Available online at www.ijiere.com

International Journal of Innovative and Emerging Research in Engineering

e-ISSN: 2394 - 3343 p-ISSN: 2394 - 5494

Refractance Window Technology – A Promising Drying Technique for the Food Industry

Maharshi Trivedi[a], Venecia D'costa[a], Jayati Shitut[a], S. Srivastav[a]
[a]Department of Food Processing Technology, A. D. Patel Institute of Technology, Anand, India

ABSTRACT:
Drying of food in recent days has gained a huge importance in food industries offering opportunities in ingredient development over and above novel and superior quality products to consumers. Recent research has revealed that a novel approach based on Refractance window technology can be now adopted to improve the efficiency and efficacy of drying so that energy consumption can be reduced whilst at the same time preserving the quality of the end product.This paper presents the principle and focuses on the benefits of Refractance Window drying, highlighting some results that exhibit its potential compared with other dryers in use for processing fruits, vegetables, and other heat-sensitive products.

Key words: Refractance Window drying, freeze drying, drum dryer, spray dryer, nutritional status of mango slices, tomato powder

1. INTRODUCTION

Fruits and vegetables are dried to enhance storage stability, minimize packaging requirement and reduce transport weight. Energy consumption and quality of dried products are critical parameters in the selection of drying process. An optimum drying system for the preparation of quality dehydrated products is cost effective as it shortens the drying time and cause minimum damage to the product. To reduce the energy utilization and operational cost new dimensions came up in drying techniques (Sagar.V *et al.* 2010). New drying techniques are emerging that provide certain significant advantages in terms of one or more of the following: energy consumption, product quality, safety, environmental impact, cost of dehydration, and productivity (Mujumdar, A.S. 2001).

Vega-Mercado (2001) divides all drying technologies into generations as follows: -

I. First generation – involves the use of air flowing over a product to remove water predominately from the surface of the material. For food applications these are more suitable for grains, slices and chunks.
II. Second generation – drying methods designed for liquids, slurries and purees. The food industry utilizes these in spray dryers, fluid bed dryers and roller dryers in particular.
III. Third generation – freeze and osmotic drying are two examples of this generation of methods and are employed in the food industry to better maintain structural and quality issues.
IV. Fourth generation – these are the latest developments in dehydration and include high vacuum, microwaves, radio frequency and Refractance Windows (RW).

For efficient dehydration of heat-sensitive foods, a drying technique patented by Richard Magoon (1986) was developed by MCD Technologies, Inc. (Tacoma, WA) and designated as the Refractance Window (RW). This technique features a temperature inside the food of less than 70 °C and short drying times that depend on the thickness of the drying product (3–5 min for purée materials). Essentially, the material to be dried in the form of pulp, juice or sliced food (fruit or vegetable) is placed on a plastic film which is transparent to infrared radiation and has special characteristics regarding refraction (e.g. Mylar). This film floats on the surface of hot water kept at 95–97 °C so that the thermal energy for moisture evaporation is transferred from the hot water to the wet material mostly through the infrared radiation (Nindo and Tang, 2007; Nindo et al., 2003; Kudra and Mujumdar, 2009).

The Refractance Window dryer discussed in this article is a relatively new development that falls within the contact, indirect, or film-drying techniques. In this drying method, thermal energy from hot water is transferred to wet material deposited as thin film on a plastic conveyor belt (as shown in the fig.1.). The belt moves while in contact with the hot water and results in very rapid drying. The dry product is then scraped off the conveyor using a doctor blade that spans the full width of the belt. The heated water is recycled and reused, thereby improving the thermal efficiency of the system. The use of hot water as the heat transfer medium and at temperatures just below boiling is a design feature that is unique to this drying method (Nindo and Tang, 2007). The use of process water at temperatures just below boiling and a thin plastic conveyor with infrared transmission in the wavelength range that matches the absorption spectrum for water all work together to facilitate rapid drying. A thicker plastic material with low thermal conductivity, on the other hand, would provide higher resistance to transfer of thermal energy.
Water has high absorption for infrared with wavelengths of 3.0, 4.7, 6.0, and 15.3 mm (Sandu. C *et. al.* 1986). According to the inventors of RW drying system, the infrared transmission is stronger when the plastic interface is in intimate contact with water on one side and a moisture-laden material on the other side. Unlike direct dryers, cross contamination does not occur in indirect dryers such as RW system because the product does not contact the heat transfer medium. Other indirect or contact drying methods that closely relate to RW drying include drum and the solid steel belt or combined cylinder and belt (CBD) dryers. Most contact dryers use saturated steam, hot water, glycol solutions, or some commercially available heat transfer fluids for heating (Nindo and Tang, 2007).

Nindo and his group (C.I Nindo *et al.* 2006) attempted to develop an evaporator based on the Refractance Window technology. The system utilizes circulating process water, usually at 95–98 ^{o}C, to convey thermal energy via a transparent plastic interface to concentrate fluid products that make several passes on the surface of the plastic sheet. The evaporator can function either as stand-alone equipment or be used to preconcentrate fluid foods before drying. The principles of operation are the same for the evaporation equipment but the configuration is different with the bed being at an angle. This equipment allows for the concentration of liquids to higher total solids by partial removal of moisture whilst maintaining a liquid state (Phillip T. Clarke, 2004).

THE REFRACTANCE WINDOW PRINCIPLE:

The diagrammatic representation of the concept of working of Refractance window technology is shown below:

1. Infrared energy gets transmitted by convection into the water once it is placed over a source of heat. This heating energy is then radiated from water chiefly by evaporation.

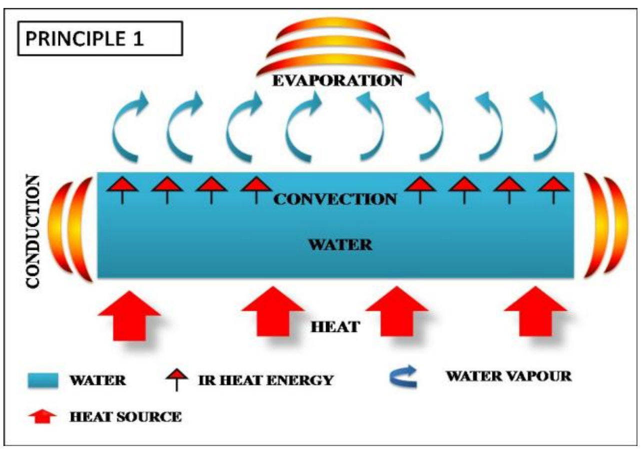

Fig.2. Principle 1-When water is heated

2. If this hot water is covered by a membrane that is transparent to the infrared heat radiation present in water, evaporation and its related heat losses will be blocked or refracted and thus conduction solely occurs. The membrane acts as if it's a mirror that reflects the infrared heat energy back in the water.

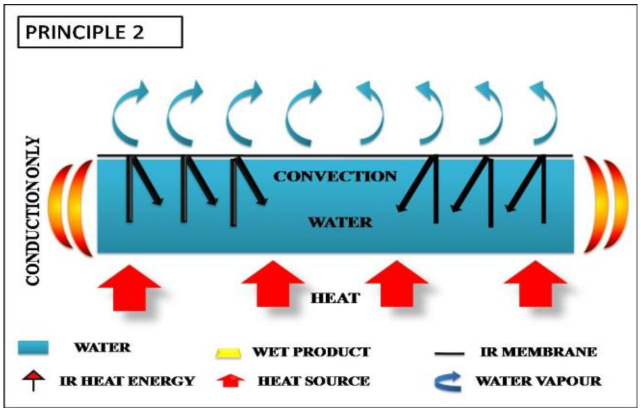

Fig.3. Principle 2-When hot water is covered by an IR

3. But when the surface of the membrane is laden with a moist product, the water in the product will create a "window" 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.

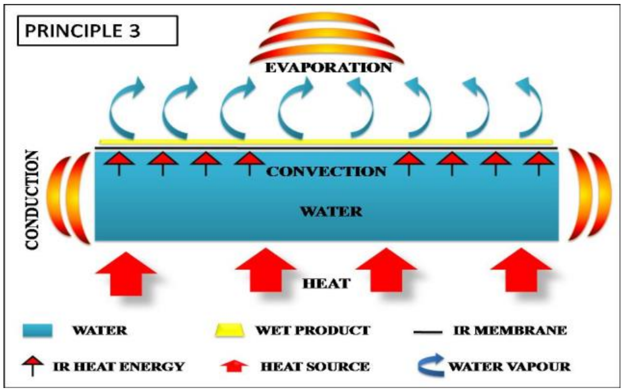

Fig.4. Principle 3 – When wet product is applied uniformly on IR membrane

4. As time proceeds, the water in the product covered on the membrane gets evaporated and the "window" closes and infrared energy is "refracted" into the hot water and thus the material is no longer exposed to heat.

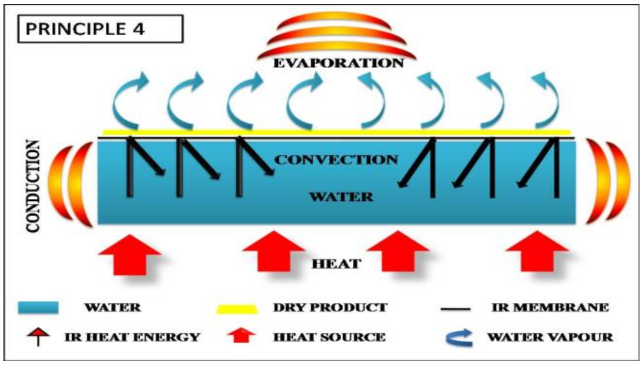

Fig.5. Principle 4-When dried product is obtained

EVALUATION OF REFRACTANCE WINDOW DRYING

1. HEAT TRANSFER AND DRYING KINETICS

During RW drying, the three modes of heat transfer namely conduction, convection and radiation are active. The process water is heated by steam within an insulated tank and then circulated in shallow troughs to transfer thermal energy to the plastic conveyor. Since the plastic conveyor is very thin, it reaches the temperature of hot water flowing beneath it almost immediately. Thermal energy from the hot water is transmitted through the plastic conveyor by conduction and radiation. In the last stage of RW drying when the product is almost dry, heat transfer by conduction becomes predominant and the rate of heat transfer to the product slows as the product dries further. The cooling section at the discharge end of the RW dryer is intended to reduce the product temperature, preferably to below the glass transition temperature of the product, to facilitate product removal (Nindo and Tang, 2007).

1.1. Drying kinetics

The drying rate curves (as shown in fig.6.) reveals that while it takes 6 minutes to remove 1kg of water from carrot puree with the Refractance Window™ system, it takes about twenty times as much 120 minutes to remove 1 kg of water in the tray drier (Abonyi *et al.* 1991).

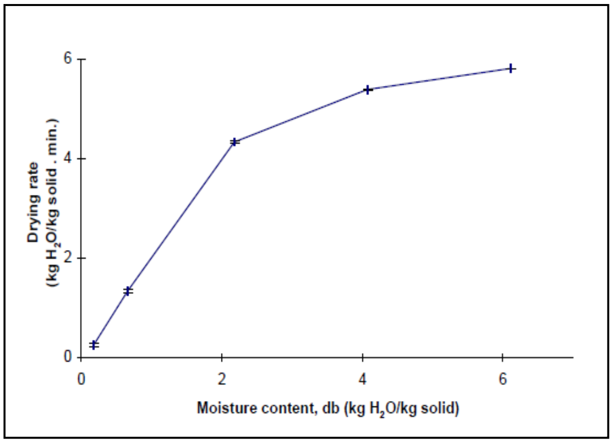

Fig.6. Refractance window drying curve for carrot puree-drying rate v/s moisture content (Abonyi et al. 1991)

1.2. Moisture reduction

Moisture content of Refractance window dried samples was lower than freeze dried samples (V. Baeghbali *et al.* 2010). For RW technique, the moisture content of mango slices decreases rapidly to a value below 5% wb (0.05 db) in about 30 min for 1-mm samples, and 60 min for 2-mm samples. In contrast, it took about 240 min to obtain similar results with the tray drying technique at 62°C (C.I. Ochoa-Martinez *et al.* 2011). Nindo *et al.* (2003b) reported a comparison of the drying kinetics for asparagus purée for the RW and tray drying techniques and concluded that to reach a moisture content of less than 0.1 (db), residence times of 0.074 and 3.5 h were required for RW and tray drying, respectively. Similar results were reported by Abonyi *et al.* (2001) for drying of carrots and strawberry purées, and by Nindo *et al.* (2003a) for drying of pumpkin purée.

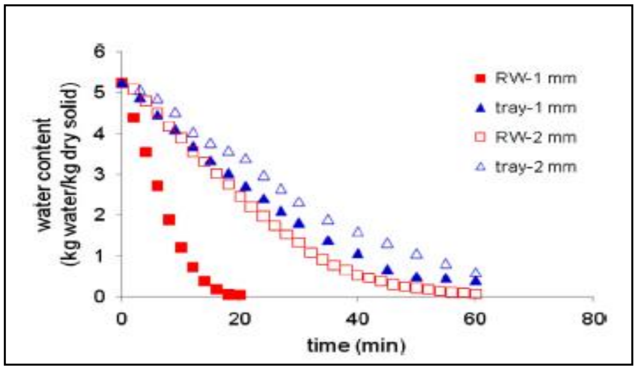

Fig.7. Kinetics of moisture content for RW and tray drying at 90 ℃ for 1mm and 2 mm samples (C.I. Ochoa-Martínez et al. 2011)

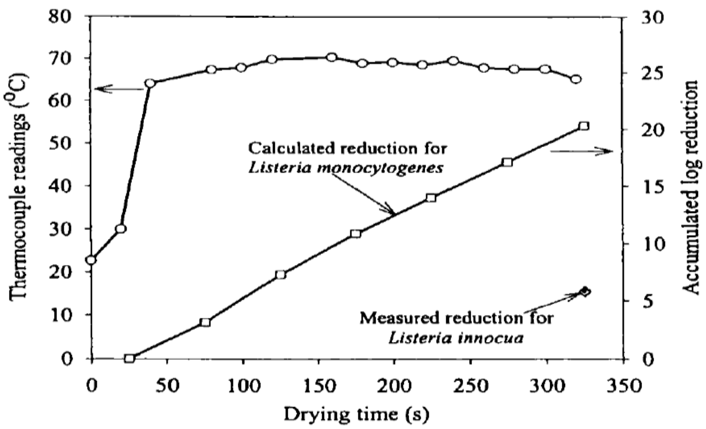

Fig.8.Puree temperature and accumulated log reduction in population of Listeria Monocytogenes as a function of drying time

2.PRODUCT QUALITY

2.1. Microbial reduction

Pre-treatment of raw materials, in particular fruits and vegetables, by blanching or pasteurisation, are often undertaken to reduce the microbial load. However, in the drying of heat sensitive materials the retention of quality aspects such as colour, vitamins and flavour are of such importance that pre-treatment is not always desired and able to be undertaken. This raises concerns about the ultimate safety of the dried product particularly upon reconstitution in applications where the microbial count may increase dramatically in the presence of water. Therefore a drying process that can dehydrate these products and reduce the microbial load to an acceptable level together with the retention of desirable quality attributes would represent an enhanced drying system (Phillip T. Clarke, 2004).

The microbial counts after RW drying were greatly reduced for four microorganisms. At a circulating water temperature of 95°C, R W drying of inoculated pumpkin purees resulted in at least 4.6, 6.1, 6.0, and 5.5 log reductions of total aerobic plate counts (APC), coliforms, *Escherichia coli* and *Listeria innocua* respectively. A typical temperature-time history in pumpkin puree and microbial reduction during drying is presented in Fig. 8. The initial total aerobic count (APC) in non inoculated pumpkin puree was 7.17 log CFU/ml and after drying the APC was reduced to 2.54 log CFU/mL, and 4.63 log reduction. It can be seen that the three test micro-organisms coliform, *Escherichia coli* and *Listeria innocua* were all reduced to well below the minimum detection level of <5 CFU/ml (C I Nindo *et al.* 2003).

Table.1.Microbial count in log cfu/ml as affected by RW drying -Adopted from C.I Nindo et al. (2003)

Mean	**APC**	**Coliforms**	***E. Coli***	***Listeria Innocua***
Control	7.17	6.78	6.73	6.14
Treated	2.54	<0.69	<0.69	<0.69
Log reduction	4.63	6.09	6.04	5.45

2.2. Colour retention

Food color is a major determinant of product quality and affects consumer preferences and may be used as an indicator to predict the chemical and quality changes due to thermal processing (Ahmed.J, 2002) From a consumer acceptance viewpoint, color is an important attribute of the dried product. Color parameters are represented by Hunter a and b values, while any change in a and b values is accompanied by simultaneous change in L values (Khazaei.J, 2008).

Table.2. Color measurement comparison for drying technologies (L* a* b*), darkness factor b*/a* and total color difference ΔE for strawberry -Adapted from Abonyi (2002)

Item	L*	a*	b*	b*/a*	ΔE
Fresh					
No Carrier	36.1	25.6	19.8	0.77	0
With Maltodextrin	45.3	27	22	0.81	0
Spray dried					
No Carrier	ND	ND	ND	ND	ND
With Maltodextrin	77.8	23.9	16.8	0.7	34.4
RW dried					
No Carrier	53.8	27.9	16.9	0.6	18.5
With Maltodextrin	63.2	29.3	20.2	0.7	19.3
Freeze dried					
No Carrier	53.8	30	18.8	0.63	18.7
With Maltodextrin	71.5	25.6	16.6	0.65	28.1

Overall colour retention and colour change due to a range of drying techniques including RW drying were studied by Abonyi (1999), Nindo (2003) and Abonyi (2002). Nindo found that pureed asparagus dried by RW was bright green in colour suggesting that most chlorophyll had been retained. He also noted that RW dried powder was the closest to freeze-dried in greenness. Abonyi (2002) carried out studies on carrot and strawberries. His results for the carrot trials showed that RW drying produced product closer to freeze drying than both drum and spray drying and that RW dried puree was characterised by higher L, a and B and chroma values indicating more vivid and more saturated red and yellow colours both probably due to high carotenoid content and retention. In the studies on strawberries the spray dried samples showed the greatest colour degradation.
The RW product was equal to, or superior to, spray dried material when maltodextrin was added as a carrier to the strawberry puree (Phillip T. Clarke, 2004). Table2 shows a compilation of the results obtained. The color of RW dried mango powder and reconstituted mango puree was comparable to freeze dried (FD) product, while significantly different from drum dried (DD) (darker), and spray dried (SD) (lighter) as shown in fig.9. (O.A. Caparino *et al.* 2012).

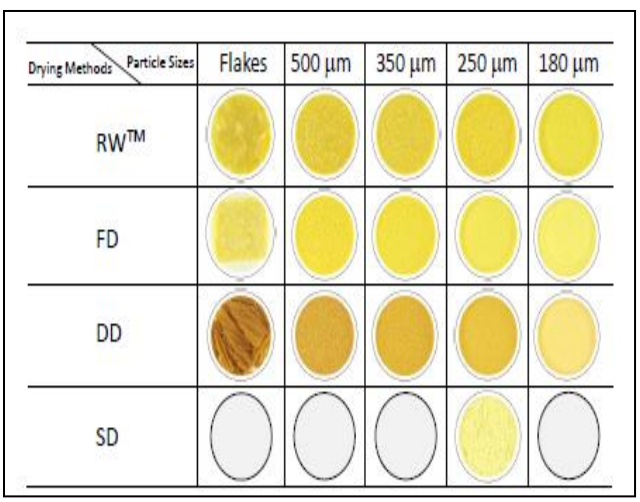

Fig.9. photographs of mango flakes or powder at different particle slices obtained from different drying methods. - Adapted from O.A. Caparino et al. (2012)

2.3. Bioactive Retention

One of the major benefits of the RW drying technology is the retention of nutrients and bioactives in the final powder. This low temperature short time drying technology enables products with attributes much more closely aligned to freeze drying to be manufactured at a lower cost particularly when energy efficiency and throughput are taken into account. Two components of fruits and vegetables which are essential to the human diet but which are both very sensitive to heat are carotene (Vitamin A) and ascorbic acid (Vitamin C). Beta carotene and ascorbic acid together with total antioxidant activity (TAA) are often used as markers to evaluate quality retention and heating effects in different drying technologies and to determine the best conditions for the dehydration of fruits and vegetables in any given drying system (Phillip T. Clarke, 2004).

2.3.1. Ascorbic acid

Ascorbic acid is more sensitive to heat, oxygen and light than most other components in food. In a study on asparagus Nindo (2003) found that using ascorbic acid retention as an indicator for comparison showed that RW dried product was almost identical to the raw material and superior to freeze drying and far superior to all thermal forms of dehydration. This work confirmed that done by Abonyi et al (2002) who showed a loss of ascorbic acid of 6.4% during the drying of strawberries, which was comparable to freeze-drying. Work undertaken at Washington State University for MCD showed similar results for ascorbic acid loss for RW and freeze drying for carrot where the losses were 77% and 82% respectively and for corn they were 59% and 74%.

2.3.2. Total antioxidant activity

TAA of asparagus after RW and freeze-drying was significantly higher than after tray drying, spouted bed and combined microwave spouted bed drying.(CI Nindo,2003)

2.3.3. Carotene

One of the major sources of carotene or vitamin A is carrots. Processing has been shown to reduce the carotene content by up to 82% (Rukimini 1985) depending on the type of process used. Comparative trials were undertaken by Abonyi (1999) between RW, drum drying and freeze-drying as shown in the figure.

Table.3. Comparison of carotene losses in carrot due to RW drying with other methods–Adapted from B.I. Abonyi et al. (1991)

Treatment	Alpha-Carotene loss %	Beta-Carotene loss %	Total carotene loss %
RW dried	7	10	9
Freeze dried	2	5	4
Drum dried	55	57	56
Convection oven			24
Food dehydrator			18
Microwave oven			28.63
Freeze dried		24	45-55
Air dried	82	72	
Explosive puff dried		36	
Air dried		48	

2.4. *Water Activity*

Water activity (aw) is an important variable in drying studies because it determines the quality of a product and its health safety; values lower than 0.6 are typical for preservation of dried mango (Dissa et al., 2008). The drying technique strongly affects the water activity. By using the RW technique, it is possible to reduce aw below 0.5 in 60 min, whereas for tray drying, 240 min are required to bring aw to 0.5.(C.I.Ochoa-Martinez,2012)

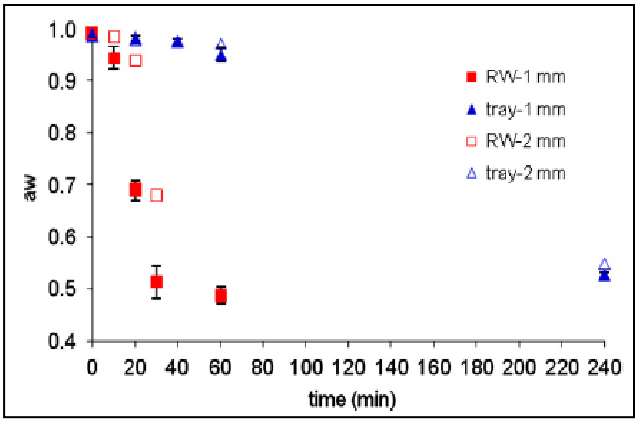

Fig.10. Water activity behavior for RW and tray drying for 1 mm and 2 mm of mango slices (C.I.Ochoa-Martinez,2012)

2.5 *Effective Diffusivity*

C.I. Ochoa-Martínez et al. (2011) studied the drying characteristics of mango slices using the Refractance Window technique and found out that the values of effective diffusivity for RW are higher than those for tray drying (for both values of thickness) showing that the effective diffusivity increases when temperature is higher. The sample temperature for RW drying is close to 70 ºC (according to table.3.), whereas for tray drying is less than 60 ºC (because the air temperature is 62 ºC). This temperature effect on the diffusivity has also been reported by Dissa et al. (2008) and Corzo et al. (2008). The larger diffusivity values are possibly due to the fact that the drying of the thicker sample (2 mm) occurs at a lower temperature (see Fig. 4), and consequently, it undergoes less shrinkage than the thinner sample (1 mm). Thus, the greater shrinkage undergone by the thinner sample ends up outweighing the effect of the higher temperature on the effective diffusivity.

Table.4. Effective diffusivity coefficients for mango slices -Adapted from C.I. Ochoa-Martínez et al. (2011)

Drying Method	Thickness in mm	$D_{eff}(m^2/s)$
RW	1	4.40E-10
Tray-62ºC	1	2.08E-11
RW	2	1.56E-09
Tray-62ºC	2	6.83E-11

3. THERMAL EFFICIENCY

The RW drying system is comparatively more efficient with very comparable efficiency rates of RW having 48-28% for pilot scale and 52 to 70% for commercial scale when compared with other dryers existing in the market (CI Nindo,2003) as shown in above table.4

Table.5. Comparison of evaporative capacity and thermal efficiency of Refractance Window drying system with selected dryers(Adapted from CI Nindo, 2003 and Abonyi, 1999)

Dryer Type	**Evaporative Capacity (kg H_2O/hr)/m^3 or m^2**	**Typical Energy Consumption (kJ/kg H_2O)**	**Thermal Efficiency**
Tunnel	-	5500-6000	42-38%
Band	-	4000-6000	58-38%
Impingement	50 m^2	5000-7000	46-33%
Rotary	30-80m^3	4600-9200	50-25%
Fluid bed		4000-6000	58-38%
Flash	5-100 m^3-depends n particle size	4500-9000	51-26%
Spray	1-30m^3	4500-11500	51-20%
Drum(for pastes)	6-20 m^3	3200-6500	78-35%
RW **Pilot** **Commercial**	 6-10 3.1-4.6 m^2	4700-8100	 48-28% 70-52%

4. ENERGY CONSUMPTION

V. Baeghbali et al. (2010) investigated functionality of a batch Refractance Window system and concluded that the total dehydration time for a 150g batch, was 5-7 minutes for RW system and 20-24 hours for freeze dryer. Energy consumption of RW system was 4.5 kWh and it was 3.5 kWh for freeze dryer. Therefore total energy consumption for dehydrating a 150g batch was only 375-525 W for RW system which was considerably lower than 70-84kW for freeze drying.

5. DRYING EFFICIENCY AND COST

Abul Fadl. et al. (2011) studied the average drying efficiency between RW dryer and convection dryer for tomato powder and found out that there was a wide variation in the average drying efficiency between convection dryer at 60°C(7.9%) and RW dryer of 51,35.6 and 29.8% at three different tested temperatures of 90, 75 and 60°C respectively. They also conducted economic evaluation between RW drying and convection drying methods for producing tomato powder using production cost and concluded that the yearly total cost (fixed and operating cost) for the studied RW dryer was 5389.23 LE/yr compared to 4656.01 LE/yr for convection dryer. The calculated production cost of 1 kg tomato powder by convection dryer was found to be 60 LE/kg $_{powder}$ where as 14.02, 17.02 and 21.3460 LE/kg $_{powder}$ for RW dryer at temperature of 90, 75 and 60°C respectively.

Table6. Comparison of average drying efficiency and cost for producing 1kg of tomato powder by RW dryer and convection dryer -Adapted from Abul Fadl. et al. (2011)

Item	**Tomato dried by**			
	Convection drying	**Refractance window drying**		
	60°C/16hr	**90°C/40 min**	**75°C/60 min**	**60°C/75 min**
Average drying efficiency	7.9	51	35.6	29.8
Yearly cost (LE/yr.)	4656.01	5389.23	-	-
Cost (LE/kg $_{powder}$)	60	14.31	17.02	21.34

THE FUTURE

RW Dryer has been evaluated for its functionality and scope in achieving high standards of quality and safety in drying food supplements predicting a potentially bright future. Studies conclude that RW Being a gentle dehydration process excellent retention of nutrients, flavor and color in the food material being dried can be achieved. Working of the RW dryer is simple and this mechanical simplicity can allow it to be deployed with modest resources in engineering and fabrication while dryers such as spray dryers and freeze dryers require high levels of engineering and fabrication to build. RW dryers have a good throughput. For a product such as blueberry puree an RW dryer which has 400 square feet of heated surface area, such as an RW dryer that has a belt 5 feet wide with 80 foot heated length, the throughput can be 20 kg/hour with good dryness. RW drying is the most economical methods among other high cost method having excellent retention. The quality of the dried products is comparable to those obtained by freeze drying, yet the cost of the equipment is several times smaller than freeze drying. Diverse energy sources can be utilized i.e. Water can be heated in a variety of ways to allow use of the least expensive energy source in a region. A temperature that is up to 95°C used in RW might even be considered low quality heat output by a power plant or other industrial facility and this waste heat could be the energy used for an RW plant. Besides solving the food loss problem, the value added and extended shelf life products can boost the nutritional status of people in those countries. Investigations are continuing on retention of antioxidants, changes in structure (molecular weight), and shelf stability of fruits and food polysaccharides processed by this technology.

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