Low pressure superheated steam drying of onion slices: kinetics and quality comparison with vacuum and hot air drying in an advanced drying unit

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Abstract Pungency is important characteristics of onion and during processing it is generally reduces. Low pressure superheated steam drying (LPSSD) is gaining importance due to energy and product benefits. It results in better retentions of bioactive components. So, in current study onion slices were dried using low pressure superheated steam, and compared with vacuum and hot air drying at different temperature in NIFTEM advance drying unit. Among the selected models, Page's model gave a better prediction and satisfactorily described drying characteristics of onion slices. The Activation energy was found to be 41.87 kJ/mol in LPSSD. Quality of product, i.e. retention of color, rehydration ratio, thiosulphinate content, total phenol content and antioxidant activity, were better at 70 °C using LPSSD, at 60 °C using VD and HAD, as compared to other drying temperature in respective drying technologies used. Significant differences in quality of the dried product were also observed due to drying temperature in different drying techniques.

Keywords Onion · Superheated steam · Kinetics · Thiosulphinate · Antioxidant

Abbreviation

LPSSD	Low pressure superheated steam drying
VD	Vacuum drying
HAD	Hot air drying
d.b.	Dry basis

TC	Thiosulphinate content
NiftEMA-DU	NIFTEM advance drying unit
adj. R ²	adjusted R ²
MR	Moisture ratio
D _{eff}	Effective diffusivity
N	Number of observation
RMSE	Root mean square error
L	Lightness
a	Redness
b	Yellowness
ΔE*	Total color change
BI	Browning index
A	Absorbance
B	Cell path length
TPC	Total phenol content
TAA	Total antioxidant activity
IC	Inhibition capacity
RI	Relative inhibition
OD	Optical density

Introduction

Onion is among the seven major crops grown worldwide and India is the second largest producer of onion (Pérez-Gregorio et al. 2011). India exported approximately 50,000 t of dehydrated onions in 2016 as compared to 30,000 t in 2015 (Anon 2017). According to the International Trade Centre Geneva, the demand for dehydrated onions alone in European Union was estimated at more than 45,000 t per year (Grewal et al. 2013). Production of the dehydrated onions is increasing every year, indicating its growing demand by processing industries and consumers.

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Onion has antioxidant and phenolic compounds with selected vitamins and minerals which have beneficial properties like anti-cholesterolaemic, hypo-cholesterolemic, thrombolytic and anti-mutagenic (Mitra et al. 2015). Sulfur compounds (S-alk(en)yl cysteine sulfoxides) are basically responsible for the flavor of onion. Upon tissue rupture or breakdown during cutting or crushing allinase enzyme is released to hydrolyze the sulfur compounds. During hydrolysis different primary products like thiosulphinate or pyruvate are produced (Block et al. 1992). Thiosulphinate or pyruvate are volatile components and are degraded upon heating or drying. So, retention of pungency/flavor, while drying of onion is considered as a major concern to the processor. The pungency of onion can be estimated either by thiosulphinate content (TC) or by pyruvic acid content (Mitra et al. 2015).

Drying is one of the most common technologies to extend shelf life of perishable commodities. Onion has been dried for various studies using solar, convective air, vacuum, infrared, catalytic flameless gas-fired infrared, freeze drier and osmotic drying systems etc. (Mitra et al. 2012).

Conventional drying techniques have drawbacks which include loss of nutrients, color degradation and non-uniform product quality (Sehrawat et al. 2016, 2018a); longer drying time (Kumar et al. 2005; Leeratanarak et al. 2006). Infra-red drying technique, microwave drying technique reduces drying time but are more effective in combination with vacuum to retain the quality (Kumar et al. 2005) and costly also. Freeze drying is well known for maximum retention of nutrients as well as volatile components but longer drying time and high processing cost makes it unsuitable for commercial purpose. Osmotic drying accompanied with convective drying is having the limitation of poor rehydration and textural properties due to use of osmotic reagents (Grewal et al. 2013). Low pressure superheated steam drying (LPSSD) is gaining importance due to energy benefits (Jangam and Mujumdar 2015) product benefits as results in better retentions of bioactive components (Kongsoontornkijkul et al. 2006).

Keeping these points in view, this research proposes LPSSD as an alternative method for drying onion slices and comparing its kinetics and quality with vacuum drying (VD) and hot air drying (HAD) at different drying temperature (60–80 °C). All the experiments were conducted in NIFTEM advance drying unit (NiftEMA-DU) to study the comparative effect on drying kinetics (model fitting, effective diffusivity and activation energy). Fitting the drying kinetic data in thin layer models provides different drying constants which can describe the transport properties (moisture diffusivity, thermal diffusivity and interface heat and mass transfer coefficients). Moreover these models help in generalizing the drying process/time and need to

be considered while designing drying equipment for scale-up production. Activation energy significance lies in the selection of appropriate drying method as it is indicative of energy required to carry out the drying process. Quality of dried onion (color, rehydration ratio, thiosulphinate content total phenol content and antioxidant activity) was also evaluated.

Materials and methods

Drying experiment

For the experiment white onion (*Bhima Shweta* var.) were procured from Azadpur market, New Delhi. Onion bulbs were hand peeled and cut into slices of 3 mm using a slicer (Meat slicer, New Delhi).

Advance drying unit (NiftEMA-DU) available in Food Engineering Department of NIFTEM, India was used in this study as explained by Sehrawat et al. (2017, 2018b). During VD and LPSSD absolute pressure of 10 kPa was maintained in the setup. LPSSD, VD and HAD of onion slices were carried out at three temperatures (60, 70 and 80 °C). Onion slices (300 g) were uniformly spread on the tray. During drying process weight of the samples was measured at regular interval until a constant weight was observed. Moisture content was determined using vacuum oven method at 80 °C using 800 mbar for 24 h. Total drying time was noted as needed to reduce the moisture content of fresh onions slices to 7–8% (db). Packed dehydrated sample (of a reputed brand) was also procured from local market and quality analysis was carried out.

Mathematical modeling

Onwude et al. (2016) reviewed twenty-two thin layer models for drying of fruits and vegetables. In the current study, only five models (Newton, Page, Modified Henderson and Pabis, Approximation of diffusion and Peleg model) were used. The non-linear least square regression analysis based on Trust Region algorithm was used to estimate the constants of the models using MATLAB (version 2012).

The moisture ratio (MR) of the onion slices was calculated using Eq. (1). It was simplified from Eq. (2) due to long drying time (Kaymak-Ertekin and Gedik 2005).

$$MR = \frac{M_t}{M_i} \quad (1)$$

$$MR = \frac{M_t - M_e}{M_i - M_e} \quad (2)$$

where M_t is the moisture content at a time, t (kg water/kg dm), M_i is the initial moisture content (kg water/

kg dm), M_e is the equilibrium moisture content (kg water/kg dm).

The coefficient of determination i.e. adjusted R^2 (adj. R^2) and root mean square error (RMSE) were used as the criteria to select the best equation expressing the LPSSD, VD and HAD kinetics of onion slices.

Effective moisture diffusivity and activation energy

Fick's unsteady state law of diffusion, symbolized as a mass-diffusion equation (Eq. 3) for drying fruits and vegetables in a falling rate period is given as:

$$\frac{\partial M}{\partial t} = D_{\text{eff}} \frac{\partial^2 M}{\partial r^2} \quad (3)$$

where M is the moisture content (kg water/kg dm), D_{eff} is the effective diffusivity (m^2/s), r is the diffusion path and t is the drying time (min).

The onion slices were dried in the form of infinite slabs with thickness of 3 mm. For an infinite slab, Crank recommended Eq. (4) for calculating effective moisture diffusivity, based on Fick's second law of diffusion (Tütüncü and Labuza 1996; Demiray et al. 2017). It is based on the assumption that the moisture distribution is uniform throughout the product; unidirectional mass transfer and moisture content at the surface of product achieve equilibrium instantaneously with the surrounding medium.

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\frac{(2n-1)^2 \pi^2 D_{\text{eff}} t}{4L^2}\right) \quad (4)$$

where L is the thickness of the slab (m) before the drying, n is the number of integers in the series. This can be simplified by considering the first term and assuming that the effect of other terms on diffusivity was insignificant. Demiray et al. (2017) and Tütüncü and Labuza (1996) also stated that the first term of Eq. (5) is used for a long drying time, therefore it can be written as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right) \quad (5)$$

Diffusivity is then determined from the slope of the line plotted between $\ln(MR)$ and time. In drying process the dependence of moisture diffusivity on drying medium temperature was calculated using an Arrhenius relation as given in Eq. (6) (Demiray et al. 2017):

$$D_{\text{eff}} = D_0 \exp\left(\frac{E_a}{RT}\right) \quad (6)$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.3143 kJ/mol K), and T is the absolute air temperature (K). Thermodynamically, E_a is the

relative ease with which the water molecules pass the energy hurdle when migrating within the product.

Physical analysis

Rehydration ratio (RR) of dried slices were determined by keeping them in boiling water at 100 °C for 10 min and after removal of slices, water on the surface was wiped with tissue paper. It was then calculated as the ratio of mass obtained after rehydration to that of the initial mass of slices (Devahastin et al. 2004; Sehrawat et al. 2018b).

The color of fresh and dried onion slices were determined by hand held Chroma Meter (Konica Minolta, CR-400, Japan). The color changes were calculated according to Eq. (7):

$$\Delta L^* = \frac{L^* - L_i^*}{L_i^*}, \Delta a^* = \frac{a^* - a_i^*}{a_i^*}, \text{ and } \Delta b^* = \frac{b^* - b_i^*}{b_i^*} \quad (7)$$

where L^* , a^* and b^* represent the lightness, redness and yellowness of the dried onion samples, respectively. L_i^* , a_i^* and b_i^* are the lightness, redness and yellowness of the fresh onion samples respectively. The total color change (ΔE^*) was calculated from Eq. (8):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (8)$$

Browning index (BI) was measured by Eq. (9):

$$BI = \frac{100(x - 0.31)}{0.17} \quad (9)$$

where $x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*}$

Chemical analysis

Thiosulphinate content (TC) was estimated by the method described by Mitra et al. (2011). The TC ($\mu\text{mol/g dm}$) of the hexane solution was calculated using the Eq. (10) as:

$$TC = \frac{A}{\epsilon \times B} \quad (10)$$

where, A is absorbance and B is path length (cm). The molar absorptivity of thiosulphinate solution (ϵ) at 254 nm was found to be 0.014 $\text{g}/\mu\text{mol cm}$ by Samaniego-Esagueria et al. (1991).

For estimation of total phenol content (TPC) and total antioxidant activity (TAA), extraction of components was carried out in the 80% methanol as described by Sehrawat et al. (2017). Ten gram of sample was mixed with 150 ml of 80% (v/v) methanol and it was homogenized in tissue homogenizer at 8000 rpm for 5 min. The extract obtained was further centrifuged (Sigma, 3-18 KS, Germany) at 10,000 g for 20 min. followed by filtration using Whatman filter paper no. 42. After taking out the supernatant, in the remaining residues 100 ml of 80% methanol was added

and extraction was repeated once again. Combined supernatants from first and second extraction, were used for further analysis. Estimation of TPC, was carried out by following the protocol given by Singleton and Rossi (1965). TAA of the extract was assessed by measuring the percent inhibition of DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals using the protocol followed by Sehrawat et al. (2017). Relative inhibition (RI) was calculated as given in Eq. (11):

$$RI = \frac{IC \text{ of dried onion slices}}{IC \text{ of fresh onion slices}} \quad (11)$$

where IC = inhibition capacity

$$IC = \frac{\%inhibition}{Weight \text{ of sample (in dry matter)}}$$

$$\%inhibition = \frac{OD_{blank} - OD_{sample}}{OD_{blank}}$$

where OD = optical density of blank or sample.

Statistical analysis

Experimental data were analyzed by analysis of variance (ANOVA) using a statistical program SPSS (Version 24). Duncan's multiple range tests were employed to establish the multiple comparisons of mean values. Mean values were considered significantly different when $p < 0.05$. Each experiment was performed in triplicate.

Results and discussion

Effect of drying temperature on drying time

Onion slices were dried using LPSSD, VD and HAD at 60–80 °C till moisture content was reduced to 7–8% (d.b.) and drying time taken are given in Table 1. It was found that time taken while drying of onion slices were higher in HAD and lower in VD whereas for LPSSD it was found to be intermediate between HAD and VD. However, the time taken by LPSSD and HAD at 60 °C was same. While VD, heater was only source of thermal energy for drying, and it was used more frequently to maintain constant temperature which would have led to more radiation effect thereby higher drying rates. Lower rates in LPSSD could be due to steam condensation. It takes place in the beginning of the LPSSD as there is difference in product and superheated steam temperature. At higher temperature LPSSD depicts higher rate due to quick increase in surface temperature by superheated steam. Moreover superheated steam has higher specific heat as compared to hot air at the same temperature. Similar observations are also reported for potato by Leeratanarak et al. (2006) while drying of potato using

LPSSD and HAD. Higher drying rates lead to lower time required for drying and so was found in the present case of onion slices (Devahastin et al. 2004). Devahastin et al. (2004) observed higher drying rates during VD followed by LPSSD in case of carrots.

As evident from Table 1 and drying curves (Fig. 1), the drying time was reduced with increase in temperature, in all the three drying techniques used. It could be due to increase in vapor pressure inside samples thereby pressure gradient between surface of onion slices and inside the slices which in turn leads to higher heat transfer rate at higher temperature (Mitra et al. 2011). As shown in Fig. 1 the drying curves depicts drying of onion slices in falling rate period and absence of constant rate period. These results were in accordance with the previous studies on drying of onion by Mitra et al. (2011) and Demiray et al. (2017).

Drying characteristics

MR values versus time data obtained from three different drying technique at three temperatures studied were fitted to Newton, Page, Modified Henderson and Pabis, Approximation of diffusion and Peleg model. The value for adj. R^2 (fitting ability of the equation) $RMSE$ (the deviation between the predicted and experimental moisture ratio values) and model constants are shown in Table 2. Page model in all the drying techniques at different temperatures gave the best fit although, other models also fitted well to experimental data (adj. R^2 were above 0.97). The value of adj. R^2 and $RMSE$ varied from 0.9963 to 0.9992 and 0.0107 to 0.0231 respectively using Page model. Rate constant (k) increased with increase in drying temperature in the models studied except Peleg model which did not include k in the empirical equation. Moreover the k was higher in LPSSD and VD in comparison to the HAD process. The experimental values and predicted values clearly depicts the good agreement using page models for LPSSD, VD and HAD at 60–80 °C are shown in Fig. 1, clearly depicting the good agreement between predicted moisture ratio values and experimental values. Page model has been reported as the most appropriate model for predicting the drying behavior for onion slices in case of VD by Mitra et al. (2011), in case of convective drying by Demiray et al. (2017). Page model was also asserted as best model in case of LPSSD of Paneer (Shrivastav and Kumbhar 2011).

Moisture diffusivity and activation energy

Moisture diffusivity values were found to be highest in VD followed by LPSSD and HAD and thus lowest E_a values were obtained by VD (39.50 kJ/mol) followed by LPSSD (41.87 kJ/mol) and HAD (42.36 kJ/mol) (Fig. 2). It was

Table 1 Drying time, effective moisture diffusivity and activation energy of dried onion slices

Drying technique	Temperature (°C)	Time taken (min)	Effective diffusivity ($10^{-9} \text{ m}^2/\text{s}$)	Activation energy (kJ/mol)
LPSSD	60	180 ± 5.03	1.36	41.87
	70	150 ± 4.04	1.88	
	80	75 ± 2.51	3.65	
VD	60	150 ± 3.60	1.66	39.50
	70	120 ± 3.51	2.21	
	80	75 ± 0.00	3.73	
HAD	60	210 ± 4.58	1.15	42.36
	70	180 ± 4.00	1.40	
	80	120 ± 3.60	2.27

Fig. 1 Moisture ratio curves of experimental and predicted values of dried onion slices

observed that moisture diffusivity increased with increase in temperature (Table 1) and similar results have been reported on onion drying (Mota et al. 2010; Mitra et al.

2011; Demiray et al. 2017). These values were comparable with other reported studies in case of onion. In case of onion, diffusivity was reported to be varied from 0.13 to

Table 2 Mathematical models applied to drying curves of onion slices

Model	Parameters	LPSSD			VD			HAD		
		60 °C	70 °C	80 °C	60 °C	70 °C	80 °C	60 °C	70 °C	80 °C
Newton model	Equation	$MR = \exp(-kt)$								
	k	0.0188	0.0270	0.0399	0.0229	0.0303	0.0418	0.0150	0.0239	0.0360
	$RMSE$	0.4700	0.0170	0.0312	0.0382	0.0170	0.0310	0.0255	0.0183	0.0270
	adj. R^2	0.9848	0.9978	0.9932	0.9896	0.9977	0.9933	0.9952	0.9972	0.9944
Page's model	Equation	$MR = \exp(-kt^n)$								
	k	0.0077	0.0211	0.0240	0.0088	0.0213	0.0237	0.0070	0.0205	0.0217
	n	1.3430	1.0690	1.1520	1.2500	1.1000	1.1740	1.1590	1.0280	1.1520
	$RMSE$	0.0185	0.0149	0.0231	0.0222	0.0112	0.0202	0.0107	0.0148	0.0204
Modified Henderson and Pabis model	Equation	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$								
	a	3.4280	− 5.3230	− 2.3620	2.3450	0.2400	0.9816	− 0.1647	0.0632	− 0.1189
	b	0.4663	5.2880	− 0.0041	3.3900	0.5525	0.1615	0.1037	1.0100	0.4280
	c	− 2.8940	1.0350	3.3660	− 4.7350	0.2944	− 0.1431	1.0610	− 0.0731	0.6910
Approximation of diffusion	g	0.1492	0.7484	0.7114	0.0429	0.0240	0.0481	0.9648	0.0242	0.0411
	h	0.0560	0.0282	0.0579	0.0792	0.5477	0.8404	0.0160	0.8484	0.0411
	k	0.0170	0.0208	0.0470	0.0180	0.0220	0.0481	0.0153	0.0183	0.0389
	$RMSE$	0.0184	0.0227	0.0402	0.0231	0.0408	0.0401	0.0253	0.0246	0.0323
Peleg model	Equation	$MR = I - t/(a + bt)$								
	a	− 11.8300	− 4.7710	− 3.3290	− 9.6910	− 0.1368	0.3066	− 7.5520	− 1.8220	− 0.1191
	b	0.9382	0.9339	0.8717	0.9357	0.3200	1.0000	0.9332	0.8936	0.0490
	k	0.0371	0.0391	0.0679	0.0423	0.0418	0.0718	0.0252	0.0324	0.610
Peleg model	$RMSE$	0.0202	0.0155	0.0254	0.0235	0.0183	0.0367	0.183	0.0193	0.0228
	adj. R^2	0.9973	0.9982	0.9955	0.9963	0.9973	0.9907	0.9973	0.9970	0.9963
	a	47.3600	28.7800	21.2300	35.6400	26.1500	20.0300	57.380	31.0500	21.0700
	b	0.7410	0.8193	0.7655	0.7945	0.8077	0.7738	0.7597	0.8432	0.8331
Peleg model	$RMSE$	0.0645	0.0421	0.0475	0.0623	0.0440	0.0502	0.0420	0.0410	0.0574
	adj. R^2	0.9722	0.9868	0.9844	0.9725	0.9859	0.9826	0.9869	0.9860	0.9763

a, b, c, g, h, k, n constants; t time; $RMSE$ Root mean square error; $LPSSD$ Low pressure superheated steam drying; VD Vacuum drying; HAD Hot air drying

1.09×10^{-9} (Mitra et al. 2011) while VD and 3.33 to 8.55×10^{-9} while convective drying (Mota et al. 2010). E_a required for convective drying of onion slices was reported to be 45.60 kJ/mol (Demiray et al. 2017).

Color

$L^*, b^*, \Delta E^*$ and BI values of fresh and dried samples using $LPSSD$, HAD and VD are provided in Table 3. As expected the lightness values decreased and yellowness values increased after drying in all the treatments. It is desirable to have higher lightness values of dried onions. It was found to be higher in samples dried using $LPSSD$ (66.20–69.69) followed by VD (61.62–65.64) due to

oxygen free environment and comparatively darker in case of HAD (51.96–60.57) due to oxidation reactions (Deva-hastin et al. 2004). a^* values are not of much consideration in indicating quality of dried of onion (Gabel et al. 2006). It is desirable to have low $b^*, \Delta E^*$ and BI values, as higher values indicates severe effect of drying on the color attributes of samples. Color values of market samples were similar to samples dried using HAD at $60^\circ C$. It was also observed that process severity increased with increase in temperature resulting in lower L^* , higher $b^*, \Delta E^*$ and BI values except in case of $LPSSD$ at $70^\circ C$, it could be due to shorter time taken while drying and less severe effect than $80^\circ C$. It was also observed from the data that $LPSSD$ at $70^\circ C$, VD and HAD at $60^\circ C$ helps in better retention of

Fig. 2 Arrhenius-type relationship between the effective diffusivity and absolute temperature of drying

Table 3 Color value of dried onion slices

Drying technique	Temperature (°C)	L^*	b^*	ΔE^*	BI
LPSSD	Fresh	73.54 ± 0.36	3.16 ± 0.04	–	–
	60	66.20 ± 0.34^b	7.62 ± 0.70^{bc}	1.23 ± 0.18^f	10.80 ± 1.27^{de}
	70	69.69 ± 0.42^a	5.55 ± 0.60^d	1.38 ± 0.33^{ef}	08.68 ± 1.51^e
	80	66.50 ± 0.54^b	6.71 ± 0.55^{cd}	1.91 ± 0.18^{cde}	11.94 ± 0.17^d
VD	60	65.64 ± 0.45^b	7.59 ± 0.57^{bc}	1.63 ± 0.24^{def}	12.48 ± 1.28^{cd}
	70	63.51 ± 0.54^c	8.09 ± 0.40^b	2.16 ± 0.31^{bcd}	15.14 ± 0.28^{bc}
	80	61.62 ± 0.70^d	8.08 ± 0.15^b	2.58 ± 0.18^b	16.81 ± 0.48^b
HAD	60	60.57 ± 0.48^d	8.62 ± 0.65^{ab}	2.24 ± 0.31^{bc}	16.88 ± 1.74^b
	70	53.84 ± 0.24^e	9.47 ± 0.49^a	3.43 ± 0.20^a	24.55 ± 1.42^a
	80	51.96 ± 0.35^f	9.57 ± 0.57^a	3.67 ± 0.22^a	26.44 ± 1.64^a
Market sample	–	60.75 ± 0.28^d	8.41 ± 0.33^{ab}	2.11 ± 0.18^{bcd}	16.15 ± 1.11^b

Values are represented as mean $\pm$ SD. Different superscript letters within the same column indicates that the values are significantly different ($p < 0.05$)

color in respective drying techniques for onion slices. It was reported that LPSSD helps in better retention of color than VD in case of carrots (Devahastin et al. 2004) and Indian gooseberry (Kongsoontornkijkul et al. 2006). Also in potato chips better color was preserved in case of samples dried using LPSSD when compared to HAD (Leeratanarak et al. 2006).

Rehydration ratio (RR)

RR of samples dried using LPSSD, VD and HAD varied from 3.85 to 4.76, 3.86 to 3.99 and 3.17 to 3.40 as given in Table 4. RR of all the dried samples was found to increase with an increase in temperature. It could be due to the more porous structure at the higher temperature thus helps in absorption of more water on rehydration. Samples dried using LPSSD at 60 °C had the lowest RR whereas at 70 °C and 80 °C differences were not significant. In case of VD at 60–80 °C, significant differences were not observed. Similar results were obtained in case of HAD. Higher RR values were obtained in samples dried by LPSSD, VD and then by HAD. As in LPSSD the steam evolves due to pressure within the product thereby making it more porous whereas rigid and collapse structure might have hindered the water absorption in case of samples dried using VD and HAD. Previous studies by Devahastin et al. (2004) on carrot reported higher RR in case of LPSSD than VD and Jamradloedluk et al. (2007) obtained higher RR in durian slices dried by LPSSD as compared to HAD. Sharma et al. (2005) reported RR of 2.4 for commercially dried onion slices and in all the dried samples in this study RR was more than 3.15.

Thiosulphinate content (TC)

Thiosulphinate content (TC) in all the samples is shown in Table 4. It can be observed that the retention of TC in case of LPSSD is higher, that may be due to oxygen free environment which would have restricted the oxidation and browning reaction responsible for degradation of constituents (Jangam and Mujumdar 2015). In samples dried using LPSSD better retention of TC was found at 70 °C (7.92 ± 0.11 $\mu\text{mol/g d.m.}$), in case of VD differences were not significant at 60–80 °C ($p < 0.05$). In HAD higher retention was achieved at 60 °C (5.55 ± 0.05 $\mu\text{mol/g d.m.}$) and differences were not significant at 60 °C and 70 °C ($p < 0.05$). In case of LPSSD it was found that at 70 °C higher retention was observed which could be due to longer drying time taken at 60 °C and severe effect of temperature at 80 °C. The TC of market sample was found to be low 5.17 ± 0.33 $\mu\text{mol/g d.m.}$ and values were in close approximation to that of samples dried using HAD at 70 °C.

Mitra et al. (2011) dried red onion slices (1–5 mm) using VD (50–70 °C) and reported thiosulphinate content from 3.19 to 3.92 $\mu\text{mol/g}$ which were lower than the present study. It was also stated that increase in temperature leads to slight decrease in thiosulphinate content (Mitra et al. 2011, 2015).

Total phenol content (TPC)

The differences in TPC of different drying techniques at different conditions are reported in Table 4. In comparison to samples dried using VD and HAD, TPC was higher in

Table 4 Rehydration ratio and changes in thiosulphinate content, total phenol content, total antioxidant activity of dried onion slices

Drying technique	Temperature (°C)	Rehydration ratio	Thiosulphinate content ($\mu\text{mol/g d.m.}$)	Total phenol content (mg GAE/100 g d.m.)	Total antioxidant activity (Relative inhibition)
LPSSD	Fresh	–	10.25 ± 0.01	840.81 ± 1.51	–
	60	3.85 ± 0.19^b	7.22 ± 0.22^b	749.08 ± 1.29^a	0.68 ± 0.007^b
	70	4.63 ± 0.17^a	7.92 ± 0.11^a	752.13 ± 2.15^a	0.69 ± 0.003^a
	80	4.76 ± 0.17^a	7.26 ± 0.06^b	733.67 ± 1.93^b	0.64 ± 0.002^c
VD	60	3.86 ± 0.09^b	6.68 ± 0.12^c	709.71 ± 1.72^c	0.62 ± 0.002^d
	70	3.94 ± 0.16^b	6.47 ± 0.14^{cd}	682.69 ± 1.08^d	0.62 ± 0.004^d
	80	3.99 ± 0.14^b	6.10 ± 0.05^d	657.66 ± 2.37^e	0.59 ± 0.002^e
HAD	60	3.17 ± 0.12^c	5.55 ± 0.05^e	624.93 ± 1.51^f	0.57 ± 0.005^e
	70	3.40 ± 0.13^c	5.16 ± 0.27^e	594.08 ± 1.64^h	0.53 ± 0.001^f
	80	3.37 ± 0.21^c	3.65 ± 0.43^f	506.87 ± 3.23^i	0.51 ± 0.006^g
Market sample	–	–	5.17 ± 0.16^e	613.00 ± 4.24^g	0.57 ± 0.007^e

Values are represented as mean $\pm$ SD. Different superscript letters within the same column indicates that the values are significantly different ($p < 0.05$)

samples dried using LPSSD (733.67–749.08 mg GA/100 g d.m.) and the lowest in HAD (506.87–624.93 mg GA/100 g d.m.). Presence of lower TPC could be due to degradation of antioxidant compounds like ascorbic acid in the presence of oxygen while HAD (Sarsavadia 2007) as well as longer drying time than in LPSSD and VD.

It was noticed that with an increase in temperature there was decrease in TPC. Differences were not significant at 60 °C and 70 °C ($p < 0.05$) using LPSSD. While in case of VD and HAD differences were significant in the temperature range from 60 to 80 °C ($p < 0.05$). The TPC of market samples were intermediate to samples dried using HAD at 60–70 °C.

TPC of onion is reported to be 472 mg/100 g in the sun dried onion slices whereas 512–780 mg/100 g when dried using oven from 50–70 °C (Arslan and Özcan 2010). Contradictory results have been reported in the literature regarding the effect of drying techniques and temperature on total phenol content. Researchers reported that drying resulted in decrease in TPC (Zanoelo et al. 2006) due to degradation of heat sensitive components, whereas others reported insignificant differences in the TPC (Dewanto et al. 2002) and it was also observed that bound phenolic compounds are released due to breakdown of cellular constituents as accelerated by drying process which resulted in higher phenolic than fresh samples (Ren et al. 2017). In the current study it was found to decrease after the drying process in all the three drying techniques used.

Total antioxidant activity

Antioxidant activity in terms of relative inhibition of dried samples is reported in Table 4. It was found to be the highest at 70 °C for LPSSD (0.69) and at 60 °C and 70 °C (0.62) for VD and at 60 °C (0.57) for HAD. For the market samples relative inhibition (0.57) was found to be same as that of HAD at 60 °C (0.57). It was noticed that relative inhibition of all the dried samples decreased after drying. It could be ascribed to heat sensitive nature of the antioxidant compounds which would have got degraded during the drying process (Santos et al. 2014). The initial activity of enzyme (prior to their inactivation) could also be responsible for degradation of polyphenols, as polyphenols also contribute to antioxidant activity (Lim and Murtijaya 2007). Ren et al. (2017) also reported polyphenols in onions are main antioxidant compounds. Similar trend was observed in TPC of dried onion as represented in Table 4. In the samples dried using LPSSD, the presence of higher polyphenols would have resulted in higher relative inhibition. Hiranvarachat et al. (2008) reported higher relative inhibition in carrots samples dried using LPSSD as compared to HAD and VD.

In case of LPSSD and HAD significant differences were observed at a different temperature. Differences were not significant at 60 °C and 70 °C using VD ($p < 0.05$). In case of LPSSD at 60 °C losses could be attributed to fact that at a lower temperature the enzyme gets inactivated after a long time as compared to higher temperature. Presence of enzyme for longer duration would have caused the degradation of polyphenols responsible for antioxidant activity (Suvarnakuta et al. 2011) where as in case of higher temperature (80 °C) the thermal degradation might be more significant. Suvarnakuta et al. (2011) analyzed relative inhibition of xanthenes in mangosteen rind using LPSSD at 65–90 °C and asserted the highest retention at 75 °C due to proper drying time and temperature to help inactivate polyphenol oxidase enzyme as well as minimizes thermal degradation.

Conclusion

The conventional drying techniques often result in loss of bioactive compounds, color and affect the rehydration properties. There is now a growing interest in the use of drying processes which involve lower heat damage and is efficient in terms of energy saving aspect. Superheated steam drying has been developed recently and only few studies have been reported about the same. This study explored the drying of onion in a multi-purpose drying unit in which all the three processes i.e. hot air drying, vacuum and low pressure superheated steam was carried out. Based on kinetic modeling and on physico-chemical analysis, low pressure superheated steam drying at 70 °C has been found the best drying condition followed by vacuum drying and hot air drying both at 60 °C. These results have shown that low pressure superheated steam drying is an innovative method to retain high pungency, better color, and rehydration of dried onion.

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