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A review on refractance window drying of fruits

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Abstract
Drying of fruits is one of the preservation technique used to remove moisture from the product which results in retardation of spoilage causing microbes as well as chemical reactions. Refractance Window Drying (RWD) is an innovative and efficient drying technique that preserves the nutritional value and quality of fruits more effectively than traditional drying methods. RWD utilizes a unique heat transfer mechanism that involves conduction, convection, and radiation, enabling rapid moisture removal while maintaining the bioactive compounds in the fruit. This method is particularly advantageous for its energy efficiency, consuming 28-38% less energy compared to conventional dryers such as hot air, freeze, and spray drying. This significant reduction in energy usage not only lowers operational costs but also minimizes environmental impact. RWD has been shown to preserve vital nutrients, including vitamin C, antioxidants, and phenolic compounds, which are often degraded in other drying methods. Additionally, the shorter drying time associated with RWD helps in retaining the colour, aroma, and texture of the dried fruits, making them more appealing to consumers. The technology has been successfully applied to a variety of fruits, demonstrating superior retention of nutritional and sensory properties. Future advancements in RWD technology aim to integrate renewable energy sources, such as solar power, to enhance sustainability and further reduce the environmental footprint of the drying process. In conclusion, RWD presents a promising alternative to traditional drying methods, offering substantial benefits in terms of energy efficiency, nutritional preservation, and product quality.

Keywords: Drying, efficient, fruits, product, quality, refractance window, temperature

Introduction
A substantial amount of moisture ranging from 80 to 95% is found in fresh foods such as fruits and vegetables. The high moisture content of these foods is however one of the primary reasons why they decay so rapidly, which leads to significant losses and waste of food (Raghavi *et al*., 2018) [64]. Drying is a time-bound preservation method that has been utilized by humans for ages (Dhiman *et al*., 2021) [22]. A further alternative for addressing this issue is to make use of drying. The process of drying effectively decreases the growth ofmicroorganisms and increases the rate at which chemical reactions occur, all while maintaining the food's nutritious integrity (Kumar *et al*., 2022) [39]. Many possibilities exist in realizing drying technology, including sun drying where the product is exposed to direct sun in the open air, hot air drying (convection) technology, high technological and developed patented dryer products, combination of the two technologies and other environment friendly various technology that cause less harm to the environment.

The design of technologies for energy efficiency and utilization of the opportunities of the environment is still gaining much attention today (Maraveas *et al*., 2021) [47]. Industrial drying equipment is used to a great extent within food processing sectors and apparently a considerable amount of energy is used in this sector (Shende and Datta, 2018) [69]. Earlier, the largest part of the energy needed for these systems was supplied with the help of fossil fuel, being the major emitting causing the greenhouse effect (Gruda *et al*., 2019) [27].

The Refractance Window (RW) Drying is one of the technologies that become the focus when it comes to the choices that can be made. Altogether, this method is not very old, however it has several advantages. The drying ratio is relatively short, the bioactivity is retained and the energy and heat energy ratios are high. In addition, it is a procedure that is simple and clear (Bernaert *et al*., 2019) [12]. In a research carried out by Raghavi *et al*., (2018) [64], the procedures associated with the dehydration of asparagus were the subject of an

experiment. Specifically, in 5 minutes only, the moisture level of the plant reduced from 90% to only 4%. This finding shown that about a faster rate at which asparagus can dehydrate in terms of moisture content. The short processing time helps in maintaining the quality elements as colour and aroma among others which are required by law (Raghavi *et al*., 2018) [64]. Compared to a traditional concentrator, it has been found out that milk dehydration reduces the time for processing to a great extent to approximately 61% (Al-Hilphy *et al*., 2020) [5]. Studies have further shown that the RW dryer consumes approximately 28-38% less energy in comparison to traditional dryers (Acar *et al*., 2020) [1]. As compared with the conventional methods of preservation such as freeze drying, RWD was found more effective. Active agents like vitamin C, antioxidants and phenolic compounds were observed to be better preserved by RW (Celli *et al*, 2016) [16].

Refractance Window Drying (RWD) is an innovative drying technique specifically designed to preserve the quality and nutritional value of fruits (Bernaert *et al*., 2019) [12]. This technology utilizes a unique heat transfer mechanism involving conduction, convection and radiation, allowing for rapid and efficient moisture removal. Unlike conventional drying methods, RWD maintains the bioactive compounds in fruits, which are often degraded during traditional drying processes such as hot air drying, freeze drying and spray drying (Belwal *et al*., 2022) [11]. RWD technology involves the use of a transparent polymeric film placed over a hot water bath. The fruit to be dried is spread in a thin layer on top of the film. Infrared energy from the hot water is transmitted through the film to the fruit, causing moisture to evaporate rapidly while minimizing thermal damage (Pawar and Pratape, 2015) [62]. This method is highly energy-efficient, consuming significantly less energy compared to conventional drying methods. Studies have shown that RWD can reduce energy consumption by 28-38%, making it a more sustainable option for industrial-scale drying processes (Hnin *et al*., 2018) [29]. The high efficiency of RWD not only reduces operational costs but also minimizes the environmental impact associated with drying processes (Karam *et al*., 2016) [36]. Additionally, the rapid drying time helps in retaining the colour, aroma and texture of the fruits, enhancing their market value. Various fruits such as mango, jackfruit and dragon fruit have been successfully dried using RWD, showing superior retention of nutritional and sensory properties compared to other drying methods (Nwankwo *et al*., 2023) [56]. In summary, RWD offers a promising alternative to traditional drying techniques by combining high energy efficiency with excellent preservation of fruit quality. Future advancements aim to integrate renewable energy sources into the RWD process, further enhancing its sustainability and reducing its environmental footprint.

Indeed, the RW approach reveals a lot of potentiality as a drying option. However, there are some parts which can be considered for revisions to make it more appropriate for industrial use. For instance the search for another source of energy that can be used to power the equipment. This paper aims at shedding light on the most recent developments and the possibility of integrating such technologies with the RW approach or other newly developed solutions like ultrasonic and infrared energy or other new created systems. As a result, the objective of this research is to introduce a set of probable enhancements that may be added to the RW approach and does provide a brief consideration of the future trends regarding the application of the renewable energy in drying techniques.

Principle of RWD technology and its applications for drying fruits

Refractance Window Drying (RWD) operates on a unique principle that combines conduction, convection, and radiation to efficiently dry fruits (Akinola *et al*., 2023) [4]. In this process, a transparent polymeric film is placed over a hot water bath. Fruits are spread in a thin layer on top of this film (Yoha *et al*., 2023) [74]. The heat from the water is transferred through the film to the fruit, causing rapid moisture evaporation while preserving the bioactive compounds (Chen *et al*., 2024) [18]. This method stands out due to its energy efficiency and shorter drying times compared to conventional methods like hot air and freeze drying. RWD is particularly effective in retaining essential nutrients such as vitamin C, antioxidants, and phenolic compounds, which are often degraded in other drying processes (El Gamal *et al*., 2023) [24]. Applications of RWD in fruit drying include mango, jackfruit and dragon fruit, where it has shown superior retention of nutritional and sensory properties (Islam *et al*., 2024) [31]. Moreover, its integration with renewable energy sources like solar power can further enhance sustainability, making RWD a promising technology for industrial-scale drying with reduced environmental impact.

Heat Transfer Mechanism in Fruits for Drying with RWD Technology

Refractance Window Drying (RWD) employs a unique combination of conduction, convection, and radiation to effectively dry fruits. The process involves placing a thin layer of fruit puree or slices on a transparent polymeric film that floats on a hot water bath (Mwaurah *et al*., 2022) [49]. Heat from the water is conducted through the film to the fruit, causing rapid evaporation of moisture. Initially, all three modes of heat transfer occur: conduction from the hot water through the film, convection within the moist fruit and radiation through the "refractance window" created by the water content of the fruit (Cunha *et al*., 2024) [19]. As drying progresses, the moisture in the fruit decreases, reducing the window for infrared energy transfer and thereby gradually lowering the heat transfer rate (Pal *et al*., 2023) [59]. This controlled heat transfer helps in minimizing thermal degradation and preserving the nutritional and sensory qualities of the fruit. Studies have shown that this method not only enhances energy efficiency but also significantly retains vital nutrients such as vitamins, antioxidants, and phenolic compounds, which are often compromised in other drying techniques (Fernandes and Rodrigues, 2023) [25].

According to (Manyatsi *et al*., 2022) [45], all three heat transfer methods- conduction, convection and radiation occur in the heating of water. The loss of heat or energy from water to its surroundings happens primarily through conduction and evaporation, with convection and radiation being internal processes (Zalpouri *et al*., 2022) [75]. When a transparent layer of material is placed on the surface of water, the energy loss can only take place by means of conduction. Moisture in a moist raw material generates a "window" that lets infrared energy pass through the material (Pateiro *et al*., 2022) [60].

It has been observed that heat behaves as if there were no membrane present and is directly transferred to the water

remaining in the material. At this stage, all three methods of heat transfer can occur, inducing very rapid heat transfer into the product and rapid evaporation of moisture (Fig. 1). As explained by (Duan *et al*., 2015) [23], this "window" gradually closes as the product loses moisture, leading to a decrease in heat transfer. Subsequently, the "window" of infrared energy closes and "refracts" back into the heated water source, no longer exposing the material to heat (Baeghbali *et al*., 2010) [9] (Fig. 1).

The research conducted by (Baeghbali *et al*., 2010) [9] indicates that this process has an inbuilt regulator, which assists in the entrapment of flavour and in maintaining high-quality standards. This novel mechanism has significant implications for the drying of fruits and other heat-sensitive products, as it allows for rapid but controlled heat transfer, ultimately contributing to the preservation of product quality (Baeghbali *et al*., 2010) [9]. The refrigerated window drying process provides a unique approach to maintaining flavour and quality in dried fruits and other food products. Its ability to regulate heat transfer and minimize exposure to external environments makes it a promising method for enhancing food processing technologies (Baeghbali *et al*., 2010) [9].

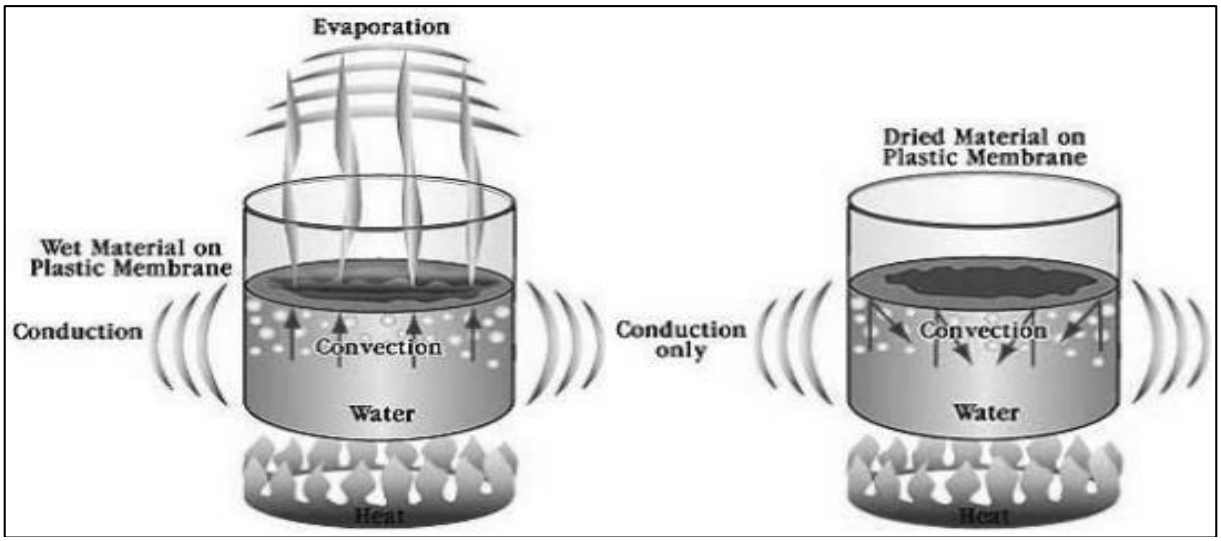

Fig 1: Refractance window: Drying concept (Baeghbali *et al*., 2010) [9].

In accordance with the findings of the research that has been conducted, several kinds of industrial machinery function according to a common principle (Nindo *et al*., 2003) [54]. To reduce the amount of microbial activity that occurs during the process of dehydrating pumpkin puree, an investigation was carried out using both commercial and pilot equipment. The objective was to achieve greater energy efficiency. Research was conducted with the use of MylarTM plastic film that had a thickness of 0.2 millimetres, and the temperature of the water was kept at around 95 degrees Celsius (Nindo *et al*., 2003) [54]. A film measuring 3 metres by 0.6 metres by 0.2 millimetres was meticulously positioned on top of the hot water for the pilot-scale apparatus. On an industrial scale, the film had dimensions of 12.90 metres by 1.41 metres by 0.2 millimetres (Nindo *et al*., 2003) [54]. Within a span of less than 5 minutes, the presence of moisture was reduced from 80% to around 5%. From 50% to 70%, the commercial equipment had an energy efficiency rating. Results that were satisfactory were obtained from the analysis of the microbiological activity in the product that was acquired using equipment on a pilot scale (Nindo *et al*., 2003) [54]. Coliforms, Escherichia coli, and Listeria innocua were all shown to have had a discernible reduction in their levels (Nindo *et al*., 2003) [54].

Baeghbali *et al*. (2016) [8] carried out a study with the purpose of analysing the quality of pomegranate juice as well as the energy efficiency of the various procedures that are employed in the process of dehydrating pomegranate juice. The research looked into RW, freeze-dryer and spray dryer as some of the procedures that were evaluated. During the process of drying residual water, the following configurations were put into place: The temperature of the water was measured to be 91 °C, the speed of the track was 3.9 millimetres per second, and the length of the mat was 0.5 millimetres. Dryer is required that has an internal diameter of 115 centimetres and a height of 165 centimetres in order to perform spray drying. It is also essential to keep the pressure at one bar throughout the process (Baeghbali *et al*., 2016) [8]. The feed rate was 0.75 litres per hour, and the temperature of the feed was 40 °C. The temperature of the air entering the system was roughly 140 °C and the temperature of the air leaving the system was around 75 °C (Baeghbali *et al*., 2016) [8]. In the course of the freeze-drying procedure, the freeze-dryer was made to operate under a predetermined set of parameters. The temperature of the condenser was -40 °C; the pressure was 3.0 kPa and the temperature of the heating plate was 20 °C. Until the desired moisture content of 5.3%, 2.9%, and 8.5% on a wet base (wb) was attained for RW, spray dryer and freeze-dryer, respectively, the drying trials were carried out until the desired drying conditions were met. RW drying was found to be superior to other methods in terms of energy usage, energy efficiency as established by the findings of the study (Baeghbali *et al*., 2016) [8]. Even though the freeze-dryer is widely used as a fundamental method for the production of dry goods of superior quality, it is important to point out that its energy efficiency is not particularly great. Nindo and Tang (2007) [53] found that this technique can be rather priced. A comparison of the findings reveals that the freeze-dryer approach only achieved 1.12% efficiency, but the drying process that utilised RW obtained an efficiency of 31.56% (Nindo and Tang, 2007) [53].

Determining the effects of several drying processes (freeze-drying, convection, and RW) on guava pulp was the

objective of a study that was carried out by Leiton-Ramírez *et al*. The study involved considering a number of aspects. RW displayed the shortest drying time, going from 80% db to 4% db in just 76 minutes. Because of this, the finished product's hue was preserved to a greater extent. When compared to the convection approach, the freeze-drying and RW procedures indicate improved preservation of both the physical and nutritional characteristics of the food. (Leiton-Ramírez *et al*., 2020) [41] conclude that RW is an appropriate method for the production of guava snacks based on these data.

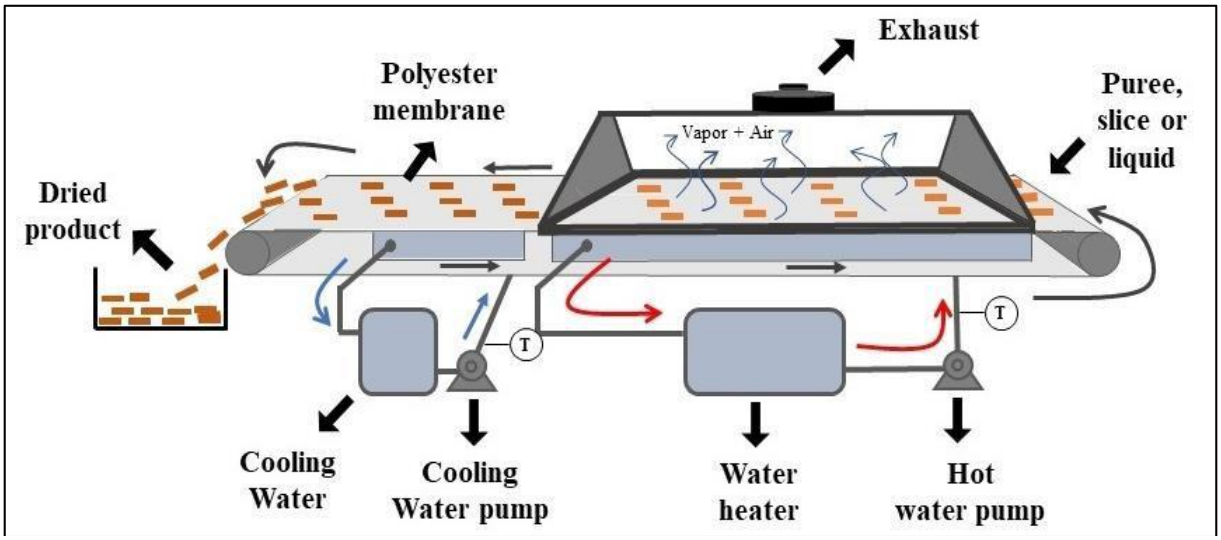

Fig 2: Industrial Refractance Window dryer scheme (Santos *et al*., 2022) [67]

Comparison Between Different Drying Methods for Fruits and Their Quality Parameters

Refractance Window Drying (RWD) is a relatively new and innovative method compared to traditional drying techniques such as hot air drying, freeze drying and spray drying (Dadhaneeya *et al*., 2023) [20, 21]. RWD stands out for its energy efficiency and ability to preserve the nutritional and sensory qualities of fruits. Traditional hot air drying often leads to significant losses in flavour, colour and texture due to high temperatures and prolonged drying times, which can degrade heat-sensitive nutrients like vitamins and antioxidants (Wu *et al*., 2024) [18]. Freeze drying, while excellent at preserving nutritional content and texture, is highly energy-intensive and expensive, making it less suitable for large-scale industrial applications. Spray drying, typically used for liquid foods, often results in lower nutrient retention due to the high temperatures required to convert the liquid into powder form. In contrast, RWD uses a combination of conduction, convection and infrared radiation to achieve rapid drying at lower temperatures (Obajemihi *et al*., 2022) [57]. This method preserves a higher percentage of bioactive compounds, such as vitamin C, antioxidants and phenolic compounds, which are often lost in other drying methods. Studies have shown that fruits dried using RWD retain better colour, texture and rehydration properties compared to those dried using conventional methods (Largo-Avila *et al*., 2024) [40]. For example, mango slices dried using RWD retained more ascorbic acid and carotenoids compared to those dried using hot air or freeze drying, demonstrating superior nutritional retention (Liu *et al*., 2024) [43]. Overall, RWD provides a balanced approach that combines energy efficiency with high-quality preservation, making it a promising alternative to traditional drying methods for fruits and other heat-sensitive food products.

Table 1: Fruit drying technologies: Limitations and Benefits

Technologies	Limitations	Benefits	References
Fluidized Bed drying	Energy efficiency is less than 50%. Loss of flavor, color and texture	Efficient Mass Transfer and Heat Transfer, Fast drying	(Sivakumar *et al*., 2016) [70]
Freeze drying	High cost, Time consuming,	Maintain the volatile components, Physical and chemical quality improved	(Kandasamy and Naveen, 2022) [32]
Hot air Drying	Excessive shrinkage and Loss of nutrients	Ease of handling, Simplicity, Uniformity, Affordability	(Senadeera *et al*., 2020) [68]
Infra-red Drying	High cost and difficult to maintain, High radiant heat causes charring	Low processing time, Heat transfer rate is high	(Rastogi, 2012) [66]
Low pressure super-heated steam drying	Industrial scale-up is limited	Improve energy efficiency	(Haubjerg, 2016) [28]
Microwave Drying	Charring, non-uniform heating	Improved product physical qualities, Better heat and mass transfer,	(Li *et al*., 2011) [42]
Radiofrequency drying	High cost, non-uniform heating	Fasten drying, High penetration	(Huang *et al*., 2018) [30]
Vacuum drying	Need of operating pressure, Energy consuming	Suitable for heat sensitive materials, Effective moisture removal under pressure	(Jangam, 2011) [33]

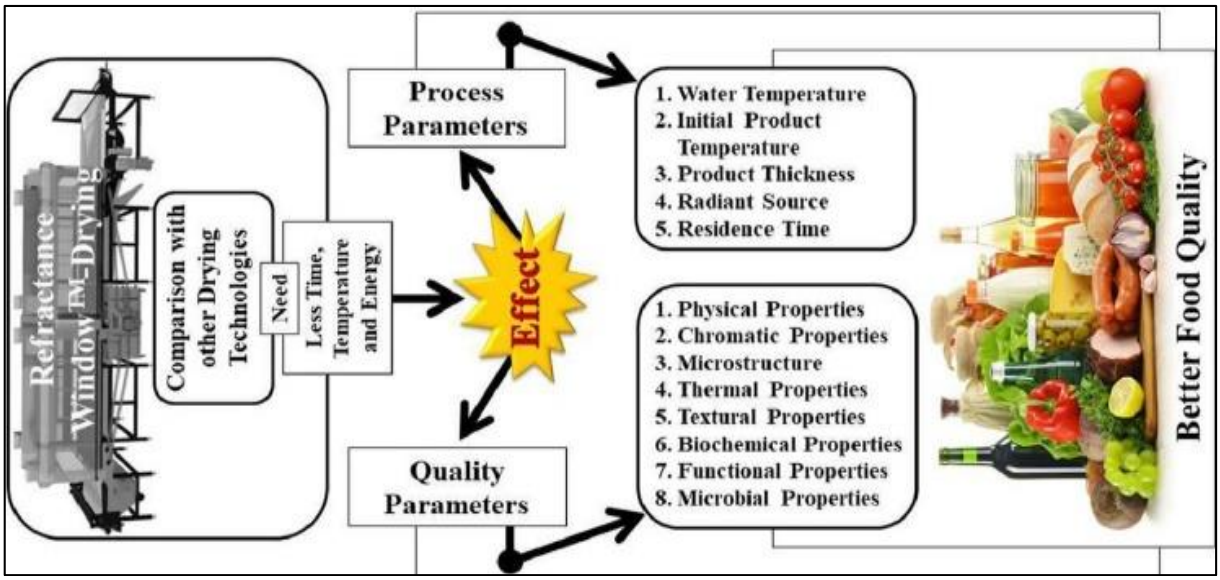

Fig 3: Refractance window drying effects on process and quality (Mahanti *et al*., 2021)

The rate of drying and the amount of time it takes for the product to dry in RWD can be affected by a number of different factors. Among these are the temperature of the water, the beginning temperature of the product, the thickness of the product, the type of radiation source, the length of exposure, and the thickness of the film (Muyonga *et al*., 2021) [48, 50]. Heat and mass are transferred through a plastic sheet and a window that is see-through in order for the RWD system to function properly. In accordance with (Nindo and Tang, 2007) [53], this transfer is made easier by the presence of wet material interactions on the sheet surface. According to Nindo and Tang (2007) [53], this helps to maintain the product and reduce the amount of thermal damage that occurs. In addition, the influence of air convection in RWD should not be ignored. According to Baeghbali and Niakousari (2018a) [52], this component plays a significant impact in determining the temperature of the product as well as the amount of moisture that is lost during the process (Zotarelli *et al*., 2015) [76]. This is especially effective when compared to natural convection. On the other hand, the drying process for caste tape is comprised of two basic processes: the rate at which the solvent evaporates from the cast surface, and the rate at which solvents permeate through the tape via the drying front (Niakousari, 2018) [52]. These procedures can be modified using a variety of different approaches, which enables alterations to be made in the volatility of the solvent. Changing the kind of solvent, modifying the concentration of solvent vapour in the local atmosphere, and varying the temperatures of both the local air and the solvent are all ways to accomplish this goal (Jabbari *et al*., 2017) [32]. Because of this, the impact of each parameter is extremely important for maintaining the quality of the product, and it will be briefly covered in the sections that followed this one. The following is a compilation of the different research that was undertaken on the comparison between RWD technology and other drying technologies, including the examination of quality parameters.

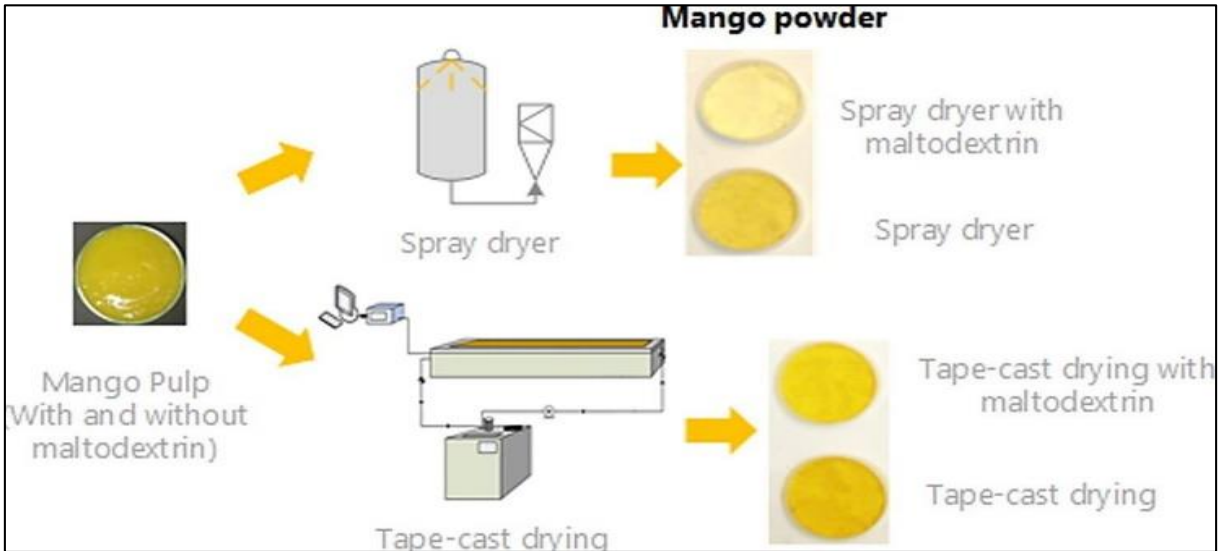

Fig 4: Spray drying, Tape-cast drying: Mango powder production (Zotarelli *et al*., 2017) [77].

In the process of making fruit powder, a number of different drying techniques have been investigated (Zotarelli *et al*., 2017) [77]. Cast-Tape Drying, often known as CTD, is a technique that is ideally suited for the manufacturing of food powder. It is interesting to note that the drying process that is commonly referred to as the refractance window (RW) is

actually a particular case of CTD (Zotarelli *et al*., 2017) [77]. During this process, the solution that needs to be dried is carefully put onto a Mylar (DuPont®) film, which is a translucent polyester film. The film is then brought into contact with hot water, which provides the product with the heat that is required for the drying process (Nindo and Tang, 2007) [53]. The use of CTD to pulps of fruits and vegetables can result in the production of films or flakes, whilst grinding can be employed to make powdered items. The ability to employ moderate temperatures (6080 °C) and short drying times (upto few minutes) is one of the advantages of this drying method. This is accomplished by controlling the thickness of the pulp layer that is being dried. In a number of research, the utilisation of this technique has been documented for the purpose of drying strawberry and carrot pulps (Abonyi *et al*., 2002) [1], pumpkin (Nindo *et al*., 2003) [54], açaí (dark purple berry) (Pavan *et al*., 2012) [61], mango (Zotarelli *et al*., 2015) [76] and tomato (Castoldi *et al*., 2014) [15].

In the research carried out by Caparino *et al*. (2013) [14], the preparation of mango powder was investigated by utilising a variety of drying techniques. Methods such as drum drying (DD), freeze-drying (FD), refractance window (RW), and spray-drying (SD) using maltodextrin were included in this category of techniques (Zotarelli *et al*., 2017) [77]. Specifically, the researchers investigated the effects of these processes on the mango solids, and they did so without making use of any carrier agents. In comparison to the mango powders made by SD and DD, Zotarelli *et al*., (2017) [77] discovered that the mango powders created by RW, which did not include the use of any carrier agents, were of a higher grade. Caparino *et al*., (2013) [14] studied the effects of moisture sorption, glass transition temperatures, and microstructure on the stability of powders that were formed by RW and FD employing mango particles. They gave information that was really helpful on these aspects. The powders that were generated by both procedures had water sorption capabilities that were comparable to one another, as demonstrated by type III isotherms (Zotarelli *et al*., 2017) [77].

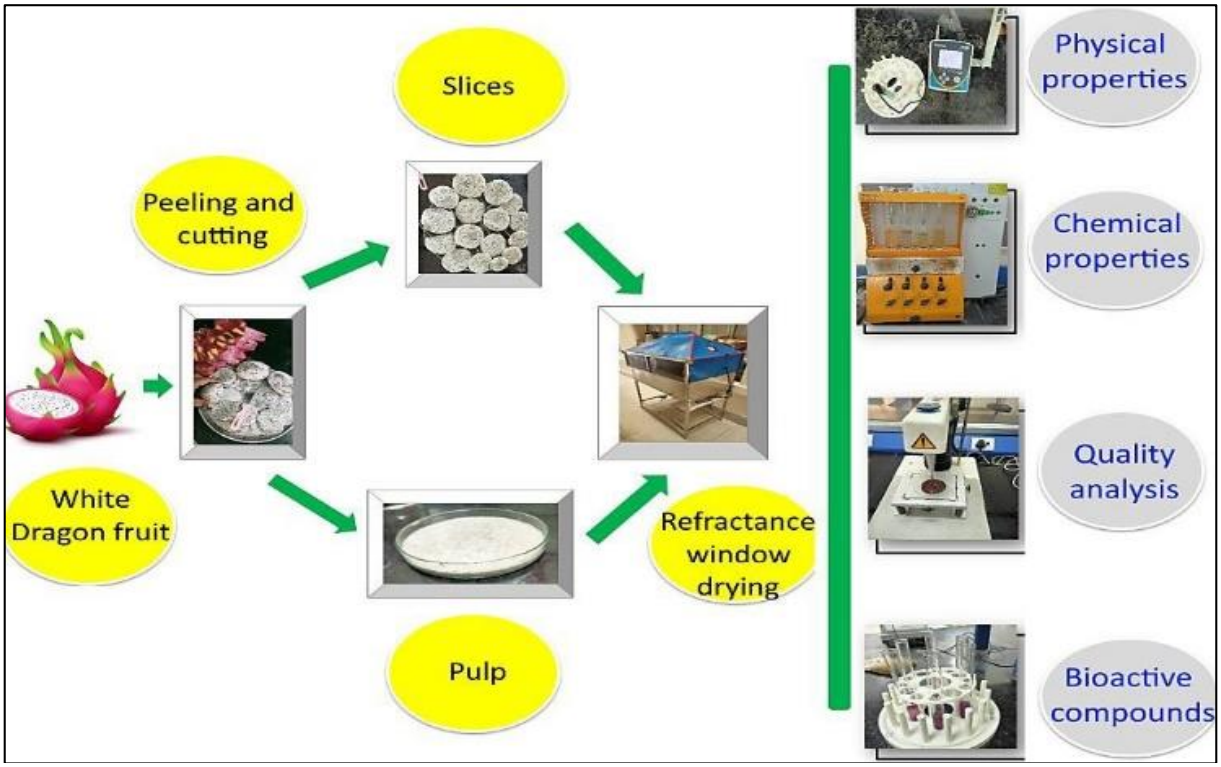

Fig 5: Refractance window drying method of Dragon fruit slices and pulp (Dadhaneeya *et al*., 2023) [20, 21].

Refractance Window Drying, also known as RWD, is a cutting-edge drying technology that has been utilised to preserve the great quality of dragon fruit pulp and slices (Dadhaneeya *et al*., 2023) [20, 21]. A study was carried out to investigate the results of evaluating the qualitative qualities of dragon fruit slices and pulp using RWD, in addition to other drying methods such as hot air oven drying (HD), vacuum drying (VD) and freeze-drying (FD). The investigation was carried out to examine the results of the analysis. The findings of the study demonstrated that the dragon fruit samples that were dried using the RWD approach exhibited a higher level of nutritional quality when compared to the samples that were dried using other methods (Dadhaneeya *et al*., 2023) [20, 21]. It took only 960 minutes for the RWD method to attain a final moisture content of 6.50% (dry basis), making it one of the most notable drying methods available. When the various methods were compared, it was discovered that the FD, VD, and HD procedures required a much longer amount of time to dry. The drying periods for these methods were 1320, 1200, and 1080 minutes, respectively, in order to attain the desired moisture content. In addition, the dragon fruit samples that were collected through research had greater amounts of total phenolic content (TPC), which was measured at 182 mg GAE/100 g, and crude fibre content, which was measured at 0.98%. As a result of these findings, it appears that the research has found the possibility of a preservation approach known as RWD to maintain the quality of dried materials. It would appear that the RWD approach not only makes drying more efficient, but it also helps to maintain the vital nutrients and bioactive substances that are present in the dragon fruit (Dadhaneeya *et al*., 2023)

[20, 21]. In order to investigate how temperature influences the phenolic content, antioxidant activity, colour, and texture of dragon fruit slices and pulp, a study was carried out. RWD provides a sufficient drying temperature as an alternative to freeze-drying, which results in higher quality and nutrient preservation of the dried dragon fruit samples. Refractance Window Drying (RWD) method is an extremely effective method for drying dragon fruit pulp and slices. Not only does it maintain the fruit's nutritious worth, but it also considerably shortens the amount of time it takes to dry the fruit in comparison to more traditional ways. The potential of RWD to improve the drying process of dragon fruit has the potential to deliver tremendous value to the food industry.

Table 2: Drying Time and Energy Efficiency

Fruit	Drying Temperature (°C)	Drying Time (minutes)	Energy Efficiency (%)	References
Mango	92.5	60	70	(Ochoa-Martínez *et al*., 2012) [58]
Jackfruit	92	60.47	85	(Nansereko *et al*., 2021) [48, 50]
Pomegranate	91	45	90	(Baeghbali *et al*., 2016) [8]

Table 3: Nutrient Retention with RWD at different Temperature

Fruit	Drying Temperature (°C)	Nutrient	Retention (%)	References
Apple	90	Ascorbic Acid (Vitamin C)	96	(Rajoriya *et al*., 2019) [65]
Jackfruit	93.4	Antioxidant Activity	82.34	(Nansereko *et al*., 2021) [48, 50]
Mango	80-95	Total Phenolic Content	>80	(Nguyen *et al*., 2022) [51]

Table 4: Comparative quality metrics

Fruit	Quality Metric	RWD Value	Conventional Method Value	References
Apple	Color Retention	ΔE = 5.5	ΔE = 8.0	(Rajoriya *et al*., 2019) [65]
Kiwifruit	Rehydration Ratio	1.5	1.2	(Jafari *et al*., 2016) [78]
Golden berry	Texture (Hardness)	20 N	30 N	(Puente *et al*., 2020) [63]

Table 5: Effective moisture diffusivity

Fruit	Effective Moisture Diffusivity (m^2/s)	Drying Temperature (°C)	References
Mango	4.40 × 10-10 to 1.56 × 10-9	92	(Ochoa-Martínez *et al*., 2012) [58]
Avocado	4.25 × 10-10 to 7.24 × 10-10	80-95	(Nguyen *et al*., 2022) [51]

Table 6: Activation energy for moisture evaporation

Fruit	Activation Energy (kJ/mol)	Drying Temperature (°C)	References
Avocado	32.06	80-95	(Nguyen *et al*., 2022) [51]
Mango	66.03	80-95	(Nguyen *et al*., 2022) [51]

Case Studies for Fruit Drying with RWD Technology

Several case studies highlight the effectiveness of Refractance Window Drying (RWD) technology in drying various fruits while preserving their nutritional and sensory qualities.

1. **Dragon Fruit:** Dadhaneeya *et al*., (2023) [20, 21] examined the qualitative properties of dragon fruit slices and pulp dried using RWD compared to hot air drying (HD), vacuum drying (VD), and freeze-drying (FD). The findings showed that RWD preserved higher nutritional quality, with a drying time of 960 minutes to achieve a final moisture content of 6.50% (dry basis), compared to longer times required by FD, VD, and HD.
2. **Mango:** In another study, mango slices were dried using RWD and demonstrated higher retention of ascorbic acid and carotenoids compared to hot air and freeze drying (Ahmad *et al*., 2023) [3]. The rapid drying process of RWD maintained the colour, aroma, and texture of the mango slices better than the conventional methods.
3. **Jackfruit:** Research focused on optimizing drying conditions for jackfruit pulp using RWD found that this method preserved the phenolic content and antioxidant activity effectively (Kamal *et al*., 2023) [34]. The study concluded that RWD is suitable for drying jackfruit pulp, providing high-quality dried products with enhanced nutritional value.
4. **Pomegranate:** A comparative study on the quality retention and energy efficiency of pomegranate dried using RWD, freeze-drying, and spray drying found that RWD provided superior energy efficiency and better preservation of bioactive compounds (Maphosa *et al*., 2023) [46]. This study highlighted the potential of RWD in maintaining the quality and extending the shelf life of pomegranate juice.
5. **Guava:** An investigation into the drying of guava slices using RWD revealed that this method significantly preserved the physical and nutritional characteristics of the fruit (Kaur and Ghosh, 2024) [37]. RWD showed the shortest drying time and the highest retention of color and nutrients compared to convection and freeze-drying methods.

These case studies demonstrate the efficacy of RWD technology in preserving the quality of dried fruits while offering energy efficiency and shorter drying times compared to traditional methods. The integration of RWD in fruit drying processes can lead to high-quality, nutritionally rich dried fruit products suitable for commercial applications.

Discussion

RWD is an advanced and efficient method of drying fruits with many advantages in contrast to the regular methods of

drying. Richness in different vitamins and nutrients, as well as the maintenance of the quality of the fruits, are also among the advantages of RWD. A selection of studies has revealed that RWD has been proven to retain more vitamins, antioxidants, and bioactive compounds than conventional drying methods. For instance, mango slices dried using the RWD method were analysed and it was evidenced that the ascorbic acid and carotenoid content of such mangoes are higher than the mangoes dried with hot air or freeze driers (Nansereko *et al*., 2021; Shende and Datta, 2018) [48, 50], 69]. It is evident that RWD is energy efficient as compared to other structuring method like freeze drying and spray drying. According to Nansereko *et al*., (2021) [48, 50] RWD can greatly reduce energy consumption. In a study conducted by Baeghbali *et al*. (2016) [8], it was found that RWD required much less energy as compared to systems such as spray drying and freeze drying. Of them, RWD incurred an energy consumption of only one-third and 1/40th of the energy spent in spray drying and freeze drying, respectively, to produce the same amount of soy protein isolate. The RWD process also facilitates the process of drying and retention of heat to avoid overheating fruits that are heat-sensitive thus maintaining good quality fruits. Several studies also have been conducted on fresh jackfruit pulp and it has been determined that there is potential for attaining a better range of drying conditions in a shorter period without compromising on the nutrient content and antioxidant value (Nansereko *et al*., 2021) [48, 50].

RWD provides the better dried fruits with better colour, texture and rehydrated property as compare to convective drying. The method allows the dried products to be solid and possess sensory appeal, thus customers will be inclined to buy the products (Rajoriya *et al*., 2019; Jafari *et al*., 2016) [65, 78]. Although RWD has its advantages, this approach has primarily relied on electricity from the grid that is generated from fossil energy sources. This source is environmentally sensitive because it emits greenhouse gases which are known to cause climate change (Santos *et al*., 2022) [67]. Further research is needed to improve the existing drying conditions for one or another type of fruits. Current researches have employed response surface methodology (RSM) to identify the nutrients in several fruits such as jackfruit and mango. These investigations have shown positive impacts that make the use of innovation appealing. (Nansereko *et al*., 2021; Nguyen *et al*., 2022) [48, 50, 51]. RWD has numerous prospects of application and they are not limited to fruits only. They include use on vegetables, herbs and in some cases pharmaceutical products. The implementation of RWD across different sectors supports the expansion of RWD acceptance and technology growth (Raghavi *et al*., 2018) [64]. Further studies concerning the environmental impacts of RWD as compared to other drying methodologies can provide interesting insights within the improvement of environmentally friendly technologies for food processing (Franco *et al*., 2019) [26]. Lastly, RWD has been proved to be a more advantageous technology in drying fruits because of the following reasons of energy conservation, better preservation of nutrients, and quality of the final product. Thus, the problems of reliance on the fossil fuel and the costs associated with the initial investments regarding more opportunities of the renewable energy can be victorious if more opportunities of the renewable energy are investigated and more researches are carried out. This will inevitably contribute to attaining a solution that would be more desirable and practiced in the food industry.

Future Scope

Refractance Window Drying (RWD) technology, though already proven to be efficient and effective for drying fruits, has significant potential for further development and broader applications (Kong *et al*., 2023) [38]. Future research should focus on integrating renewable energy sources, such as solar and wind power, to enhance the sustainability of RWD systems. This integration would not only reduce the dependency on fossil fuels but also decrease greenhouse gas emissions, aligning with global environmental goals. Additionally, optimizing the RWD process for various fruits and expanding its application to other food products like vegetables, herbs, and even pharmaceutical items can provide substantial benefits (Teshome *et al*., 2023) [72]. Using response surface methodology (RSM) to fine-tune drying conditions can help in maximizing nutrient retention and improving the overall quality of dried products (Cervantes-Arista *et al*., 2024). Exploring hybrid drying techniques, combining RWD with other emerging technologies like ultrasound and infrared drying, could further enhance drying efficiency and product quality (Nowacka *et al*., 2024) [55]. This approach can help in reducing drying time and energy consumption while maintaining high nutritional and sensory properties. Moreover, comprehensive environmental impact assessments comparing RWD with other drying methods can provide valuable insights into developing more eco-friendly food processing technologies (Arslan and Alibaş, 2024) [7]. These studies can highlight the advantages of RWD in terms of energy conservation and quality preservation, promoting its wider adoption in the food industry.

Conclusion

Consequently, RW drying is getting more prospective nowadays to preserve the nutritive quality of fruits and vegetables. Drying is faster; the bioactive properties are preserved, all under full energy saving. Besides, there are many more benefits it offers. The utilization of the RW drying has low sustainability and therefore, renewable power sources such as solar electricity should be added to its configuration for maximum sustainable power. However, in the situation of retaining bioactive compounds, similar to several articles, it has been pointed out to offer an apparent advantage over conventional techniques like freeze drying. Similar to any other energy-saving RW drying oxidations, this technology can also be enhanced further by having a look into other modes of diffusion and the feasibility of other types if there is another type of process that could yield better results. In general, drying by the RW method can enhance the food processing technologies and the preservation of top- quality dried foods. In conclusion, the future of RWD technology lies in its ability to integrate renewable energy sources, optimize drying conditions for a variety of products, and combine with other advanced drying techniques. These advancements will contribute to more sustainable, efficient, and high-quality food processing methods, positioning RWD as a leading technology in the industry.

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