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Refractance window drying: A novel drying technique for quality retention

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Abstract

Drying is a process that removes water from biological products, resulting in solid forms. It extends the shelf life of perishable items and reduces costs involving in packing, storage and shipping. Different generations of drying techniques are used for specific materials. Traditional sun drying has limitations, which have been overcomed by hot air, oven and infrared drying. Osmotic dehydration preserves nutrients but cannot achieve desired moisture levels. Freeze drying has low output and high costs. Specific drying methods have their challenges, such as quality loss and high investment. Refractance window drying is a fourth-generation technique widely used for drying the liquid or puree of fruit and vegetable. This technique offers cost and energy savings, as well as maintain the product quality especially for heat-sensitive produces. This article summarises the working principle of refractance window drying and its effects on different biochemical parameters *viz.*, anthocyanin, vitamin C, carotenoids, antioxidant activity and colour of the produces.

Keywords: Drying, refractance window drying, novel drying technique, biochemical parameters

1. Introduction

The process of drying involves removing water from products by applying heat, leaving behind a solid as a result. Depending on the process, the finished product is in the form of sheets, flakes, film, powder, or granules (Nindo and Tang 2007) [21]. It is employed mainly for products that are highly perishable, such as fruit and vegetables having high moisture content (> 80%) (Changrue *et al.*, 2006) [10]. Drying offers several significant advantages, including extending the shelf life of products, ensuring year-round availability, and reducing costs associated with packaging, storage, handling, and shipping (Moses *et al.*, 2014) [18]. However, it is important to note that drying processes are energy-intensive, accounting for approximately 12-20% of the total energy consumption in the food processing industry (Changrue *et al.*, 2006) [10].

Drying techniques are classified into four generations: first, second, third and fourth. The first-generation dryers, such as kilns, trays, rotary flow conveyors and tunnels are well-suited for solid materials like food grains and horticultural commodities, utilizing hot air as the heat transfer medium. Second-generation dryers, such as spray and drum dryers, are more suitable for slurries and pastes that need to be converted into flakes and powders. Third-generation technologies include osmotic drying and freeze drying, commonly used for drying of fruit and vegetables (Vega-Mercado *et al.*, 2001) [35]. Fourth-generation technologies encompass novel drying methods like microwave drying, radio-frequency drying, and refractance window drying. These techniques are particularly adopted for heat-sensitive produces (Chou and Chua, 2001) [11].

Sun or shade drying is a traditional and widely recognized method for drying fruit puree to produce leather. It relies on the sun's heat and does not require specialized energy sources or equipment. However, sun drying has certain drawbacks, including extended drying time, dependency on external factors, and a high risk of microbial contamination and subsequent deterioration (Suna *et al.*, 2014) [30]. To overcome these limitations in the production of pestil and fruit leather, alternative drying methods such as hot air drying, oven drying, and infrared drying have been implemented (Ruiz *et al.*, 2012) [26]. Tunnel drying, on the other hand, may result in color deterioration and browning reactions (Topuz *et al.*, 2009) [33]. Osmotic dehydration, known for its lower drying temperatures and reduced energy consumption, is utilized to preserve nutrients in the final dried product. However, the addition of sugar or salt prevents the attainment of the desired moisture content (Bahmani *et al.*, 2016) [5]. Freeze drying, while effective, is associated with low output and high production costs (Caparino *et* *al.*, 2013) [7].

In drum dryer, drying temperature generally ranges between 120-170 ℃, causing a serious quality loss in the product. During spray drying, raw material with high moisture content is required so that the feed could be atomized. The atomization and air temperature ranged from 150 to 300 ℃. To attain this much high temperature, high capital investment is required (Nindo and Tang 2007) [21]. Microwave drying demands a higher initial investment and has some impact on the texture and aroma of the food, whereas fluidized bed drying requires high pressure for the operation, which demands huge amounts of energy (Changrue *et al.*, 2006; Daud, 2008) [10, 12].

Refractance window drying, along with infrared drying and microwave drying, belongs to the fourth generation of drying methods (Vega-Mercado *et al.*, 2001) [35]. It was initially developed by Richard Magoon of MCD Technologies (Tacoma, Washington, USA) for the purpose of drying heat-sensitive fruit and vegetable slices and pulp (Magoon, 1986) [17]. When compared to other drying techniques, refractance window drying stands out as a highly efficient and cost-effective method, requiring 50-70% less capital investment and consuming over half the energy needed for freeze drying (Nindo and Tang, 2007) [21].

2. Refractance window drying

Refractance window drying is a novel drying technique in this different liquid, viscous solutions and suspensions can be converted into powder or flakes forms (Zotarelli *et al.*, 2017) [38]. Refractance window drying, often referred to as conductive hydro-drying (Baeghbali *et al.*, 2019) [4], is a variation of Cast-Tape Drying (CTD).

2.1 Principle of refractance window dryer

Refractance window dryer works on the basic 3 principle of heat transfer *viz.*, conduction, convection and radiation as described below:

- **Principle I:** When water is heated - When a source of heat is applied, infrared energy is transferred to the water through convection. Subsequently, this heating energy is primarily emitted from the water through evaporation.
- **Principle II:** When hot water is covered by an IR - When the hot water is covered by a membrane that is transparent to the infrared heat radiation found in water, it effectively blocks or refracts evaporation and its associated heat losses, allowing only conduction to take place. The membrane acts as a reflective surface, similar to a mirror, reflecting the infrared heat energy back into the water.
- **Principle III:** When wet product is applied uniformly to IR membrane - But when the surface of the membrane is laden with a moist product, the water in the product will create a "windosw" that acts as a passage for flow of infrared energy through the material. Heat is directly transmitted into the remaining water present in the product as if the membrane is entirely absent.

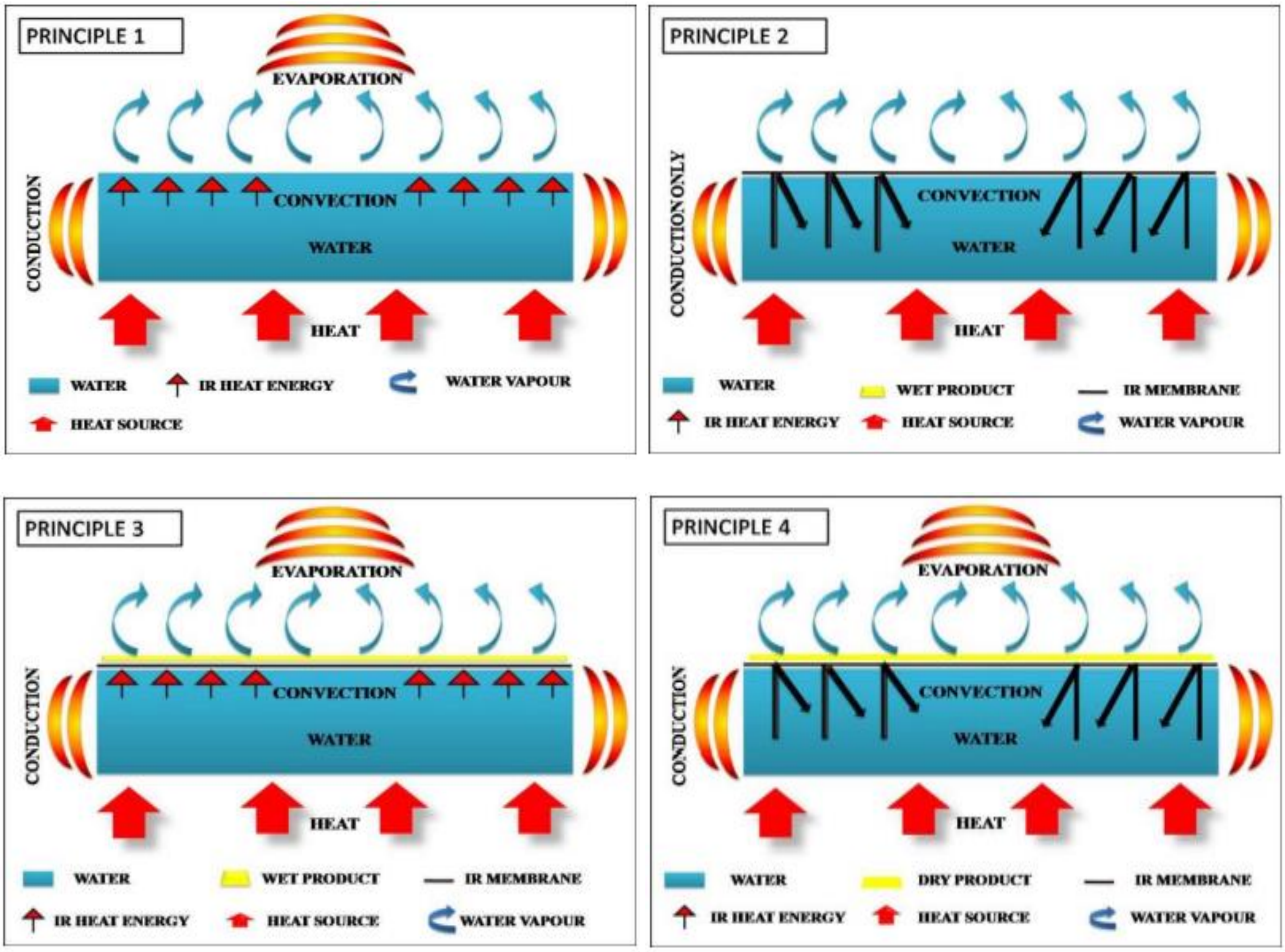

Fig 1: Working principle of refractance window drying technique (Source: Trivedi *et al.*, 2017) [34]

2.2 Main components and working of refractance window dryer

The refractance window drying system consists of several main components, as depicted in Figure 2. This method involves spreading a uniform thin layer of the pulpy wet product onto a Mylar sheet, which is a type of polyester film that is transparent to infrared radiation (Abonyi *et al.*, 2002) [1]. The Mylar sheet can either be stationary or in motion during the drying process. When it is in motion, the food is typically moved in the same direction as the hot water, with belt speeds ranging from 0.6 to 3 m/min (Kudra and Mujumdar, 2009) [16].

In the refractance window drying technique, the food material is spread as a thin layer over the film and heat is transferred to it through conduction, radiation and the thermal energy carried by moving water. The water, maintained at temperatures between 94 and 98 °C, transfers sensible heat to the food material through the film. This unique approach defines the essence of the refractance window drying technique. The rapid transfer of heat energy causes the water within the food to evaporate quickly, establishing a state of thermal equilibrium (Raghavi *et al.*, 2018) [24].

Furthermore, the refractance window drying process also involves the influence of radiation, which varies depending on the material properties. The mechanism relies on the concept of a "window" that enables heat and mass transfer to take place. This window allows infrared energy to pass through the plastic membrane's surface, where the moist material is placed. However, it is important to note that less than half of the total thermal radiation actually reaches the food material spread over the film (Zotarelli *et al.*, 2015) [37]. Heat is transferred directly to the water molecules during the refractance window drying process, and the temperature of the product can reach up to 74 °C (Castodi *et al.*, 2015) [8]. However, in most cases, temperatures range from 39 °C to 47 °C (Bolland, 2000) [6], and are highly dependent on factors such as moisture content, bed thickness, and product consistency.

As the product loses moisture, the drying "window" gradually closes, and the refracted thermal radiation is reflected back into the heated water source, particularly with an increase in refractive index. At the end of the drying process, the product is cooled by being moved over cold water and separated from the belt using a scraper device (Nindo and Tang, 2007) [21]. The purpose of cooling the product at the end of the refractance window drying process is to reduce its temperature below the glass transition temperature, preventing stickiness (Azizi *et al.*, 2017) [2]. The circulating water is commonly recycled after reheating to enhance the system's thermal efficiency. It is worth noting that the entire process takes place under atmospheric conditions. Consequently, refractance window drying is classified as a contact, indirect, film-drying technique (Nindo and Tang, 2007) [21], which also ensures that there is no cross-contamination among the drying products.

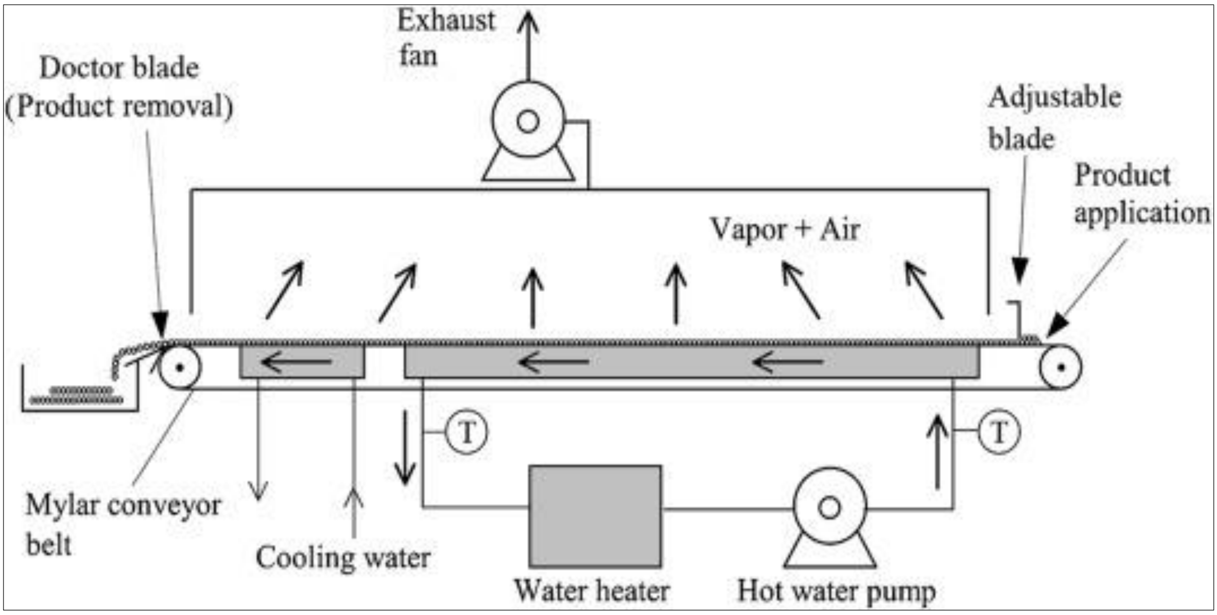

Fig 2: Components of a refractance window dryer (Source: Shende and Datta 2019) [27]

3. Effect of refractance window drying on different biochemical compounds

Various researchers have carried out the experiment to study the effect of refractance window drying on different biochemical compounds that has been summarized in Table 1.

3.1 Anthocyanin

Anthocyanin is a crucial water-soluble phenolic compound and natural pigment. Its beneficial effects in managing diseases like cancer, coronary heart diseases, and other degenerative disorders have been confirmed by Gan *et al.*, in 2019 [14]. The stability of anthocyanins relies on factors such as their structure, concentration, and drying process parameters like temperature, light, and oxygen, as discussed by Wrolstad in 2004 [36]. Tontul and Topuz (2017) [31] observed that, anthocyanins exhibit high susceptibility to thermal treatment at temperatures of 50, 60, or 70 °C. However, the researchers demonstrated that refractance window drying (using circulating water at temperatures of 90, 95, and 98 °C) effectively prevents the degradation of anthocyanins. The study observed that the highest retention of anthocyanin occurred in pomegranate leather dried using refractance window drying at 98 and 95 °C, followed by samples dried using hot air drying at 50 and 60 °C.

Baeghbali *et al.*, (2016) [3] conducted a study investigating the drying effects of refractance window drying, freeze drying and spray drying on pomegranate juice concentrate. The research demonstrated that RW drying resulted in a higher retention rate of total anthocyanin content, with 85.01% compared to 71.2% in freeze drying and 60.9% in spray drying pomegranate juice concentrate. The study also revealed that the maximum degradation of anthocyanins occurred in the spray dried product, potentially due to the thermal damage inflicted on the anthocyanin compounds. According to Celli *et al.*, (2016) [9], the retention of anthocyanins in refractance window dried (using hot water at a temperature of 95 ℃) haskap berries from the initial frozen fruits was found to be more than 90% when evaluated using HPLC and spectrophotometric assays. In a study by Nayak *et al.*, (2011) [19] it was found that purple potato flesh contained a higher total anthocyanin content compared to red, yellow, and white potato cultivars. However, upon conducting drying processes, it was observed that purple potato flakes experienced losses in total anthocyanin content of 45%, 41%, and 23% after freeze drying, drum drying and refractance window drying, respectively.

3.2 Vitamin C

Several researchers have examined the impact of refractance window drying on the preservation of vitamin C and its retention. Vitamin C, also known as ascorbic acid, is commonly utilized as a food additive. Its instability can lead to the degradation of other vitamins in food products, making it a significant component in the nutrient quality assessment of foods. The retention of ascorbic acid is influenced by various factors, such as oxygen, light exposure, temperature, moisture content, and processing duration.

Tontul and Topuz (2017) [31] investigated the effect of convective drying and refractance window drying on cornelian cherry pulp. The researchers employed hot air drying, also known as convection drying, at temperatures of 50, 60, and 70 ℃, along with air speeds of 1, 2 and 3 m/s, until the moisture content of the cornelian cherry pulp reached 8 g/100g. For refractance window drying, a same moisture content level was set, using temperatures of 90, 95 and 98 ℃. When comparing the ascorbic acid content of the convective and refractance window-dried cornelian cherry pulp, it was observed that the refractance window-dried pulp had a higher ascorbic acid content (approximately 0.9 g/kg dry matter). This could be attributed to the drying process at a lower temperature and with a faster air flow, resulting in a 20% increase in ascorbic acid powder production. In a similar vein, Nindo *et al.*, (2003) [20] conducted research on asparagus spears and obtained comparable findings. They discovered that refractance window drying, using circulating water at temperatures of 95-97 ℃, achieved the highest retention of ascorbic acid at 98%. This was followed by 84% retention in freeze drying (FD), 64% retention in microwave spouted bed drying with a 1.5 kW magnetron operating at 2450 MHz, 52% retention in spouted bed drying at 60 ℃, and a minimum of 40% retention in tray drying at 60 ℃.

Shende and Datta (2020) [28] conducted a study to investigate the effect of refractance window drying (using a hot water temperature of 95 ℃), tray drying (95 ℃), and oven drying (95 ℃) on mango pulp. Their findings indicated that refractance window drying exhibited the highest retention of ascorbic acid at 66.3%, while tray drying and oven drying retained 34.8% and 30.1% of ascorbic acid, respectively. Moreover, the study revealed that at a drying temperature of 85 °C, the ascorbic acid content was measured as 58.4 mg/100 gm. However, at 95 °C with a pulp thickness of 2 mm, the ascorbic acid content increased to 62.2 mg/100 gm. The results suggested that higher drying temperatures contribute to increase in retention of ascorbic acid, likely due to shorter thermal treatment periods and reduced nutritional oxidation. Interestingly, the study also observed that a pulp thickness of 3 mm resulted in the highest retention of ascorbic acid at 64%, compared to 62.6% for 2 mm and 61.8% for 4 mm. This variation could be attributed to the increased drying surface area of the 2 mm pulp, leading to higher ascorbic acid oxidation. Conversely, slower drying of the 4 mm pulp allowed more time for ascorbic acid degradation through oxidation.

3.3 Carotenoids

Carotenoids are highly valuable compounds known for their beneficial effects in preventing cardiovascular diseases and cancers. The drying process conditions, including light exposure, oxygen exposure, and high temperature, have a notable impact on the stability and retention of carotenoids. Durigon *et al.*, (2016) [13] conducted a comparison of the physicochemical characteristics of tomato juice powder dried using refractance window drying (hot water temperature of 90 ℃) with those produced through freeze-drying (0.02 kPa) and spray drying (air outflow temperature of 99 ℃). The study revealed that all three drying processes resulted in over 50% losses in the dried powder compared to fresh tomato juice. In terms of preserving the color of the tomato powder, refractance window drying was found to be equally effective as freeze-drying. However, freeze-drying exhibited less degradation of lycopene, likely due to its operation at lower temperatures and lower oxygen concentrations.

Puente *et al.*, (2020) [23] conducted a study on goldenberry pulp and obtained similar findings. The research indicated that freeze drying was highly effective in retaining the carotenoid content in the final dried sample, followed by refractance window drying products and then infrared drying. The degradation of carotenoids in the drying process may be attributed to the presence of oxygen and high temperatures. Additionally, losses in carotenoid content could be attributed to oxidative changes caused by the activity of polyphenol-oxidase and lipoxygenase enzymes. Abonyi *et al.*, (2002) [1] obtained similar results regarding carotene retention. The study revealed that the carotene losses in RW dried carrot puree were slightly higher compared to FD samples, although the difference was not statistically significant. The carotene losses in RW dried samples were 8.7% (total carotene), 7.4% (α-carotene), and 9.9% (β-carotene), while in FD samples, the losses were 4.0% (total carotene), 2.4% (α-carotene), and 5.4% (β-carotene). However, in the case of drum dried samples operated at 138 ℃, a significant reduction in carotene content was observed, with a decrease of 56.1% (total carotene), 55.0% (α-carotene), and 57.1% (β-carotene).

Table 1: Effects of refractance window drying on different biochemical compounds of foods

Biochemical Parameters	Food Product	Research findings	References
Total anthocyanin Content	Pomegranate Juice	Total anthocyanin content of refractance window dried sample was significantly higher than the freeze dried and spray dried samples.	Baeghbali *et al.*, (2016) [3]
	Haskap berry	Anthocyanin content of frozen haskap berry powder retained to 93.8%.	Celli *et al.*, (2016) [9]
Ascorbic Acid	Sapota	As the water temp. increased from 84.3-91℃, ascorbic acid content increased but further increased in water temperature substantially decreased the ascorbic acid content. The higher pulp thickness resulted in higher retention of ascorbic acid.	Jalgaonkar *et al.*, (2020) [15]
	Apple slices	RW drying preserved maximum concentration compared to hot air drying. At 90℃, 80% retention of ascorbic acid found for refractance drying which is comparable with freeze drying (83%).	Rajoriya *et al.*, (2019) [25]
Carotenoids	Carrots & strawberry	Carotene loss in refractance window drying (total carotene-8.7%; α-carotene-7.4% and β-carotene-9.9%) was comparable with the freeze drying (total carotene-4.0%; α-carotene-2.4%, and β-carotene-5.4%) and maximum loss was observed in drum drying (total carotene-56.1%; α-carotene-55.0%; β-carotene-57.1%)	Abonyi *et al.*, (2002) [1]
	Paprika purees	Highest retention of β-carotene in natural convective drying method followed by refractance window drying, freeze drying and oven drying	Topuz *et al.*, (2011) [32]
Antioxidant activity	Blanched Aspargus Slices	Dried asparagus showed significantly higher values than tray dried and combined microwave spouted bed drying.	Nindo *et al.*, (2003) [20]
	Aloe vera	In refractance window drying 29.6% inhibition of DPPH radicals while, 54.1% inhibition of DPPH radicals for spray drying and 27.0% for freeze drying.	Nindo and tang (2007) [21]
Colour	Thawed frozen carrot puree	Higher L, a, b & chroma values; more saturated red and yellow colour for refractance window drying samples while freeze dried carrot puree exhibited brighter colour.	Aboyni *et al.*, (2002) [1]
	Thawed frozen mango puree	Showed characteristic yellow colour than the freeze dried powder; higher chroma and hue values.	Caparino *et al.*, (2013) [7]

3.4 Antioxidant activity

Measuring the antioxidant activity is a widely used method for assessing the ability of foods to inhibit or scavenge reactive oxygen species (ROS). Baeghbali *et al.*, (2016) [3] found that the antioxidant (AO) activity in reconstituted pomegranate juice after refractance window drying was comparable to the freeze dried sample and significantly higher than the spray-dried (SD) product. According to Nayak *et al.*, (2011) [19], dehydration methods such as freeze drying (FD), drum drying (DD), and refractance window drying of blanched coloured potatoes (*Solanum tuberosum* L.) for the production of potato flakes resulted in no significant losses in the total antioxidant (AO) capacity. These coloured potatoes, mainly purple, containing polyphenols, carotenoids, and ascorbic acid, can serve as an excellent source of AO-rich ingredients for the development of nutritionally enhanced food products.

Nindo *et al.*, (2003) [20] has obtained the highest retention of total AO activity after combined microwave and spouted bed drying of asparagus. Refractance window drying and freeze drying significantly enhanced this AO capacity compared with using heated air. According to Pavan (2010) [22], freeze drying (FD) demonstrated superiority in retaining the antioxidant (AO) capacity of açai fruit, known for its high antioxidant properties. Refractance window drying (RWD) exhibited a higher AO capacity value compared to air drying (AD) powders. These findings suggest that refractance window drying is a promising technology for producing powders with a high AO capacity, based on the studies mentioned above.

3.5 Colour

The quality of food is significantly influenced by its color, which directly impacts consumer acceptance (Tontul and Topuz, 2017) [31]. Changes in the color of dried products indicate the intensity of drying methods and conditions employed. The color of food products is closely associated with the concentration of pigments. Due to its gentle nature, refractance window drying causes minimal alterations in color parameters, resulting in less formation of undesirable pigments (Topuz *et al.*, 2009) [33]. In the study conducted by Caparino *et al.*, (2013) [7], the color characteristics of mango powder were examined using various drying methods: RW drying (circulating hot water temperature of 95 and 97 °C), freeze drying (FD) (20 Pa, condenser at 60 °C), drum drying (152 °C), and spray drying (SD) (inlet temperature of 190 °C and outlet temperature of 90 °C). The color difference between RW dried powder and FD powder was not significantly different. However, significant differences were observed in the L value among the powders produced by all four drying methods, except for refractance window drying and freeze dried powder with particle sizes of 500 and 350 µm, which showed no significant difference. Furthermore, for the smallest particle size of 180 µm, refractance window drying, freeze drying and drum-dried powders exhibited identical L-values, indicating an insignificant effect on reflectance. The researchers noted that spray-dried particles displayed the lightest color powders, attributed to the incorporation of maltodextrin, which helps reduce stickiness and facilitates efficient drying. Conversely, the darker color observed in drum-dried products can be attributed to the high drying temperature, leading to browning reactions or Maillard reactions resulting from chemical interactions between sugars and proteins. The predominant color in mango powder, represented by the b* value, is yellow. No significant variation in the b* value was observed between refractance window dried and freeze-dried powder, whereas a significant variation was noted between spray-dried and drum-dried powder.

Shende and Datta (2019) [27] conducted a study on drying mango puree using a refractive window dryer, oven dryer, and tray dryer to produce mango powder. The findings indicated that the refractive window dried mango powder exhibited a brighter color compared to the other two drying methods. This was attributed to the moderate time-temperature combination employed during refractive window drying, which resulted in minimal pigment degradation. The refractive window dried mango powder showed higher L* value and b* value, indicating increased lightness and yellowness, respectively, while the a* value was lower, indicating reduced redness. These color attributes reflect the limited degradation of pigments during the drying process. Baeghbali *et al.,* (2016) [3] found that there was no significant difference in the 'a' value, which indicates the redness, between pomegranate powder obtained from a refractive window dryer and a freeze dryer. However, the spray-dried product exhibited the lowest 'a' value, suggesting a greater loss of anthocyanin pigment. This indicated that the spray drying process resulted in a more pronounced reduction in the red color associated with anthocyanin content compared to the other drying methods.

According to Singh (2019) [29], guava, which is a good source of vitamin C, tends to darken when dried using a hot air dryer due to non-enzymatic browning. The study revealed that guava powder obtained through the refractive window drying method exhibited a lower total color change (ΔE) value compared to powder obtained from a convective tray dryer. Similarly, when kiwi was dried using a refractive window dryer, it resulted in a lower ΔE value compared to oven drying. This lower ΔE value indicates reduced carotenoid decomposition and the formation of undesirable pigments during the drying process. Hence, the refractive window drying method helped preserve the natural color of guava and kiwi by minimizing colour changes and maintaining the integrity of carotenoids.

4. Conclusion

The refractance window drying is a novel fourth generation thin layer drying technology alternative to existing techniques. Various research studies proved that refractance window drying is gentle dehydration technique to produce safe dried products. As drying is conducted at reduced temperature, this technique can be effectively used for thermally sensitive and nutritional compounds such as ascorbic acid, anthocyanin, antioxidant activity, carotenoids and colour. Temperature and thickness of the sample has significant effect on quality and physico-chemical properties of final dried product. It offers faster drying time compared to other drying techniques which results in high quality products. The quality of refractance window dried products is similar to the freeze-dried material with the very less equipment cost. The refractance window drying is favourable technique with high potential to retain the nutritional and quality parameters and extend the shelf life of liquid foods.

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