Refractance Window Drying: An Innovative Drying Technique for Heat Sensitive Product

S. V. Karadbhajne, V.M. Thakare, N.B. Kardile, S.M. Thakre

Abstract*: *A unit operation in which moisture is evaporated from the material to make the product shelf stable by applying heat is known as drying. During drying of fruits and vegetables, it loses most of the essential phytochemicals due to the application of heat, as they are sensitive to heat. Refractance Window (RW) drying is a novel drying technology for converting puree and slices of fruits and vegetables and the biomaterials into powder, flakes, or sheet and value added products without losing essential heat sensitive nutritional components. It is relatively new drying technique which belongs to the fourth generation of drying techniques. RW drying is included in film (thin) drying technologies having high transfer rates of heat and mass which fastened the drying rate relatively with low temperature of product to give better quality product. It also provides advantages in terms of energy consumption, impact on environment, dehydration cost, safety, and productivity.

Keywords: biomaterials, quality, Refractance window dryer, shelf stable.

I. INTRODUCTION

The process of removal of moisture from the product by the application of heat is known as drying. Drying is carried out to halt or slow down the growth of spoilage causing microorganisms and at the same time occurrence of deteriorative chemical reactions [11]. The process of drying also provides advantages in terms of minimizing storage, transportation and packaging cost of the product. It is a complex process that involves transfer of heat and mass as well as various rate processes, chemical or physical transformations that may cause changes in the quality of product and mechanisms of transfer of heat and mass. Physical changes that can occur during drying are puffing, shrinkage glass transition and crystallization. In certain cases, desirable or undesirable chemical or biochemical reactions may takes place which leads to changes in colour, texture, odour or other properties of the solid product [3]

Dried fruits, vegetables and many other ingredients are being used widely in many food industries, which demands raw materials with good quality. In drying of heat sensitive fruits and vegetables maintaining quality parameters such as colour, aromas and nutrients has always been a challenging task and today's consumer demands dried product with high quality that encourage developers to develop improved and innovative drying techniques which gives better result in terms of energy consumption, product quality, impact on environment, dehydration cost, safety and productivity[8].

Refractance window drying is a recently developed non-thermal drying technology among them to dry products including heat sensitive purees, and slices of fruits and vegetables, manufacturing meat powder and it can also be used in an algae, pharmaceuticals, nutraceutical, cosmetics and pigment handling industries where it has found several application [12] . It can be used to encapsulate the microorganism probiotic with proper survival of the microorganism in the food product [21]. It is relatively new drying technique which belongs to the fourth generation of drying techniques. It was patented by Richard Magoon (1986) was developed by MCD Technologies, Inc. (Tacoma, WA)[15]. It is a modular technology and 5 models are available up till now. The important characteristics of Refractance window drying technique are low product temperature and short drying time. Moisture in the product is removed by using thermal energy which is transferred from hot water through the belt above the hot water tank to remove moisture in the product [8] and ambient air above the product remove the evaporated moisture from the product by convective heat transfer.

The main advantages of this advanced drying technology are low drying cost due to working at lower temperature and atmospheric pressure, short drying time and low product temperature during drying, as well as cross contamination are avoided as it is an indirect contact drying technique which produces dried product of high quality. The dryer is mechanically simple; consume low energy, and relatively inexpensive. Drawbacks of RW dryer are its modest throughput, it is intended primarily to dry liquids, it is inconvenient in handling powder with high sugar content (stickiness) and high cost as compared to the drum and spray drying [17, 20].

The aim of this study is to give detailed description of film dryers or Refractance type drying of heat sensitive product which can be used for design and development. It also gives information about benefits of using Refractance window drying including colour retention, microbial reduction, and preservation of essential phytochemical and less energy consumption as compare to spray drying and freeze drying [25].

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II. WORKING PRINCIPLE OF REFRACTANCE WINDOW DRYING

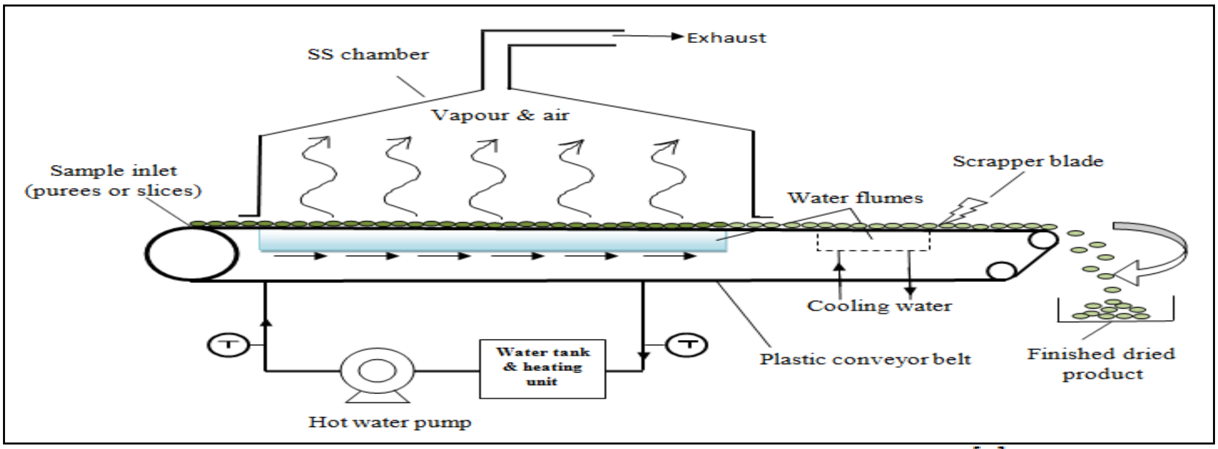

Fig. A.1 Schematic diagram of Refractance window dryer [8]

The dryer, shown schematically in Figure 1, consists of a conveyor belt made up of infrared transparent polyester such as Mylar, on which the thin layer (0.2-1 mm thick) of product is deposited [23]. The relatively thin (<0.2 mm) conveyor belt is placed above the shallow trough containing hot water. The temperature of this hot water is below boiling point (95-98). Here, the conveyor belt transmits thermal energy from hot water to the material to be dried. The can either be moving or stationary. In case of moving the belt, velocity ranges from 0.6 to 3 m/mins. [12]. In RW drying, material is dried by all the three mode of heat transfer viz. conduction, convection and radiation. At the start of the process conduction, radiation and convection are active, as at the start of the drying operation, the material to be dried contains moisture that absorbs electromagnetic radiation in the wavelength range spanning from 3.0 to 15.3 µm. The moisture in the material to be dried creates a window for the passage of infrared radiation, when the thin layer of it is place on the surface of the conveyor belt due to minimized refraction at the belt material interface. As soon as the moisture in the product falls down during drying, the infrared window gradually closes and infrared radiation get refracted due to increase in refractive index of the material and conduction becomes the predominant heat transfer mode. As plastic is the poor conductor heat, little heats is transferred to the nearly dried material and the risk of overheating is greatly reduced.

In RW drying, generally the temperature of the product is relatively low due to convective cooling provided by the ambient air flow above the drying material and the moistened air is removed from the dryer by the exhaust. For most of the RW drying cases, the actual temperature of the product is usually under 70°C. At the end of the drying operation, the temperature of the product is lowered to avoid over heating by moving the conveyor belt over cool water section and then scraper blade removes the product of the conveyor belt [12]. To reduce the temperature of the product below glass transition temperature to avoid stickiness of the product (cohesion and adhesion) and to facilitate discharge, the arrangement of cooling section is there at the discharge end of the dryer [23].

III. HEAT TRANSFER AND AVAILABLE HEATING RATE

RW drying is a new indirect contact drying technology that uses circulating hot water below boiling point as a heat transfer medium where all the three mode of heat transfer i.e. conduction, radiation, and convection are active. Here the energy or heat losses from the water to its surroundings occur by either conduction or convection (evaporation) and radiation being the internal process [7, 26].

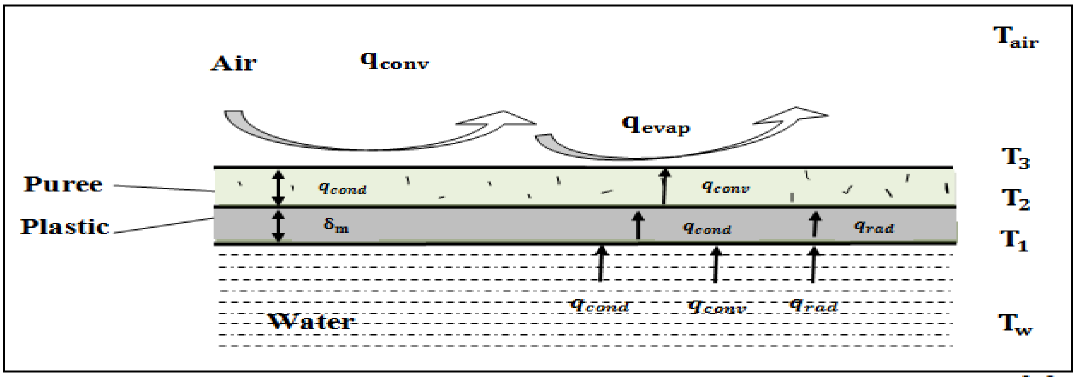

Fig. 2 Schematic diagram showing thermal energy transfer in RW drying system [7]

In RW drying circulating hot water provide thermal energy to the wet material that is required for drying through transparent plastic film conveyor belt. It transmits energy from the circulating hot water via conduction and radiation. The net energy transfer via conduction or radiation depends on the amount of resistance offers by the plastic film these two heat transfer mode [19] . And the moisture evaporated by conduction and radiation is removed by convection through the supply of air above the product. It also helps to lower the temperature of the dried product. Again there is an arrangement of cooling system which contain cooling water in a tank below the same conveyor belt on which product to be dried is applied.

A. *Available heating rate q kW:*

T. H. Ghanem [22] evaluated available heating rate at equilibrium state of the dryer without neither air flow nor liquid film based on the three mode of heat transfer i.e. conduction q_k, convection q_c, and radiation q_r in kW from hot water through the glass plate respectively, which can be represented as follows:

Conduction through the glass plate:

$$q_k = A\,(T_w - T_g)/\,(L_g/K) \qquad (1)$$

Convection through air above the glass plate:

$$q_c = h_c\,A\,(T_g - T_a) \qquad (2)$$

$$h_c = 2.4493(T_g - T_a)^{0.25} \qquad (3)$$

Radiation from the hot water to the glass cover:

$$q_r = \varepsilon\sigma A\,(T_w^4 - T_g^4)/A\,h_r(T_w - T_g) \qquad (4)$$

T_w is the Water temperature ºK,

T_g is the glass plate temperature, ºK,

K is the thermal conductivity of glass plate kW/m ºK,

h_c is convection heat transfer coefficient kW/m2.oºK,

h_r is radiation heat transfer coefficient kW/m2.oK,

ε_g is the emittance of the glass cover; 0.9,

σ is the Stefan-Boltzman constant, 5.6697×kW/m2oK4;

L_g is the glass plate thickness, 0.003m,

A is the surface area of the dryer m²

IV. AVERAGE DRYING EFFICIENCY "η_{avg}" (ADE

Abul-Fadl and Ghanem [14] calculated average drying efficiency of tomato powder during a time period of Φ to Φ+ΔΦ by using the equations given below and reported that there was a wide variation in the average drying efficiency between convection dryer at 60 ºC (7.9%) and RW dryer of 51, 35.6 and 29.8% at three tested temperature of 90, 75 and 60ºC respectively [15].

$$E_T = E_C + \int_{\Phi}^{\Phi+\Delta\Phi} P_b\,d + \int_0^x P_h\,d\Phi \qquad (5)$$

$$E_c = \frac{mC_p\Delta T}{16}(\Delta\Phi) \qquad (6)$$

Whereas:

X: is the time required for operating the electrical heater to compensate all heating losses and heat required for conduction, infrared windows and evaporation during the drying process in seconds,

P_b : Electrical power required for moving drying air kW,

P_h: Electrical power required for compensating heat losses and drying process kW,

E_C: is the heat required to raise the water temperature in the basin to 60, 75 and 90ºC for the RW dryer, distributed on daily operating hours (16%) and modified to the experimental time increment water

ΔΦ,

M: total mass of water in the dryer basin, "19.2"

Cp: specific heat of water kJ/kgºK.

Consequently the drying efficiency during a time period of Φ to ΔΦ can be written as:

$$\eta_i = \frac{W_{WE}L}{E_T} \qquad (7)$$

And the average drying efficiency can be written as:

$$\eta_{avg} = \frac{1}{n}\sum_{i=1}^{\eta}\eta_i \qquad (8)$$

Whereas:

η: is the number of values,

W_{WE} : is the moisture evaporated during times period of Φ to Φ+ΔΦ, in kg, which can be calculated using the mass balance concept as follows:

$$m_p(\Phi + \Delta\Phi) = m_p(\Phi)(1 - M_{wb}(\Phi))/(1 - M_{wb}(\Phi + \Delta\Phi)) \qquad (9)$$

$$W(\Phi + \Delta\Phi) = m_p(\Phi + \Delta\Phi) \times M_{wb}(\Phi + \Delta\Phi) \qquad (10)$$

$$W_{wE} = W(\Phi) - W(\Phi + \Delta\Phi)$$

m_p(Φ) is the mass of tomato pulp at a time period (Φ); kg

m_p(Φ+ΔΦ) is the mass of tomato pulp being dried after time increment of ΔΦ; kg,

M_{wb} is the moisture content of tomato juice % wet basis,

W (Φ) is the mass of water at a time period (Φ); kg,

W (Φ+ΔΦ) is the mass of water after time increment of ΔΦ; kg,

L is the latent heat of vaporization of water at the drying air temperature in kJ/ kg which can be calculated as follows:

L=2502.535- 2.3857(T-273.16) (8) (11)

T: is the drying temperature in ºK,

E_T : is the total energy used in heating and moving drying air during a time period of Φ to Φ+ΔΦ; in kJ.

V. EFFECTIVE MOISTURE DIFFUSIVITY AND ACTIVATION ENERGY

Moisture diffusivity and activation energy are important parameters for the optimization, modeling and designing of drying processes for food, aro-products and other materials. A. A. Akinola, *et al.*, [1] evaluated Effective Moisture Diffusivity and Activation Energy for Refractance window dried cucumber fruit slices by using the equation given below:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \qquad (12)$$

Where,

MR is moisture ratio,

D_{eff} is the effective moisture diffusivity, (m²s^{-1}),

L is the sample thickness (m), and

t is the drying time (S)

T.H. Gathem [22] stated that drying coefficient can be determined by plotting the logarithmic of moisture ratio MR against elapsed time

$$. MR = \frac{M - M_e}{M_0 - M_e} \qquad (13)$$

Where,
M is moisture content at any time,
M_e is equilibrium moisture content, and
M_0 is initial moisture content.

The activation energy can be calculated by using an Arrhenius type equation

$$D_{eff} = D_o e^{-\frac{E_a}{RT}} \quad (14)$$

Where,
E_a is the activation energy (J/mol)
R is the universal gas constant (8.314 J/mol),
T is the absolute temperature (K),
D_{eff} (m^2/S) is the effective diffusivity, and
D_0 is the pre-exponential factor of the Arrhenius equation (m^2/S)

The activation energy can be determine from the slope of the Arrhenius plot, -ln(D_{eff}) against 1/T. A plot of –ln(D_{eff}) against 1/T gives a slope of k_r from which E_a can be obtained according to the equation.

$$k_r = E_a/R \quad (15)$$

where k_r is determine by linear regression analysis of the data points.

VI. ENERGY CONSUMPTION

In RW drying mainly the energy is required for the evaporation of water from the air puree interface. Thermal efficiency of RW dryer is calculated by collecting the steam and heat balance done by measuring process water and product temperature at various point. In RW drying process water from the dryer flows back into the reservoir and reheated rather than wasted. Therefore it shows very good thermal efficiency as comparing to other conventional dryer [7].

Vahid Baeghbali [26] reported that 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 3.5 kWh for freeze dryers. Therefore total energy consumption of dehydrating a 150g batch was only 375-525 W for RW system which was considerably lower than 70-84kW for freeze drying**.** R.P. de Smidt *et al.,* [20]stated that, for one specific case the total electrical power consumption for a heat transfer area of around 45 m^2 is reported to be 86 kW, resulting in an electricity use of 2 kW/m^2 evaporation areas for this case.

Overall energy efficiency of the different drying method is compared for pomegranate juice. RW dryer shows the highest overall energy efficiency (31.56%) followed by spray dryer (12.92%) and freeze dryer (1.12%). Overall energy efficiency for carrot and strawberry sample dried by of a RW drying was calculated by B.I. Abony, Tang *et al.,*[5] was 37.9% and 27.9% which is similar to the efficiency calculated by V. Baeghbali *et al.,*[25] for pomegranate juice.

VII. PARAMETERS AFFECTING REFRACTANCE WINDOW DRYING

In RW drying, the thickness of the sample and drying time is the two important parameters that affect the final quality of product. The effects of thickness on drying of papaya puree were studied by M. U. Ocoró-Zamora *et al.,* [16] reported that the thickness of the papaya purees significantly influenced drying kinetics, water activity and the colour of the product. Lower the thickness of the product, faster the drying (as distance travel by water in order to get extracted is reduced), lower the a_w, and higher the ΔE value. Similar results were obtained in case of mango slices and kiwifruit slices. As the thickness of slices increases, rehydration ratio decreases due to decrease in area to volume ratio. Thin slices of shorter drying time required smaller penetration force comparing to fresh carrot slices as drying reduces water and internal mechanical resistance of carrot fibers to sharp objects whereas thick slices cause the final product more resistance to puncture than both the thin slices and fresh carrot slices.

Temperature of water bath is also an important factor that affects the quality of the final dried product. High water temperature results in both rapid dehydration and quite low product temperature which helps to yield better quality product [5]

VIII. EFFECT OF REFRACTANCE WINDOW DRYING ON PRODUCT QUALITY

In RW drying, the use of hot water at temperature just below the boiling point as the heat transfer medium under atmospheric pressure and short drying time produces better quality product. The quality of dried product achieved by RW drying is reportedly close to that achieved by the freeze drying but the energy cost is much lower as compare to freeze drying. The cost of the RW drying equipment is approximately one-third of that of a freeze dryer to dry a similar mass of product, whereas the energy cost to operate RW dryer is less than half of the freeze dryer [23].

A. *Preservation of heat sensitive essential photochemical:*

One of the major benefit of refractive window drying technology is the essential bioactive components retention of the final product [14]. These bioactive components are sensitive to heat which are lost during other conventional drying technique.

- Various studies on RW drying have shown that, it can preserve ascorbic acid content of the final dried product. In a study on strawberry puree, results shows that retention of ascorbic acid in the final product dried by RW drying and FD are comparable [17]
- Anthocyanins are one of the valuable and nutritional phytochemicals that are present in various fruits and vegetables. V. Baeghali *et al.,*[24] reported that RW dryer produces high quality pomegranate juice powder with antioxidant activity, anthocyanins colour and anthocyanins content close to that of the freeze dried or spray dried samples, also G.B. Celli *et al.,* [10] reported that, the Refractance window dried powder containing 98% haskap berries retains approximately 93.8% anthocyanins from the original frozen fruits, as assed by the pH-differential method.
- Carotenes are also one of the important phytochemical that is susceptible to heat and oxidation and their retention in dried product are important to achieve a high quality product. Various studies on quality retention of RW dried product in comparison with other drying techniques are given below:

Table 1 physic-chemical property evaluated of Refractance window dried product in comparison with other drying technique.

Product	**Physico- chemical property evaluated**	**Results**	**References**
Pomegranate juice	Anthocyanin	In RW dried samples Total anthocyanins content were significantly higher than that of the freeze and spray dried sample.	V. Baeghbalia *et al*, [24]
	Antioxidant activity	In RW dried samples, antioxidant activity was higher than the spray dried sample, but it is not significantly different than that of the freeze dried sample.	
Strawberry puree	Ascorbic acid	In RW dried strawberry purees 94% of ascorbic acid was retained which was comparable to 93.6% in the freeze dried sample.	N. Bernaert *et al.*, [17]
Carrot	Carotene	In RW dried carrot purees the carotene losses were 8.7% (total carotene), 7.4% (α-carotene), and 9.9% (β-carotene), which were comparable to losses of 4.0% (total carotene), 2.4% (α-carptene), and 5.4% (β-carotene) for the freeze dried carrot puree.	B.I. Abonyi *et al*, [5]
Asparagus	Ascorbic acid	The total antioxidant content of dried asparagus samples out of five different investigated drying methods, RW drying showed the highest amount of ascorbic acid followed by the freeze drying, combined microwave and spouted bed drying, spouted bed and tray drying.	C.I. Nindo *et al.*, [8]
Haskap berry	Anthocyanin	The anthocyanins content of RW dried haskap berries powder consisting of 98% haskap berries was 93.8% of anthocyanin from the original frozen fruits, as assessed by pH-differential method.	G. B. Celli *et al*, [10]
Tomato powder	Ascorbic acid	Convective dried tomato powder losses more ascorbic acid (75%) as comparing to RW dried tomato powder at three different time/temperatures conditions.	M.M. Abul-Fadl and T.H. Ghanem, [14]
	Lycopene	Lycopene content of RW dried tomato under three different drying conditions was much higher than that found (44.79%) in the convection dried tomato.	
	Flavonoids	RW drying process retains high amount of total flavonoids (86.4, 76.6 and 74.2%) in tomato samples dried at three different conditions (75°C for 60 min., 60°C for 75 min., and 90°C for 40 min.) as comparing to tomato samples dried by convection drying process (50.9%).	
Tomato slices	Phenol content	Phenol content of RW dried tomato slices is comparable to that of the fresh sample.	A. Abbasid *et al*, [2]

B. *Colour retension*

The colour of the food is an important parameter for their acceptability. The retension of colour in strawberry puree dried by Refractance window drying was comparable with freeze dried strawberry puree [5]. Colour characteristics of paparika was studied by A.Topuz *et al.*, [4] at different drying method and storage conditions and reported that RW drying is a promising paprika processing method that shows overall good colour quality, except for the ASTA values, comparable to that from FD- samples. For reflected colour, RW and Freeze drying resulted in product with better colour characteristics [12]. V. Baeghbali, *et al.*, [26] studied the color changes in tomato juice, tomato ketchup and carrot puree samples, affected by different drying methods. They reported that the color of the freeze dried sample were brighter (higher L*) than the RW dried samples and there was no significant difference found in b* (blueness) values among the RW dried and Freeze dried samples.
L*= lightness, a*= redness, b*=blueness

C. *Microbial reduction*

All in all RW Drying is a very good drying method in terms of physiochemical quality retention, its results are comparable to that of the freeze drying but it can also reduce microbial load in dried products. In a study on pumpkin puree dried from 80% to 5% moisture content (wb) by Refractance window drying which was completed in 5 minutes (with water at 95°C) resulted in 4.6, 6.1, 6.0, and 5.5 log reduction of total aerobic plate count (APC), coliforms, Escherchia coli, and Listeria innocua respectively [24]. Microbial reduction in explosion puff
drying of unblanched mushrooms was studied by Sullivan and Jo Egoville (1986) and observed a 5.2 log CFU/ml reduction in total microbial count [8].

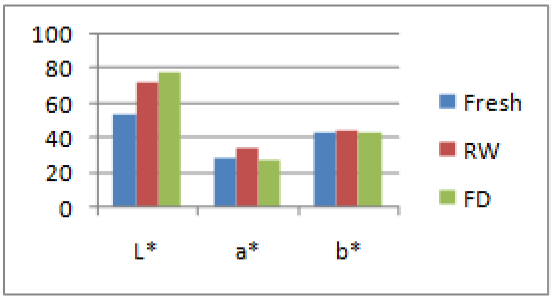

Fig.C.1 colour measurement (L*, a* and b*) of fresh, Refractance window dried and Freeze dried carrot puree [5]

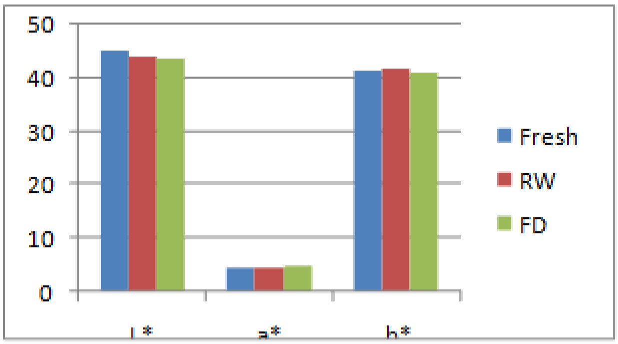

Fig. C.2 colour measurement (L*, a* and b*) of fresh, Refractance window dried and Freeze dried mango puree [18]

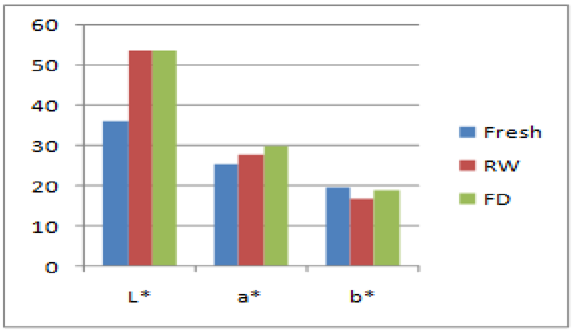

Fig. C.3 colour measurement (L*, a* and b*) of fresh, Refractance window dried and Freeze dried strawberry puree [5]

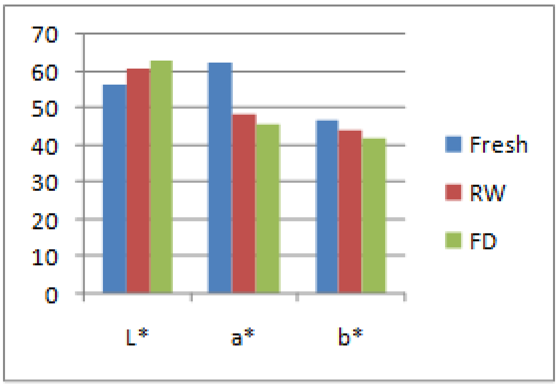

Fig. C.4 colour measurement (L*, a* and b*) of fresh, Refractance window dried and Freeze dried Tomato Juice [26]

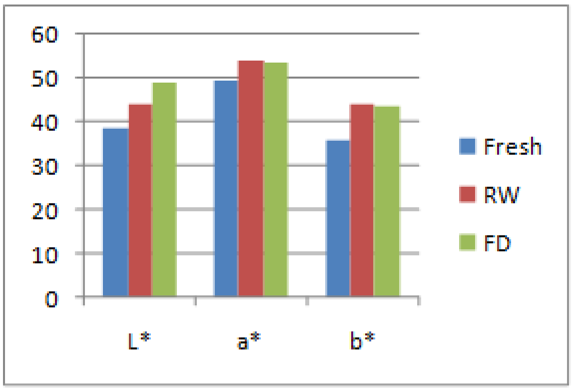

Fig. C.5 colour measurement (L*, a* and b*) of fresh, Refractance window dried and Freeze dried tomato ketchup [26]

IX. CONCLUSION

Refractance window drying is a mild drying technique that uses hot water at temperature just below boiling point as the heat transfer medium under atmospheric pressure and short drying time to produce product with excellent retention of colour, flavour and nutrients. The quality of the dried product is comparable to that obtained by the freeze drying, yet the cost of the equipment is several times smaller than the freeze drying. Because of this it can be used for preparing value added products.

Additionally RW drying technology has potential for use in parts of the world where effective drying methods such as freeze drying have been difficult to implement due to its high cost. During Refractance window drying, temperature inside the product is below 70ºC due to which it can be used in algae, nutraceuticals, pharmaceuticals, cosmetics, and pigment handling industries where it has found various applications.
Hence RW drying has a potentially bright future in achieving high standards of quality and safety in drying heat sensitive materials.

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