

# Dehydration of Kiwi Fruit (*Actinidia deliciosa*) by Consecutive Osmotic Dehydration and Freeze-Drying

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## Abstract

**Objectives:** In this study, a highly nutrient food rich in vitamins and minerals, kiwi fruit (*Actinidia deliciosa*), is dehydrated effectively at a faster rate keeping almost all its original properties. **Methods/Analysis:** A new methodology, consecutive Osmotic Dehydration (OD) and Freeze Drying (FD), was developed and applied. This technique was found to be very effective with respect to drying time, cost and quality. The OD was performed using sucrose solution at three concentrations (40°B, 55°B, and 70° B), three temperatures (40°C, 45°C, 50°C) and three time spans (2, 3 and 4 h). OD parameters were optimized by “Taguchi orthogonal design” methodology. **Findings:** Optimal time for OD was found to be 3 h, at 40°B, 50°C corresponding to 60.75% water loss and 9.86% solute gain. Notably, at optimal OD conditions, application of fructose solution resulted unfavorable result. In FD of osmotically dehydrated kiwi fruit, the thermal energy was supplied by an innovative Silver Coated Steel Heater (SCSH), which was found to be much more efficient (required only 2.5 h drying time) compared to an equal power conventional steel heater (SH) (required 3.82 h drying time) to achieve a final kiwi fruit moisture content  $\leq 5\%$  (w/w). At both optimal OD and FD, the drying kinetics was assessed using four models. The values of effective diffusivity ( $D_{eff}$ ) and activation energy indicated higher energy-efficiency for SCSH compared to SH. The proximate nutritional analyses for fresh and dehydrated kiwi samples indicated very good quality of the processed product. **Novelty/Improvement:** The uniqueness and novelty of this research work is less drying time and almost no nutritional loss as compared with other conventional techniques.

**Keywords:** Consecutive Osmotic Dehydration and Freeze Drying, Kiwi Fruit, Silver Coated Steel Heater

## 1. Introduction

Freeze-Drying (FD) has been considered as the best drying technology for food preservation regarding flavor and nutritional parameters, reduced weight of shipping, storage, and handling and enhance shelf life of the end product(s)<sup>1,2</sup>. FD is applied for 1. High nutritional valued foods, 2. With initial moisture content of 70% to 80% (w/w), 3. Costly foodstuffs<sup>3</sup> such as Kiwi Fruit (KF).

KF possesses health promoting nutrients such as phyto-chemicals, minerals and provides sufficient amount

of vitamins and antioxidants. Besides KF is high in dietary fiber, K and Mg; low in saturated fat, Na and cholesterol<sup>4,5</sup>. A study found<sup>6</sup> that KF is the most enriched fruit in terms of vitamin C content compared to papaya, mango and orange. It is important for cardiovascular health. It helps in reducing weight, cholesterol level and acts as an anti-aging substance with positive effect to regulate diabetics and colon cancer.

Conventional Freeze-Drying (CFD)<sup>7</sup> was applied for kiwifruit. The results indicated that its betterment was necessary for economization of freeze-drying. In order

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to intensify the freeze-drying rate, infrared radiation was applied as a source of thermal energy for prawn<sup>8</sup> and banana<sup>9</sup>; however, occurrence of protein denaturation was observed. More recently, Osmotic Dehydration (OD) was reported to be a pre-processing before FD for reduction of FD time with improved process economy<sup>10,11</sup>. However, to the best of our knowledge no report is available on application of OD prior to FD. Besides application of fast conductive heating<sup>12-14</sup> using high conductivity metal (such as silver) has not been reported for reduction of FD times. Notably, silver has a high thermal conductivity and antimicrobial properties.

In the present study, the OD of KF using sucrose solution has been optimized applying Taguchi orthogonal method. At the derived optimal condition, effect of fructose as osmotic solution on OD of KF has been evaluated. Subsequent FD of osmotically dehydrated KF was conducted using Silver Coated Steel Heater (SCSH) and its performance in FD was compared with conventional Steel Heater (SH). Kinetic parameters in OD and FD after OD (ODFD) were also compared. The final dehydrated KF was evaluated for quality assessment viz. Carbohydrate, sugar, protein, total fat, ash, vitamins etc.

## 2. Materials and Methods

### 2.1 Sample Preparation for Osmotic Dehydration (OD)

Fresh kiwi fruits (*Actinidia deliciosa*) were de-skinned and sliced in the form of slabs with a typical dimension of 35×33×5 mm (±0.1 mm). The initial weight and moisture content of the samples were determined (by moisture meter; KERN, Germany, Model MLS 50-3 HA 250). The OD was performed by using sucrose (99% purity) solution (SS) of three concentrations (40°B, 55°B, and 70° B) with addition of 2 to 3% sodium chloride (W/V) solution. Three temperatures (40°C, 45°C, 50°C) and three time spans (2, 3 and 4 h) were chosen for OD. The volume of the total osmotic solutions was taken 5 times of kiwi sample weight. KF samples were placed in prepared osmotic solutions for specified times as per Taguchi orthogonal experimental design shown in Table 1. After OD, the samples were withdrawn cautiously and soaked by tissue paper and the final dimension, weight and moisture content were measured. The Water Loss (WL) and Solute Gain (SG)<sup>10</sup> of the kiwi samples were calculated by following equations:

$$WL = \frac{(W_0 - W_t) + (S_t - S_0)}{W_0} \times 100 \quad (1)$$

$$SG = \frac{(S_t - S_0)}{W_0} \times 100 \quad (2)$$

$$\text{Where, } S_0 = \frac{W_0(100 - M_i)}{100} \quad (3)$$

$$S_t = \frac{W_t(100 - M_f)}{100} \quad (4)$$

To evaluate the effect of fructose (99% purity) as osmotic solution OD was done at same optimal brix, temperature and time parameters as used for Sucrose Solution (SS). The KF sample (obtained at optimal OD using sucrose solution) was frozen through conventional refrigeration for a time span of 24 hours at temperature -16°C. Then by using SCSH and SH as thermal source, freeze-drying was performed for frozen osmotically dehydrated kiwi sample. The Freeze-Drying (FD) chamber was subjected to fixed vacuum ( $5 \times 10^{-3}$  mbar) and the condenser (moisture traps) temperature was fixed at -40°C. The result of OD with Fructose Solution (FS) was inferior in terms of moisture reduction. Hence, FD was not conducted for sample obtained using fructose as Osmotic Solution (OS).

Conventional Freeze-Drying (CFD) without OD was performed at identical conditions as mentioned above and final moisture content of KF sample was recorded.

### 2.2 Experimental Methodology for Freeze-Drying (FD)

An indigenously fabricated SCSH was made (fiber body, contained two small heaters of 2.5W each; 84×84×84 mm) for supplying conductive heat in FD for both Osmotically Dehydrated Freeze-Drying (ODFD) and Conventional Freeze-Drying (CFD). The sample was placed on silver coated steel plate of Silver Coated Steel Heater (SCSH) of dimension (82×82×0.5 mm). One RTD was used for measuring the temperature of the heating plate and it was regulated with a PID controller. During FD, weight of KF sample was recorded at regular time interval. The FD time was noted when the final moisture content of the sample became ≤ 5% (w/w).

Various drying models namely Page, Wang and Sing, Henderson and Pebis and Newton models were used to compare the drying kinetics during OD and FDs. The statistical parameters such as the Mean Bias Error (MBE), the Root Mean Square Error (RMSE) and the modeling efficiency (EF)<sup>15</sup> are calculated by the following equations:

$$MBE = \frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i}) \tag{5}$$

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{0.5} \tag{6}$$

$$EF = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{exp,avge})^2 - \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (MR_{exp,i} - MR_{exp,avge})^2} \tag{7}$$

The unsteady state diffusion equation for the calculation of effective diffusion coefficient ( $D_{eff}$ ) is given as follow Crank<sup>23</sup>.

$$MR = \frac{8}{\pi^2} \text{Exp} \left[ -\frac{\pi^2 * D_{eff} * t}{4L^2} \right] \tag{8}$$

The activation energy (E) is calculated by Arrhenius equation:

$$\ln \left( \frac{D_{eff,2}}{D_{eff,1}} \right) = \left( \frac{E}{R} \right) \left[ \frac{(T_2 - T_1)}{T_1 * T_2} \right] \tag{9}$$

### 2.3 Taguchi Orthogonal Design and Optimization of OD

Water Loss (WL) was selected as the response for OD operation. The signal to noise (S/N) ratios for all the OD experiments was calculated according to the following equation. For larger is better (WL) the equation is:

$$S/N = -10 \log \left[ 1 / (n \sum_{i=1}^n 1 / Y_i^2) \right] \tag{10}$$

Where i and n are the number of replicates and trial experiments performed in all the combinations respectively.

### 2.4 Quality Assessment

The carbohydrate, sugar, protein, total fat, energy, ash, minerals (Na and K) and vitamins (A and K) of the raw KF, osmotically dehydrated KF and freeze-dried KF were measured using standard methods as given in Table 2.

## 3. Results and Discussion

Moisture content of fresh KF was determined to be 75.75% (average) on wet basis.

### 3.1 Optimal Process Conditions

The analysis of S/N ratio obtained from Taguchi

orthogonal design with the optimization criteria i.e., “larger is better” for WL in OD of KF are presented in Table 1. The maximum WL was obtained for the combination of 40° brix, 50°C temperature and 3 h OD time.

**Table 1.** Taguchi orthogonal experimental design for OD of kiwi fruit

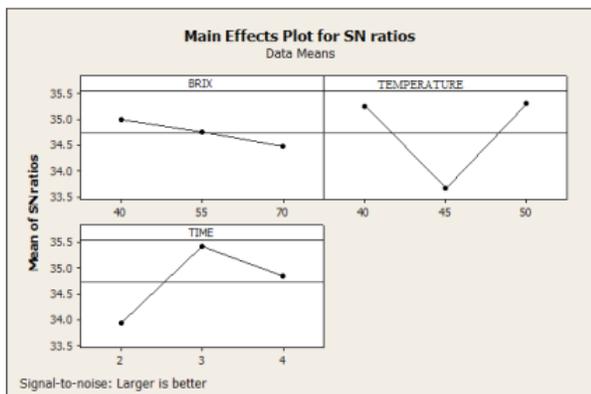
Sl. No.	Brix (°B)	Temperature (°C)	Time (h)	WL %	S/N ratio
1	40	40	2	57.229±0.2	35.15232
2	40	45	3	50.079±0.3	33.99311
3	40	50	4	61.861±0.2	35.82834
4	55	40	3	63.91±0.5	36.11138
5	55	45	4	51.397±0.5	34.21876
6	55	50	2	49.667±0.5	33.92136
7	70	40	4	52.901±0.4	34.46928
8	70	45	2	43.49±0.3	32.76779
9	70	50	3	64.376±0.1	36.17448

### 3.2 Comparison between Sucrose Solution (SS) and Fructose Solution (FS) used as an Osmotic Solution

The KF sample was also dehydrated through fructose solution (used as an osmotic solution, OS) at derived optimized conditions (40°B, 50°C and 3 h). Under the optimized conditions in OD the WL was 54.54% and SG was 14.45% which were much inferior to OD with SS (WL: 60.75% and SG was 9.86%). Thus, nearly 10% and 32% better performance on the basis of WL (%) and SG (%) for SS as compared to FS. Therefore, it may be concluded that at optimized osmotically dehydrated (OPOD) condition, the Sucrose Solution (SS) was far better Osmotic Solution (OS) than Fructose Solution (FS).

### 3.3 Effects of Individual Factors on WL

It is evident from Figure 1 that an increase in brix can cause decrease in WL% which is unfavorable; while increase in temperature from 45°C to 50°C could result an increase in WL. An interesting observation pertaining to the effect of OD time on WL revealed that an increased in OD time from 2 to 3 h could render a significance in WL; however further increase in OD time had contrasting effect on WL. This may be ascribed to the reverse osmosis during extended period of OD. It was found from the results of ANOVA (Table 3.) that all the factors (brix, time and temperature) were significant but temperature was the most important (rank 1) among all with maximum delta value (1.66).



**Figure 1.** Effects of individual process factors on signal-to-noise (S/N) ratio for water loss (WL).

**Table 3.** Effects of individual factor on OD interpreted through ANOVA (analysis of variance) [for WL, larger is better]

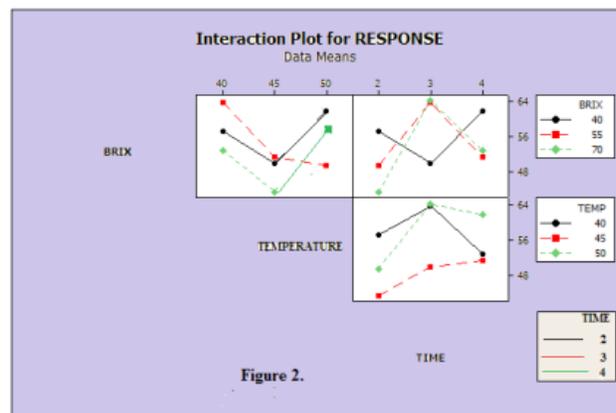
Level	Brix (°B)	Temperature (°C)	Time (h)
1	35.01	35.25	33.95
2	34.78	33.67	35.46
3	34.47	35.33	34.85
Delta	0.54	1.66	1.50
Rank	3	1	2

### 3.4 Interaction among Process Factors in Governing WL

It is evident from Figure 2, that an increase in temperature from 40°C to 45°C resulted a decrease in WL% for all brix values of Osmotic Solution (OS). However, increase in temperature from 45°C to 50°C resulted increment in WL% for 40°B and 70°B. Again at 50°C, the WL% was more as compared with other two temperatures (40°C and 45°C). Also at 3 hour time the WL% reached maximum as compared with other two time parameters (2 h and 4 h). Therefore, to get WL% maximum the optimized process parameters were 40°B, 50°C and 3 h.

**Table 5.** Models for osmotic dehydration at optimal conditions (OPOD)

Model	K	a	b	n	R <sup>2</sup>	EF	MBE	RMSE
Page	0.017	—	—	0.783	0.913	0.88934	0.06774	0.00769
Wang & Sing	—	-0.006	9.8	—	0.965	0.82705	-0.00300	0.10965
			$\times 10^{-6}$					
Henderson & Pabis	0.00461	0.865	—	—	0.9745	0.83888	0.04168	0.10860
Newton	0.007	—	—	—	0.9444	0.90335	0.01708	0.08412



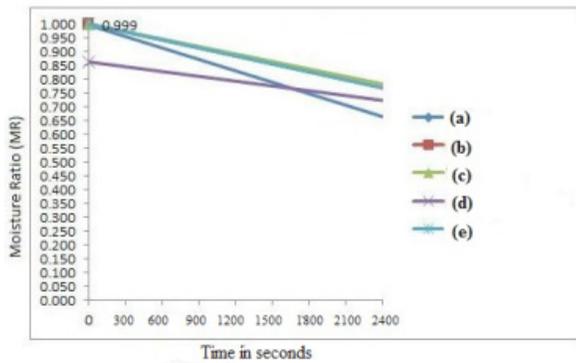
**Figure 2.** Interaction plot among process factors governing in water loss (mean) in osmotic dehydration of kiwi fruit.

### 3.5 Kinetics of Osmotic Dehydration of Kiwi Fruit Sample

The OD kinetics at optimal OD (OPOD) was compared with four models namely Page, Wang and Sing, Henderson and Pabis and Newton model (Table 4). Different constant values (K, a, b, n), regression coefficient (R<sup>2</sup>) values, modeling efficiency (EF), Mean Bias Error (MBE) and Root Mean Square Error (RMSE) values are required (Table 5) to evaluate the best representative model. The Newton model was accepted as the best drying models for OPOD. The Moisture Ratio (MR) values as a function of OD time were compared for actual (experimental) and predicted values for all the four models in Figure 3.

**Table 4.** Mathematical models selected

Serial no.	Model name	Equation used
1.	Page	$MR = \exp(-kt^n)$
2.	Wang & Sing	$MR = 1 + at + bt^2$
3.	Henderson & Pabis	$MR = a \exp(-kt)$
4.	Newton	$MR = \exp(-kt)$

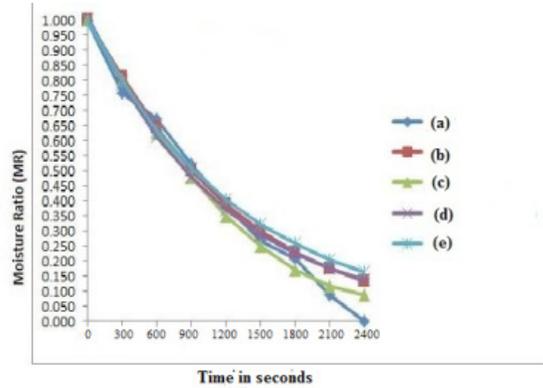


**Figure 3.** Osmotic dehydration curves at optimal condition of OPOD.(a) Experimental value.(b) Page model.(c) Wang and Sing model.(d) Henderson and Pabis model. (e) Newton model.

### 3.6 Freeze-Drying of KF after OPOD

Partially dehydrated kiwi samples (30.12% on wet basis) developed through optimized OD operation (OPOD) were subsequently subjected to freeze-drying (OPODFD) using Silver Coated Steel Heater (SCSH) till the final moisture content became  $\leq 5.0\%$  (wet basis). The actual (experimental) OPODFD kinetics obtained by plotting (Figure 4.) Moisture Ratio (MR) as a function of time was compared with four standard drying models viz. Page, Wang and Sing, Henderson and Pabis and Newton model (Figure 4.) to determine the best representative model for OPODFD dynamics. Regression coefficient ( $R^2$ ), MBE, RMSE and EF values and constants (namely k, a, b, n) are presented in Table 6.

From the Table 6 and Figure 4 it can be observed that Wang and Sing model was best fitted as compared with other three models i.e., it was the best representative drying model for freeze-drying kinetics of kiwi fruit sample.



**Figure 4.** Freeze-drying curves of OPODFD for.(a) Experimental value.(b) Page model.(c) Wang and Sing model.(d) Henderson and Pabis model.(e) Newton model.

### 3.7 Comparison of Freeze-Drying (FD) Performances between SCSH and SH

From Equation (8), the effective moisture Diffusivity ( $D_{eff}$ ) for OPOD was found as  $3.405 \times 10^{-9} \text{ m}^2/\text{s}$  (Table 7). Similarly, the effective moisture diffusivity in OPODFD (using SCSH) of KF was found  $6.04 \times 10^{-7} \text{ m}^2/\text{s}$  (Table 7). On the other hand, the effective diffusivity for OPODFD (using conventional steel heater) was found as  $2.22 \times 10^{-7} \text{ m}^2/\text{s}$ . Therefore, SCSH was much more efficient than SH for accelerating OPODFD of kiwi fruit.

**Table 7.** Effective diffusivity for optimal osmotic dehydration (OPOD), optimal freeze-drying of osmotically dehydrated (OPODFD) kiwi samples using steel heater (SH) and silver coated steel heater (SCSH)

Temperature	$D_{eff}$ for OPOD ( $\text{m}^2 / \text{s}$ )	$D_{eff}$ for OPODFD ( $\text{m}^2 / \text{s}$ )	
		Using SH	Using SCSH
50°C	$3.405 \times 10^{-9}$	$2.22 \times 10^{-7}$	$6.04 \times 10^{-7}$
45 °C	$1.886 \times 10^{-9}$	$0.57 \times 10^{-7}$	$1.50 \times 10^{-7}$
40 °C	$1.045 \times 10^{-9}$	$0.157 \times 10^{-7}$	$0.37 \times 10^{-7}$

**Table 6.** Freeze-drying models for osmotically dehydrated kiwi samples at optimal conditions (OPODFD)

Model	K	a	b	n	$R^2$	EF	MBE	RMSE
Page	0.035	—	—	1.1	0.947	0.96577	0.03093	0.05773
Wang and Sing	—	-0.042	0.00048	—	0.946	0.98062	-0.00185	0.04343
Henderson and Pabis	0.0501	1.015	—	—	0.928	0.96203	0.02170	0.06080
Newton	0.0452	—	—	—	0.940	0.72485	0.04359	0.07370

To attain a final moisture content (4.27%) of kiwi fruit sample the drying time was 2.5 h and 3.82 h for SCSH and SH respectively. Therefore, the drying time for SCSH was less (about 35%) than SH.

The activation energy (E) by using Arrhenius Equation (9) was calculated. The activation energy required during OPODFD was computed as 23.96 kJ/mol by using SCSH; on the contrary, the activation energy required during OPODFD was 53.55 kJ/mol when using SH plate. Therefore, less activation energy is required for OPODFD by SCSH as compared with SH; indicating SCSH as an energy-efficient heating device.

For Conventional Freeze-Drying (CFD) without OD, the drying time was required 5.75 h for KF sample to reach final moisture content 4.27%.

### 3.8 Quality Assessment of Raw and Dehydrated Kiwi Fruit

According to nutrition information panel<sup>16</sup> every food processing operations require to provide information on certain nutrients. Eleven quality tests were performed for three types of kiwi samples namely 'Raw', OPOD and OPODFD (final dried), shown in Table 2, where the reference of methods are also mentioned. The quality of all the three types with respect to the five parameters viz. moisture, carbohydrate<sup>17</sup>, protein, total fat and ash content (in g per 100 g sample) were evaluated which indicated satisfactory quality.

Table 2 shows that carbohydrate increased by 150.78% and sugar increased by 54.58% for OPOD sample. The

**Table 2.** Qualities of raw and dehydrated kiwi samples

Quality Parameters	Standard # values for fresh KF*	Tested fresh KF	KF samples for OPOD	KF samples for OPODFD	Test method	Reference(s)
Moisture (g/100g)	70-85	85.07	68.16	4.27	DGHS LAB MANUAL 5.0	Krokida et al., 1998
Carbohydrate(g/100g)	14.66	10.89	27.31	87.52	IS:1656-2007	fssai, act 2006, GOI; Maskan, 2001
Sugar(g/100g)	8.99	8.30	12.83	56.78	IS:6287-1985 (Reaffirmed-2005)	_____
Protein (g/100g)	1.14	1.31	1.34	2.82	IS:7219-1973 (R.A.-2005)	_____
Total Fat (g/100g)	_____	0.52	0.55	0.65	DGHS LAB MANUAL 5.0	_____
Energy Content (kJ/100g)	260	259.8	512.76	1548.64	IS:9487-1980 (R.A.-2005)	fssai, act 2006, GOI
Sodium (mg/100g)	3	2.81	432.48	1072.04	QA.16.5.2	fssai, act 2006, GOI
Potassium (mg/100g)	312	312.53	152.51	252.02	QA.16.5.2	fssai, act 2006, GOI; Deman, 2004
Ash (g/100g)	0.88-1.02	1.12	1.86	3.92	DGHS LAB MANUAL 5.0	fssai, act 2006, GOI; Fourie and Hansmann, 1992
Vitamin A (µg/100g)	Trace	20.0	20.0	20.0	QA.16.5.3	fssai, act 2006, GOI; Mudambi and Rajagopal, 1990
Vitamin C (mg/100g)	90	89.10	80.55	78.66	AOAC 18-th edition, 967.21	fssai, act 2006, GOI

#FSSAI\*Information on nutritional value of Fresh Kiwi

reason was water expulsion and sugar uptake for KF samples. Increment behavior of carbohydrates and sugars were observed for final dried samples obtained through OPODFD owing to additional moisture removal. All the dehydrated samples contained more protein than raw samples per unit mass of sample (Table 2). Previously, no report of fat content was made for KF. However, 0.52 g, 0.55 g and 0.65 g fat (per 100 g tested sample) was found for raw (fresh) KF, OPOD and OPODFD samples respectively. However, the temperature was kept within 50°C therefore no loss of fats occurred due to processing. The energy content were found higher than raw sample for OPOD (512.76 kJ per 100 g) and OPODFD (1548.65 kJ per 100 g) samples. Hence, it could be concluded that the final dried kiwi sample (100g) was an energy 'storehouse'. Both sodium and potassium present in kiwi were lost whenever thermally processed<sup>16</sup>. Plant and their products have a higher content of potassium than of sodium<sup>18</sup>. Here, during OPOD kiwi was heated at 50°C, accordingly sodium and potassium might be lost. To overcome this situation iodized common salt (5%, w/v) was added. Sodium content increased during OPOD, while potassium content decreased during OPOD, since it was 'salting out' quickly to the sucrose solution. The increase in potassium content from OPOD sample to OPODFD sample could be ascribed due to additional moisture reduction leading to final moisture content of 4.27%. By the same reason, the quantity of sodium for freeze-dried product also increased. Although, the dried KF sample contained less vitamin C (nearly 12%) as compared to raw (fresh) tested KF. None the less, loss in vitamin C reported in present study was much less compared to available reports. The raw kiwi contains ash 0.88 to 1.02 g per 100 g sample<sup>19</sup>. So, initial load of ash in tested KF sample was more as compared with standard value; as expected, the ash content both in OPOD and OPODFD sample increased per 100 g of dried product. Structural properties of foods are strongly affected by material moisture content<sup>20</sup>, therefore high moisture level (>80%) suggests that kiwi fruit was very much suited for FD preservation. It was found that, all the carbohydrate and sugar level would be back to original level (raw kiwi) when rehydration step would be performed<sup>21</sup>. Ripen kiwi is a good source of  $\beta$ -carotene. The daily requirement of an adult for vitamin A is of the order of 750  $\mu\text{g}$  of retinol or 3000  $\mu\text{g}$  of  $\beta$ -carotene per day derived from either

animal or plant origin<sup>22</sup>. Table 2 shows that in processed kiwi, vitamin A found 20  $\mu\text{g}/100\text{g}$  of sample though raw kiwi contains trace amount of vitamin A as per fssai<sup>16</sup>.

## 4. Conclusion

The present work highlighted the dehydration of kiwi fruits through a consecutive osmotic dehydration and freeze-drying protocol. Application of Taguchi orthogonal design could help in finding optimal conditions for osmotic dehydration. Notably, sucrose has been found to be a better osmotic solution when compared with fructose under identical OD conditions.

The silver coated steel heater has been observed much more energy efficient than conventional steel heater in consecutive freeze-drying to obtain the final dried kiwi fruit. The osmotically dehydrated kiwi fruit at optimal conditions subsequently dehydrated employing energy-efficient silver coated heater resulted in a final dried kiwi fruit containing acceptable quality parameters conforming to market status. It is expected that the developed economically-sustainable dehydration protocol may be applied to similar foodstuffs.

The higher effective moisture diffusivity and lower activation energy in freeze-drying are indicative of a faster and energy saving dehydration protocol through application of novel silver (coated steel) heater making the kiwi dehydration process economically sustainable.

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