal for minimizing the degradation of heat-sensitive nutrients and maintaining the colour and texture of the dried products (Nindo and Tang, 2007). In contrast, hot-air drying relies on convective heat transfer, which is less efficient. This results in longer drying times and potential nutrient degradation due to prolonged exposure to heat. Freeze-drying operates at very low temperatures (-40 to 30°C), which is excellent for preserving nutrients but is highly energy-intensive and slow. Zotarelli *et al.* (2015) indicate that the rate of RW-drying increases 1.7 times when the water temperature rises from 75 to 85 °C and doubles when the temperature increases from 85 to 95 °C.

A significant study by Castoldi *et al*. (2014) investigated the drying of tomato pulp using different heating water temperatures (65°C, 75°C, 85°C, and 95 °C), and the shortest drying time (17 minutes) was observed at the highest drying temperature. This indicates that the temperature of the water bath significantly influences how quickly the product is drying.

However, higher water temperatures can accelerate moisture removal but may also lead to thermal degradation of the product. The optimal water temperature should be determined based on the specific requirements of the product being dried.

3.2 Product Thickness

The thickness of the product layer placed on the polymeric film also plays a significant role in the RWD process. The product's thickness determines both the uniformity and the rate of drying.

Research has consistently shown that RWD is most effective with thinner product layers (1-3 mm), ensuring quick and uniform drying (Nindo *et al*., 2006). This knowledge provides food scientists and industry professionals with the best practices in food drying. Hot-air drying can handle slightly thicker layers (3-5 mm), but the drying rate decreases with increased thickness, risking uneven drying and potential spoilage. Freeze-drying can process even thicker layers (5-10 mm) while maintaining product quality, though at the expense of increased drying time and energy consumption (Kumar, 2015).

A study on mango pulp drying found that the drying rate for 2 mm thickness was 4.9 times higher than that for 5 mm thickness at the same water bath temperature. Additionally, the authors observed that, while 5 mm thickness pulp took 60–80 minutes to dry, 2 mm thickness pulp dried in about 15–20 minutes (Zotarelli *et al*., 2015).

Another significant case study by Ocoró-Zamora and Ayala-Aponte (2013), dehydrated papaya puree at 2mm, 3mm, and 5mm thicknesses, and after 60 min drying, the moisture content measured was 6.52, 11.32, and 26.24% respectively. The significant difference in moisture content indicates that product thickness dramatically influences the rate of water removal, a crucial factor in the drying process. This enlightening information can guide researchers and industry professionals in optimizing their drying techniques.

Similarly, Castoldi *et al*. (2015) investigated the RW-drying of tomato powder and concluded that when the sample thickness changed from 2 to 3 mm and the water temperature reached its greatest point (95 °C), the time needed to attain the ultimate moisture content (3% dry basis) increased by almost 30%. The increased product thickness increases resistance to heat conduction and mass transfer by regulating the removal of water vapor from the drying pulp. It reduces the effect of infrared radiation on drying.

Additionally, Zalpouri *et al*. (2023) dehydrated Onion puree using the Refractance Window dryer. The research suggested that the thickness of onion puree significantly affected the physicochemical quality of the dried onion powder. In terms of physicochemical quality and drying time, 2 mm thick samples produced the best-dried onion powder when compared to 4 mm and 6 mm thick samples.

Ochoa-Martínez et al. (2012) studied the effect of product thickness. In this research, Mango slices dried by tray drier (62°C) and RWD (92°C) were compared to determine the impact of slice thickness (1 and 2 mm), drying duration, and their interaction on water activity and color parameters. It was determined that the sample thickness significantly affected the water activity for both drying processes.

The results indicated that thinner slices exhibited faster drying rates compared to thicker slices. This can be attributed to the shorter diffusion pathways for moisture removal in thinner slices, leading to more efficient dehydration. Therefore, controlling the thickness of the product is crucial for achieving uniform drying and minimizing processing time. This practical advice empowers researchers and industry professionals to optimize their drying processes for efficient moisture removal while maintaining product quality.

3.3 Residence Time

Residence time, the product's duration in contact with the plastic film during drying, is a critical parameter in RWD. It directly impacts the extent of moisture removal and the final quality of the dried product. The product's drying time is mainly determined by the hot water's temperature, the product's thickness, and the airflow over it. Therefore, selecting the ideal drying duration is crucial for producing high-quality products (Mahanti et al., 2021). In addition to energy efficiency and operating at lower temperatures, RWD has been shown to achieve faster drying rates compared to traditional drying methods. The short residence time of RWD (0.5-1.5 hours) is due to its highly efficient heat transfer mechanism, which minimizes nutrient loss and maintains the sensory quality of the dried products (Abonyi et al., 2002). In comparison, hot-air drying requires significantly longer residence times (4-10 hours) as convective heat transfer is less efficient, leading to uneven drying and a higher risk of microbial growth. Freeze-drying has the longest residence time (20-48 hours) because of its slow sublimation process.

4.0 EFFECT OF REFRACTANCE WINDOW DRYING (RWD) ON QUALITY PARAMETERS

Food quality indicators, such as color, water activity, proximate composition, vitamins, and mineral content, are crucial in the evaluation of food products. It's reassuring to note that Refractance window-dried food products show minimal impact on visual quality, as demonstrated by existing studies. These products also exhibit significant reductions in water activity, thereby enhancing preservation potential and reducing microbial growth risk. Proximate composition analysis of RW-dried products further confirms their effectiveness, with good proteins, fats, carbohydrates, and fiber retention, and only minor reductions in vitamin and mineral content.

Pavan *et al.*, (2012) conducted a comparative study on the effects of Refractance window drying, freeze drying, and hot air drying on the quality of Açaí berry fruit juice. The RW-dried samples exhibited a moisture content of 2.19 g/100 g (wb), which is lower than monolayer values, indicating robust product stability.

In a similar study by Santos *et al.*, (2020), the physico-chemical composition of powder obtained from refractance window drying and freeze drying of purple yam paste was investigated. The results showed a significant increase in the quantities of proteins, lipids, ash, carbs, total starch, acidity, and soluble solids. This substantial increase in nutritional content demonstrates the effectiveness of Refractance window drying.

A different study assessed several qualities after drying unripe green banana flour (UGBF) using a hot air oven dryer and a Refractance (RW) dryer. The dried UGBF of RW and hot air had water activity of 0.28 ± 0.05 and 0.39 ± 0.07, respectively. The proximate analysis showed that RW-dried samples had lower water activity, Moisture content and higher Protein, fat, Ash, Fibre, and carbohydrate than hot air-dried samples (Padhi *et al.*, 2022).

In another notable study (Puente *et al.,* 2020), the pulp of goldenberries (Physalis Peruviana) was dried at 70 °C using refractance window drying. The study evaluated several qualitative attributes and compared the outcomes with freeze-drying, convective, and infrared radiation drying. The results revealed that Refractance window drying consistently produced a high-quality product, reassuring the audience of its effectiveness and potential in food processing, even under conditions of extended drying time.

However, following drying, there was a noticeable ($p < 0.05$) increase in the amounts of fat, ash, protein, and crude fibre in the pulp's proximate composition. This increase in nutritional components is a significant benefit of Refractance Window drying, as it enhances the nutritional value of the food product.

Similarly, Abonyi *et al.* (2002) researched the impact of Refractance Window drying on preserving strawberry and carrot puree quality. In strawberry purees dried by RW drying, vitamin C retention was 94%, similar to 93.6% in freeze-dried samples.

In their 2023 study, Zomorodi and Hedayat compared the RW method, hot air oven drying, microwave drying, and sun drying in reducing fresh tomatoes to tomato powder. Notably, the samples dried by microwave and RW techniques exhibited significantly higher vitamin C content than those dried by sun and hot air methods. This significant difference in vitamin C content underscores the importance of the study's findings and the potential of the Refractance Window method as a superior alternative to hot air and microwave drying.

5.0 SUMMARY

Refractance window drying (RWD) is an innovative dehydration technique that has garnered increasing attention for its potential benefits in preserving various food products. Several empirical studies have explored the efficacy of RWD, highlighting its advantages compared to traditional drying methods and identifying areas for further research.

Refractance Window^{TM} Drying technology has been applied to a wide range of fruits and vegetables and has shown promise in preserving the nutrients of these perishable foods. One of the fundamental studies in the field of RWD was conducted by Ochoa-Martinez *et al*., (2012), which investigated the drying kinetics and quality attributes of mango slices. Their findings demonstrated that RWD resulted in shorter drying times compared to conventional methods such as tray drying. Moreover, the dried mango slices were of higher quality, included more nutrients, and exhibited superior color retention. An empirical investigation by Shende and Datta (2020) examined the application of RWD for drying fruit pulps and found that it resulted in more uniform drying across the product surface, regular shape, smooth surface with uniform thickness, and improved product quality and shelf stability. This indicates the potential of RWD in preserving the quality of fruits.

Similar research by Topuz *et al*., (2009) carried out a comparative study on the drying performance of paprika using RWD, freeze drying, hot-air oven drying, and natural convective drying methods. Their results indicated that RWD achieved comparable quality in terms of colour, texture, and nutrient content to freeze drying while offering faster processing times and lower energy consumption. This suggests the potential of RWD as a cost-effective alternative to freeze-drying for vegetable preservation.

Hernández-Santos *et al. (*2016) highlighted the ability of RWD to preserve the nutritional value of roots in a study that specifically investigated the effect of Drying temperature, Slice thickness, and PET film on Refractance window drying of Carrot slices. RWD was observed to maintain higher levels of nutrients and flavor compounds in the dried root vegetable than in convective drying. This study's specific focus on carrot slices underscores the relevance of RWD in preserving the nutritional value of root crops during the drying process.

Further empirical evidence supporting the effectiveness of RWD comes from studies by Akinola, which examined the application of RWD for drying root tubers, including yam, cassava, and potatoes. These studies revealed that RWD reduced drying time considerably in comparison to a more traditional technique such as sun-drying (Akinola and Ezeorah, 2016, 2017, 2018, 2019). In addition to its effectiveness in preserving the quality of food products, RWD has also been recognized for its energy efficiency and sustainability benefits. Baeghbali *et al*., (2016) conducted an energy consumption assessment of RW-drying of pomegranate juice compared to conventional drying methods such as freeze and Spray drying. It was found that RWD significantly reduced consumption, making it a more sustainable option for large-scale drying operations and contributing to environmental sustainability in the food industry.

Advancements in RWD technology have led to innovative drying systems tailored for specific food products. For example, in two different studies carried out in 2020, Puente-Diaz *et al*. and Rajoriya *et al*. studied the influence of an Infrared-assisted Refractance window dryer during the dehydration of Physalis fruit and apple slices, respectively. The main findings suggested that using IR-assisted RW drying effectively accelerates the drying process, which decreases drying time by around 60% while significantly retaining a higher amount of nutrients.

Furthermore, several researchers have explored using alternative or non-conventional energy resources to power the Refractance window equipment. Santos *et al*., (2022) and Zalpouri *et al*., (2020) suggested integrating RWD with renewable energies such as solar or biomass, allowing more energy efficiency and cost savings while leveraging environmental capabilities.

Research efforts have been directed towards scaling up RWD technology for commercial applications. Namayengo *et al*., (2021) conducted a Techno-Economic Analysis of refractance window drying for fruits and evaluated large-scale RWD systems' feasibility and economic viability. Their findings indicated that RWD could be successfully implemented commercially, offering cost-effective and sustainable solutions for food processing industries.

Overall, the empirical evidence presented in these studies highlights the versatility, efficiency, and potential of refractance window drying as a novel and viable technology for dehydrating food products. Its ability to preserve nutritional and sensory qualities while improving energy efficiency and sustainability makes it a promising solution in food processing. While the empirical evidence points to numerous advantages of RWD, challenges and limitations have also been identified. For instance, optimizing the process parameters such as temperature, airflow rate, and product thickness for different types of produce requires further research to achieve the best results and facilitate broader adoption.

6.0 CURRENT CHALLENGES

1. Refractance window drying (RWD) holds a significant promise for preserving roots, fruits, and vegetables. Despite several challenges, its potential for widespread adoption and optimal utilization in the food industry remains a reason for optimism. One of the primary challenges is the energy source in RW drying. While most developed Refractance window dryers rely on conventional energy sources for water boiling operation, these must be substituted with renewable, inexhaustible energy sources, such as Solar, biomass, or biogas, for low-cost, sustainable heating. This shift not only makes the system more eco-friendly but also reduces operational costs and dependence on non-renewable resources, thereby making RWD more attractive for widespread adoption (Zalpouri *et al*.,2020). Furthermore, there is a pressing need for more research on the drying of solid items using RWD. The current abundance of literature on the drying of juices and purees of fruits and vegetables leaves a significant research gap that needs to be urgently addressed. An

examination of the literature also reveals the necessity for further research into the optimization of RWD parameters to improve drying effectiveness and product quality. Some studies have examined how specific variables such as temperature, product thickness, and airflow affect the drying kinetics of certain food products. These thorough studies consider that the interaction between these multiple parameters still needs to be completed (Niakousari, 2018). Additionally, limited research focuses on the effect of radiant source and film thickness (Zotarelli *et al*., 2015). Addressing these gaps would facilitate the development of robust guidelines for optimizing RWD processes tailored to the specific characteristics of each product.

2. As RW drying is a relatively new technology, a large portion of the currently available literature only compares the physicochemical quality of the products obtained through RW with those produced through conventional processes (Abonyi *et al*., 2002; Ochoa-Martínez *et al*., 2012). The role of heat and mass transfer mechanisms during drying has received very little research attention (Nindo and Tang, 2007), and There have been no controlled studies that compare the individual contribution using conduction, convection and radiation ways of heating the product while drying (Karate *et al.,* 2022). With the use of Computational fluid dynamics (CFDs), a thorough understanding of the complex underlying mechanics of heat and mass transmission and the inexplicable influence of air gaps that emerge between the film and the product during drying can be gained (Raghavi *et al*., 2018).
3. Currently, the emphasis is on combining RW-Drying with cutting-edge pre-treatment technologies like ultrasound, microwaves, or osmotic dehydration. However, much uncertainty still exists about the effects of the pre-treatment before RWD. Investigations on the effect of Pre-treatment on the quality of dried products needs to be investigated, particularly when it comes to foods with high initial moisture content that are sensitive to heat (Mahanti *et al*., 2021).
4. Extensive research is also required to understand the impact of RW drying on compounds and elements in food products, such as lipids, proteins, carbohydrates, minerals, and bioactives. More studies are needed on how these individual components respond to RW drying, which highlights the necessity for further investigation into this topic (Waghmare, 2021).
5. While a few studies have looked into the effect of RWD on the physicochemical characteristics and sensory qualities of particular food products, like berries or leafy greens, there remains a lack of systematic investigation into the impact of RWD on dairy products such as milk (Karate *et al*., 2022). Therefore, there is a solid need for comprehensive comparative analyses between RWD and conventional drying methods across different types of produce. These analyses should assess their respective advantages and limitations in preserving nutritional value, flavor, texture, and shelf-life, thereby providing a clear direction for advancing knowledge in this field.
6. Another significant limitation of the RWD is the lack of scale-up and the large area occupied by film. While scalability remains a big challenge, most of the published research papers are performed on lab-scale batch dryers, and only a few studies have looked into the possibility of a scale-up. Therefore, more research is required in RW drying optimization for operating conditions for scale-up to continuous large-scale dryers in order to maximize its application in the food industry (Shende and Datta, 2020).
7. While RWD has shown promise in preserving the nutritional content of roots compared to conventional drying methods, there remains a lack of studies assessing the variation in water activity with dehydration time; color changes with dehydration time, changes in

thermodynamic properties of products during dehydration, determination of the energy required for dehydration, and evaluation any food quality changes due to dehydration by performing a proximate analysis, mineral content and vitamin content analysis. Given the potential impact of RWD on nutrient retention and the importance of nutritional quality in promoting consumer health and well-being, future research should prioritize investigating these aspects to ensure the delivery of nutritious and safe food products to consumers.

Addressing these gaps through systematic research efforts will contribute to advancing knowledge and understanding of RWD as a promising drying technology in the food industry.

7.0 FUTURE SCOPE AND PERSPECTIVE

Applying Refractance Window drying (RWD) to preserve food products presents numerous avenues for future research and development. As the global demand for high-quality, shelf-stable food products continues to rise, advancing the understanding of RWD could significantly impact food preservation technologies. This could lead to the development of new, more efficient drying processes, thereby increasing the availability of high-quality food products and potentially reducing food waste.

One key area for future research is the urgent and significant exploration of RWD for a broader range of agricultural products, such as roots. This understanding is not just important, but crucial for the future of food preservation. In addition to characterizing drying kinetics, the scope of experiments should be expanded to investigate changes in water activity and colour over dehydration time, variations in thermodynamic properties, the energy required for dehydration, and a comparison of nutritional content in fresh and dried roots. Expanding the scope of RWD applications can provide valuable insights into its versatility and adaptability, encouraging its use across diverse food industry segments.

Another promising direction for future research is using advanced computational systems such as machine learning techniques like Artificial Neural Networks (ANN) for effective modelling, prediction and optimization of RWD operating parameters. Understanding the relationship between the inputs and outputs of non-linear phenomena, such as drying, will ensure a more controlled environment and efficient dehydration (Aghbashlo *et al*., 2015). Furthermore, studies have indicated that food products' drying kinetics and quality attributes can be significantly influenced by temperature, airflow rate, product thickness, and drying time (Kumar *et al*., 2015). Further investigation into these parameters can lead to developing a more effective drying process, making RWD more attractive for commercial adoption.

The future scope of Refractance window drying is vast and promising. However, it is important to remember that continued innovation and collaboration are not just beneficial, but essential to meeting the evolving needs of the global food industry. Each of us, as researchers and professionals in this field, plays a crucial role in ensuring the availability of high-quality food products.

8.0 CONCLUSION

Refractance Window drying (RWD) represents a significant advancement in food dehydration, offering a promising alternative to traditional drying methods. The unique mechanism of RWD, which combines conductive, convective, and radiative heat transfer, facilitates faster drying times, reduces energy consumption, and enhances the retention of nutritional and sensory qualities in dried products. Its ability to operate at lower temperatures compared to traditional methods also helps to preserve sensitive nutrients, making it particularly suitable for high-value food products.

This review has explored the efficacy of RWD in comparison to conventional drying techniques, highlighting its potential benefits and addressing its current limitations.

Despite its advantages, the adoption of RWD in commercial settings is still in its nascent stages. To facilitate broader application, challenges such as its exploration in the preservation of root tubers need to be addressed. Future research should investigate the changes in water activity (a characteristic of food safety) and nutritional content of dehydrated root tubers.

RWD offers a viable and innovative solution with significant potential to improve food preservation practices. A continuous investigation of this technology, particularly its potential to reduce post-harvest losses, will contribute to food security. This review provides a solid foundation for further exploration and development of RWD, paving the way for its successful integration into commercial food processing operations.

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