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Refractive window drying: Review

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Abstract
Refractive window drying is a novel drying method used for drying of slices, puree and juice of fruits and vegetables. In this method, product spread on the Mylar film forming thin layer. When the hot water below boiling temperature circulates in contact with below film. Thermal energy of the water receives by the product and moisture from the product removes. Refractive window drying is energy efficient and quick drying method and requires less energy and cost of operation. It helps to maintains better dried product quality in terms of nutrient and sensory attributes. This article reviews the working principle, mechanism and energy efficiency of refractive window drying. Also tries to highlight required development and future scope of refractive window drying method.

Keywords: Refractive window drying, food quality, quality attributes, drying temperature, energy efficiency, juice powder

Introduction

Drying is an operation where water is removed from products through application of heat up to a predetermined level. The end product result may be in the form of sheets, flakes, film, powder, or granules. The drying process is different from evaporation, in which final product is a liquid with a high concentration of dissolved solids. These dehydration processes require high amount of energy yet have been used in the food industry from long time to provide microbial stability, reduce deteriorative chemical reactions, facilitate storage, and minimize transportation costs. Even though these objectives of drying as a unit operation are still relevant and important. As consumers prefer more nutritious and health-promoting bioactive product. In response to this demand, development activities in the design of food dryers include product quality as a major criterion of dryer performance [Chou *et al*., 2001 and Mujumdar *et al*., 2001] [12, 17].

The quality of nutrients obtained in dried product depends upon the methods of drying and heat applied on the product [Bhandari *et al*., 1997] [7]. Sun or shade drying is the traditional method of drying used for drying of fruit puree to obtain leather. As the sun drying is free of cost, no need any equipment and it is fuel free [Tontul and Topuz, 2017] [18]. But sun drying have many disadvantages like having not control over drying period, environmental conditions, microbial contamination [Suna *et al*., 2014] [36]. To overcome these disadvantages the hot air drying, oven drying, and infrared drying can be used [Suna *et al*., 2014 and Quintero *et al*., 2012] [36, 24].

Freeze drying has been used to produce dehydrated products with good retention of shape, flavour, colour, vitamins, and rehydration ability. However, the cost of freeze drying is several times higher than spray drying [Chou *et al*., 2001 and Mujumdar *et al*., 2001] [12, 17] and air-drying [Ratti C., 2001 and Clarke P.T., 2004] [31, 13]. Freeze dried products may be porous and again rehydrated when exposed to environmental conditions [Nijhuis *et al*., 1996 and Abascal *et al*., 2005] [20, 1]. Therefore, new drying techniques are needed to be developed to provide the drying operation significant in cost of dehydration, product quality, energy consumption, productivity, safety, and environmental impact [Mujumdar *et al*., 2001] [17].

Refractive window drying is new drying technology. The first research carried on refractive window drying by Abonyi *et al*., 2002 [2]. The research was carried on the Quality Retention in Strawberry and Carrot Purees by refractive window drying method. Refractive window drying is similar to drum drying in which the product dried in thin layer on heated surface. In Refractive window drying the heated surface temperature is lower i.e., 70 to 85 °C as compared to drum drying (120 to 150 °C). It is a suitable method of drying of heat sensitive products like fruits and vegetable purees, juices and slices convert into sheets, powder or flakes.

As compared to conventional drying methods it provides less energy consumption, less drying time, and less drying temperature. The quality of the obtained product is better than the freeze-drying method [Mujumdar A.S. and Menon A.S., 1995] [18].
The objective of this review paper is to discuss refractive window drying system. As it is a novel drying system there is an increased need to explore the technology. This article covers the basic principle of refractive window drying, heat and mass transfer process, energy efficiency of drying process and nutritional and sensory quality of the obtained product. Also, the present study tries to highlight the future scope of refractive window dying.

2. Principle of Refractive Window Drying
Refractive window drying is also known as conductive hydro drying [Baeghbali *et al.*, 2019] [4]. The various parts of refractive window drying system is shown in Fig. 1. Refractive window drying system consist of Mylar film which transmit radiant heat energy to product and convey product from one side to another side. The film works as conveyor belt supported by two end pulleys on which film moves during drying process. Hot water circulates below the belt at temperature of 95 to 97 °C which provides thermal energy to the product. The product i.e., juice or puree spread over the belt which moves on hot circulating water in shallow trough. The water recycled continuously throughout the process. When the product is dried, then it is moved over the cold water which enables easy separation of product from the film. Then the product scraped off from the belt using scraping device. The time of product kept on belt for drying up to 3 to 5 min [Abonyi *et al*., 2002] [2].

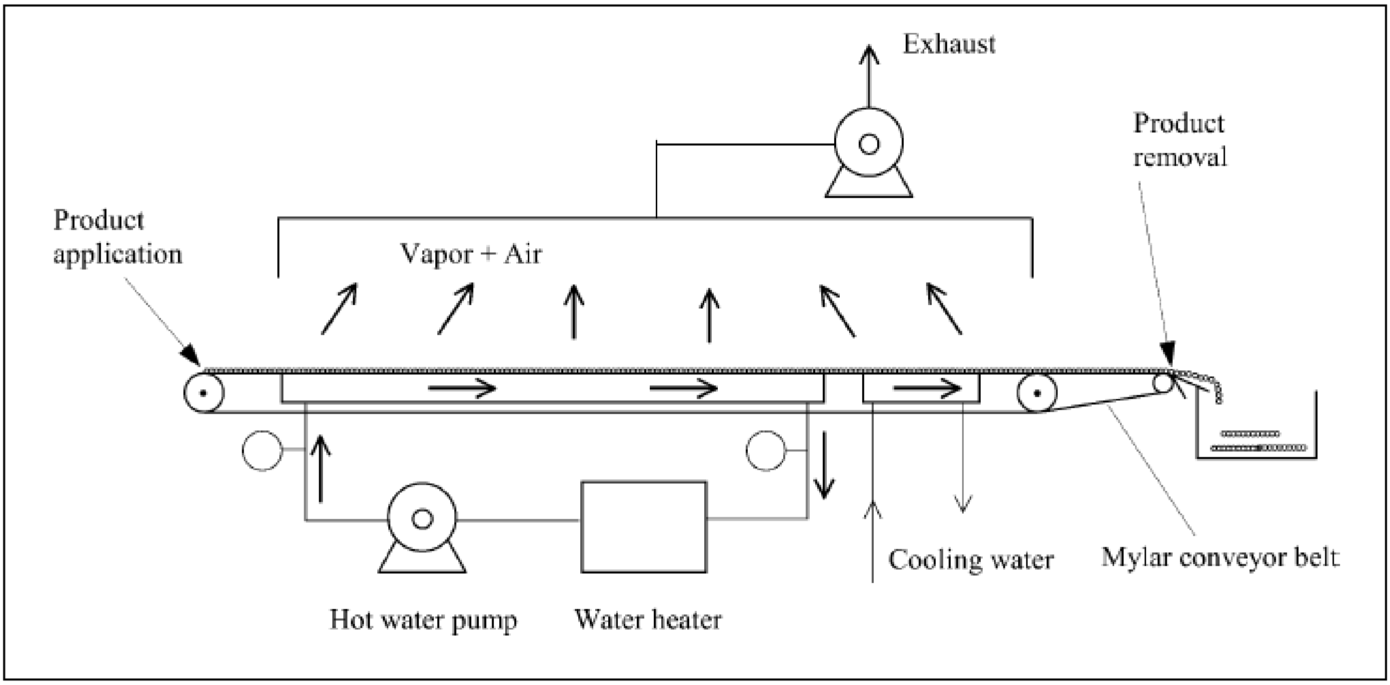

Fig 1: Schematic diagram of Refractive Window drying system.

For drying the product, heat is transferred through the film. There is no contact occurs between the heating medium and product therefore cross contamination does not occur in this system [Raouzeous G., 2003] [32]. The heat transmissivity depends on the thickness of the transferring film. As the film is thin, heat transmissivity is more but the mechanical strength reduces. Therefore, optimum thickness of the film determined as 0.25 mm [Zotarelli *et al*., 2015] [10].
The absorptivity of material to be dried depend upon thickness of the product and moisture content of the product [Nindo C.I. and Tang J., 2007] [21]. As the product over the film comes in contact with the hot water surface the window for infrared heat will be formed and allows passage for direct heat transfer of infrared heat energy through film. This is a self-governing process as the dying material progresses over the belt with drying of product, the window of infrared energy gradually closes when less moisture present in the product and product left at the final temperature at 70 and 75 °C [Sabarez H., 2016] [33].

3. Heat transfer and moisture removal process in refractive window drying
In refractive window drying process, there are three modes of heat transfer occur conduction (q_{cond}), convection (q_{conv}) and radiation (q_{rad}) as shown in Fig. 2. The hot water is heated by the steam and circulated in shallow trough below the plastic film to transfer thermal energy from to the product. As the thickness of the plastic film is thin, it reaches the hot water temperature quickly. Thermal energy of hot water transmitted through the plastic film conveyor by conduction and radiation mode. The contribution of conduction and radiation mode of heat transfer still needs to investigate. The temperature of hot water is always kept below the boiling point of water. A thick plastic film with low thermal conductivity creates higher thermal resistance to transfer of thermal energy [Nindo C.I. and Tang J., 2007] [21].

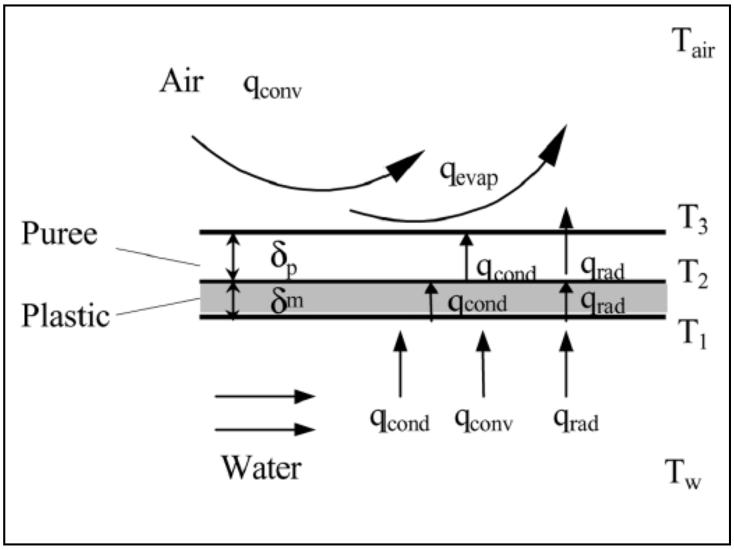

Fig 2: Schematic diagram of thermal energy transfer in refractive window drying system.

In refractive window drying process, infrared transmission of thermal energy is greater when plastic film is in intimate contact with water on one side and a moisture laden material on other side. When the high moisture product puree spread on the plastic film refraction at the plastic puree interface is minimized causing radiant thermal energy to pass through the plastic film. The absorptivity of the product puree affected by thickness and moisture content of puree [Nindo *et al.*, 2003] [22, 23]. It is observed that increase in thickness from 2 mm to 3mm increases drying time up to 30 % i.e., 17 to 22 min and decrease in drying rate up to 43 % when heating water temperature at 95°C to get moisture content of final product at 3 % dry bulb [Castoldi *et al.*, 2015] [10].

Refractive window drying of strawberry puree found that product dried within 5 min as compared to other drying processes which takes several hours to dry the product like tray drying and freeze drying of same material. The drying rate of strawberry puree shown in Fig. 3. The temperature of water kept at 95 °C and thickness of puree about 1 mm. Due to rapid mass transfer process the interaction of the product with oxygen is less which helps to maintain the quality of the product [Nindo C.I. and Tang J., 2007] [21].

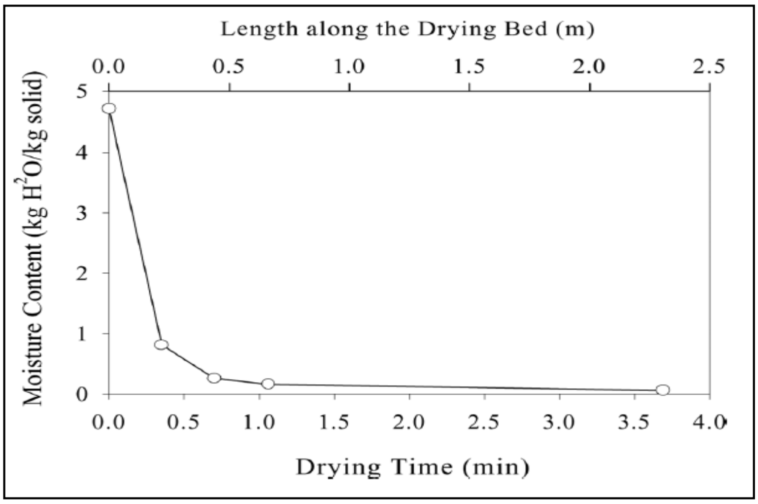

Fig 3: Drying rate of strawberry puree in refractive window drying system [Nindo C.I. and Tang J., 2007] [21].

4. Energy Requirement in Refractive Window Drying

During refractive window drying process high-rate moisture evaporation takes place when thermal energy of hot water absorbed by the high moisture product. Due to formation of air gap between the product and film, can cause evaporative cooling during the drying operation [Ortiz-Jerez and Ochoa-Martínez, 2015] [25]. Compare to drum drying thermal efficiency of refractive window drying system is in the range of 52 – 77 %. And the hot air-drying system offers only 50% thermal efficiency as compared to refractive window dryers [Strumillo *et al.*, 1995] [35]. Compared to rotary dryer refractive window drying system has much lower capacity but has comparable operational capacity with spray dryer and drum dryers [Mujumdar and Menon, 1995, Kostoglou and Korapantsios, 2003 and Nindo and Tang, 2007] [18, 15, 21]. Cost requires for refractive window drying system is 30 – 50 % of freeze-drying system and require less than 50 % energy to dry same mass of product [Nindo and Tang, 2007] [21]. Abonyi *et al.*, 2002 [2] reported that overall energy efficiency for carrot and strawberry puree was 37.9 % and 27.9 % respectively. Similar results obtain in drying of pomegranate juice with refractive window drying system [Baeghbali *et al*. 2016] [6].

Comparison of different drying methods with refractive window drying for different fruits and vegetables has shown in Table 1.

Table 1: Comparison of different drying methods for various fruits and vegetables

Sr. No.	Product	Drying method	Parameter	Obtain result	Reference
1	Açaí berry	Refractive window drying	Moisture content (g/100 g wb)	2.19	Pavan *et al.*, 2012 [26]
			Water activity	0.240	
		Freeze drying	Moisture content (g/100 g wb)	1.55	
			Water activity	0.196	
		Hot air drying	Moisture content (g/100 g wb)	1.36	
			Water activity	0.119	
2	Pomegranate	Refractive window drying	Total anthocyanins content (mg cyanidin-3-glucoside/100 ml	10.771	Baeghbali *et al.*, 2016 [6].
			Antioxidant activity	12.947	
			Energy consumption (kWh) per 1 kg sample	4.31	
			Overall energy efficiency (%)	31.56	
		Freeze drying	Total anthocyanins content (mg cyanidin-3-glucoside/100 ml	9.017	
			Antioxidant activity	12.656	
			Energy consumption (kWh) per 1kg sample	130.65	
			Overall energy efficiency (%)	1.12	
		Spray drying	Total anthocyanins content (mg cyanidin-3-glucoside/100 ml	7.723	
			Antioxidant activity	9.979	
			Energy consumption (kWh) per 1kg sample	11.01	
			Overall energy efficiency (%)	12.92	
3	Apple slices	Refractive window drying	Overall energy efficiency (%)	37.7	Baeghbali *et al.*, 2019 [5].
		Freeze drying	Overall energy efficiency (%)	2.0	
		Cabinet drying	Overall energy efficiency (%)	27.6	
4	Carrot puree	Refractive window drying	Overall energy efficiency (%)	32.3	Abony *et al.*, 1999 [3].
5	Strawberry Puree	Refractive window drying	Overall energy efficiency (%)	23.4	
6	Pumpkin puree	Refractive window drying	Overall energy efficiency (%)	28.7 - 34.8	Nindo *et al.*, 2003 [22, 23].
7	Asparagus	Refractive window drying	Drying rate (% db/min)	1301	Nindo *et al.*, 2003 [22, 23].
		Freeze drying	Drying rate (% db/min)	1.0 - 0.8	
		Tray drying	Drying rate (% db/min) at 70 °C	10.4	

5. Quality parameters of Powder obtain from Refractive Window drying

It is observed that bulk density of pomegranate juice powder obtained from refractive window (343.1 kg/m3) drying was higher than spray drying (322.1 kg/m3) but the difference is non-significant. Powder obtained from refractive window drying is flake in structure and powder obtained from spray drying is fine structure. Also, bulk density of powder significantly lower because of low moisture content [Baeghbali *et al*., 2016] [6].

Ochoa- Martínez *et al*. (2012) [24] reported that to acquire water activity of mango slices below 0.5 require 60 min with refractive window dying where tray drying require 240 min. As thickness of slice increases water activity of slices increases in both type of drying. Due to low water activity shelf life of refractive window dried product would be higher and less prone to microbial attack in storage period. Water absorption capacity of refractive window dried product would be less due to less surface area and compact structure than other drying methods like freeze drying, spray drying and drum drying [Pavan *et al*., 2012] [26].

Colour of the powder product is a very important parameter in acceptance and rejection by the consumer. Abonyi *et al.*, (2002) [2] evaluate the colour properties of strawberry and carrot puree dried powders. It was observed that refractive window dried samples are darker than freeze dried sample in case of L* value. No substantial difference was observed in freeze and refractive window dried samples in case of a* and b* value. High temperature during drying involves browning or Millard reaction due to chemical reaction of sugars, proteins, and sugar caramelization [Potter and Hotchkiss, 2012] [27].

Caparino *et al.*, 2017 [8] reported that the colour and ascorbic acid retention of mango powder dried by refractive window drying method was 68.2 to 9.5 % for stored at 22 °C and 5 °C for 6 and 12 months. Nitrogen flushing in stored packages of dried mango powder significantly reduce loss of β-carotene from 21.8 to 26.1 % at 45 °C. There is no significant difference occurs between the ascorbic acid content of refractive window dried and freeze-dried powder of tomato juice [Baeghbali *et al.* 2016] [6]. It was observed that in refractive window drying, ascorbic acid retention in strawberry and carrot purees are 93.6 % as compared to freeze drying. Similarly, the carotene losses in refractive window drying were 8.7% (total carotene), 7.4% (α-carotene), and 9.9% (β-carotene) [Abonyi *et al.*, 2002] [2].

Anthocyanins which present in plants are valuable nutritional phytochemicals susceptible to drying process. It is observed that, in process of coloured potato drying 45, 41 and 23 % losses occur in total anthocyanins content in freeze drying, drum drying and refractive window drying system respectively [Nayak *et al.*, 2011] [19]. Puree of Haskap berry dried using refractive window dryer and it is observed that more than 92 % anthocyanin retained [Celli *et al.*, 2016] [11].

Refractive window drying considered as a good drying method in terms of physiochemical quality retention properties of powder product as compared to freeze drying method. It can also reduce the microbial load in dried products. In the study of pumpkin puree drying, it is observed that the log reduction of total aerobic plate count of coliforms, Escherchia coli, and Listeria innocua was 4.6, 6.1, 6.0 and 5.5 respectively [Baeghbali V. and Niakousari M., 2018] [5].

The obtained quality parameter of refractive window dried powder for different fruits and vegetables shown in Table 2.

Table 2: Quality parameter of refractive window dried powder of different fruit and vegetables

Sr. No.	Product	Quality parameter	Result obtained	Reference
1	Haskap berry	Microscopic structure	Irregular with smooth surface and similar thickness	Celli *et al.*, 2016 [11]
		Solubility	75.63 %	
		Powder moisture content	2.9 %	
		Total anthocyanin content	93.8 %	
2	Mango	Powder properties	Sooth edges of powder particle	Caparino *et al.*, 2012 [9]
		Colour	Significantly no difference with freeze dried sample	
		Particle size	500 µm	
3	Chickpea protein isolates	Moisture content	2.86 g/100g	Tontul *et al.*, 2018 [37]
		Water activity	0.178 – 0.180	
		Surface hydrophobicity	50 % higher than freeze dried sample	
		Protein Solubility	74.5 %	
4	Pomegranate	Moisture content	5.38 %	Baeghbali *et al.*, 2016 [6]
		Bulk density	343.1 kg/m^3	
		Solubility	92.9 %	
		Total anthocyanins content	10.771 (mg cyanidin-3-glucoside/100 ml of juice)	
		Antioxidant activity	12.947 %	
5	Goldenberry (*Physalis peruviana L.*)	Moisture content	10.62 g/100g	Puente *et al.*, 2020 [28]
		Water activity	0.375	
		Total amino acids	66.86 g/100g	
		Total carotenoid content	57.57 (µg/g)	
		Colour	colour parameters closer to the FD samples	
6	Asparagus	Total antioxidant Activity	73.2 µmol/g	Nindo *et al.*, 2003 [22, 23]
		Colour	closest in greenness to the freeze-dried sample	
		Moisture content	0.04 g	
7	Apple slices	Microstructure	Pours with slight shrinkage	Rajoriya *et al.*, 2019 [30]
		Ascorbic Acid Retention	70 to 80 %	
		Colour	Lower overall colour difference	
8	Carrot	Moisture content	6.1 % (db)	Abonyi *et al.*, 2002 [2]
		Carotene retention	1.62 g/g solid	
9	Strawberry	Moisture content	9.9 % (db)	Abonyi *et al.*, 2002 [2]
		Ascorbic acid retention	1.69 mg/g solid	
		Colour	Colour values closer to freeze dried samples	
10	Sapota	Moisture content	16 g water/100 g	Jalgaonkar *et al.*, 2018 [14]
		Ascorbic acid	10.7mg/100 g	
		Hardness	26.2 kgf,	
		Cohesiveness	0.21	
		Gumminess	5.37 kgf,	
		Chewiness	3.12 kgf	
		Colour	Decrease in brightness value	

6. Case Study on Refractive Window Drying on Açaí Berry Juice

Açaí is a dark purple berry native of Amazon region in Brazil, and it is widely consumed in South America. Açaí berry fruit contain high antioxidant properties. It is highly perishable and necessary to processed quickly after harvesting to preserve its nutritional quality, sensory attributes and bioactive compounds. Freeze drying of Açaí berry fruit produces high quality products, but the high cost and capital investment require for the process. Mariana, (2010) [16] studied effect on quality parameter of refractive window drying of Açaí berry fruit juice in comparison with freeze drying and hot air drying. After the drying of juice, storage study is carried out for 3 months at 25 °C. Analysis on moisture content, water activity, colour, antioxidant capacity, anthocyanin quantification and flavour analysis were carried out.

It is observed that the moisture content of all dried samples was 2.19 g/100g (wb) which is below the monolayer values. Water activity value of refractive window dried sample was 0.240 after drying and during storage of 5-month period indicating the good product stability. Drying operation effects on both colour and flavour of açaí juice. Storage study revealed that decrease in lightness of the sample occurs because of formulation of brown pigment by Millard reaction and polymerization of oxidized phenolic compounds. For the best anthocyanin and antioxidant capacity retention in fruit, freeze drying method was observed as the better option. Refractive window dried samples shown good retention of anthocyanin content similar to freeze dried samples and antioxidant capacity higher than that of hot air-dried powders. No change was observed in anthocyanin content and antioxidant capacity during the storage [Mariana, 2010] [16].

7. Future Scope of Refractive Window Drying System

Refractive window drying have bright scope in the novel trends in drying. It is used to dry the puree and juices of various fruits and vegetables. There is a need to do research on the effect of drying with this system on dairy product such as milk. The removal of moisture from the starchy products are necessary to observe with this method of drying. In the process of refractive window drying, the product gets heated from the hot water in uncontrolled manner therefore there is need to study the controlled heat supply to the product. Many studies revealed that heat from the product gets in using conduction, convection and radiation ways. The study on individual method of heating needs to be carried out for achieving effective and major affecting heating method on product. Refractive window drying system requires wide area to dry the product, which affects the thickness of the product spread which reduces the processing capacity of the system. It also requires bulky dryer system and commercial installment in plant acquiring space and requiring cost. Therefore, further research is necessary for developing efficient drying system for industrial application.

8. Conclusions
Refractive window drying is a new method of drying of heat sensitive products such as fruit, vegetable juices and purees. High quality product obtained from this method of drying contains good retention of nutrients and antioxidants. It is an efficient method of drying as compared to spray, drum drying and freeze-drying methods. The system consists of moving Mylar film belt and heating hot water less than boiling temperature below the belt making contact with the film. The product is spread over the film for drying. Heat energy is given to the product in this system by the hot water through contacting plastic film of particular thickness. Product gets heated by the way of radiation, conduction, and convection ways through which the water evaporates from the product. Cost of operation and energy consumption of refractive window drying system require much less than other drying method. This method helps to maintain the sensory quality of end product after drying and also during storage. It can also help to reduce the microbial load in the product. A study is carried out on refractive window drying of Açaí, which is a dark purple berry juice which is native of South America and widely consumed by native people. The study observed that the powder obtained from refractive window drying method retain similar capacity of anthocyanin and antioxidant content as freeze-dried powder.

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