The Pharma Innovation Journal 2021; SP-10(12): 768-775

www.ThePharmaJournal.com

The Pharma Innovation

ISSN (E): 2277- 7695
ISSN (P): 2349-8242
NAAS Rating: 5.23
TPI 2021; SP-10(12): 768-775
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www.thepharmajournal.com
Received: 04-10-2021
Accepted: 06-11-2021

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Drying characteristics of sub-atmospheric pressure superheated steam drying of apple: Effect on physical quality attributes

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Abstract
Drying with superheated steam (SHS) as a drying medium is a novel technology with high potential benefits compared to conventional hot-air drying. This approach is becoming more common, particularly in drying of foodstuffs. The aim of this study was to explore the influence of SHS at low-pressure as a drying medium for fruits. Drying studies of apple slices were conducted in a convective batch type dryer with superheated steam at low pressure as a drying medium. Low-pressure superheated steam (LPSHS) drying was investigated at temperatures ranging between 70 and 90 °C and absolute pressure levels of 0.5 and 0.8 bar with steam flow rate at 0.1 and 0.3 m^3/h, respectively. The apple slices dried under the condition of 90 °C, 0.5 bar pressure enhanced the drying rate from 0.195 to 1.02 g/min with reduced drying time of 130 min in order to attain a final moisture content of 108% (d.b.). In terms of physical attributes, samples exposed to a lower temperature level of 70 °C and low pressure of 0.5 bar had promising results. The volume, porosity (Ɛ), rehydration ratio and percentage shrinkage of LPSHS dried samples were 0.09 g/cm^3, 0.87, 5.23 and 91%, respectively. Fruit slices with a pleasant cooked flavour can be obtained under these conditions with relatively better texture and colour.

Keywords: novel, low-pressure superheated steam, dying characteristics, pleasant cooked flavour

Introduction
Apple is one of the most important fruits with remarkable nutritional value. The fruit is consumed both as fresh or processed form such as juice, jam and dried. It is an important raw ingredient for numerous food products. Apple plantations may be found in many nations across the world. As a result, it is critical to specify the conditions under which fresh apple features can be kept, as well as the best parameters for their preservation and reuse.

Drying is the commonly employed food preservation technique to improve the physical, chemical and microbiological quality of fresh horticultural commodities. Solar drying, convective air drying, freeze drying, microwave drying and infrared drying are widely employed. The critical challenge in drying of fruits is maximizing the drying rate while minimizing the energy use and quality degradation in terms of flavour, texture, colour and nutritional value. With no energy consumption, sun drying provides products that are rich in colour, translucent and have a pleasant gummy texture. However, due to possibility of environmental contamination, microbiological safety cannot be guaranteed and hence direct sun dried food items are not acceptable for all markets (Maskan *et al.*, 2002; Belessiotis and Delyannis, 2011) [5, 4]. While conventional hot air drying can reduce the chance of contamination, wherein, operational temperature has an impact on product quality. Furthermore, a significant quantity of energy is lost in the exhaust air. Freeze dried food stuffs have maximum rehydration ability and natural colour as of fresh samples (Hu *et al.*, 2006) [6]. The downside of freeze-drying is long drying time, high investment cost and energy consumption. Dried apples can be directly consumed or used as a secondary raw material. Unfortunately, there is limited information about SHS drying of apple fruit.

Drying with superheated steam (SHS) as a drying medium is novel, air-less technology with greater potentiality as compared to conventional methods. The notable benefits of SHS drying includes: energy savings due to the ability to reuse latent heat of evaporation, better pollution control by reducing emissions through evaporation of exhaust gas, inert steam that prevents fire and explosion risks, high heat transfer co-efficients resulting in reduced drying time, no resistance to internal moisture diffusion and enhanced mobility of water within the particles and ability to get varied new products (Robert, 1985; Li *et al.*, 1998; Jensen, 2008).

This approach is also becoming more prominent, especially in drying of foodstuffs. There are limited informations available on the effects of SHS drying on specific qualities such as colour, porosity, shrinkage, rehydration ability of food materials. Specific literature on fruit drying employing SHS is minimal and be confined to a few products such as banana (Nimmol *et al.*, 2007) [16], longan (Somjai *et al.*, 2009), durian (Jamradloedluk *et al.*, 2007) [18] and gooseberry (Methakhup *et al.*, 2005) [19].

Nimmol *et al.* (2007) [16] used a combination of low-pressure superheated steam (LPSHS) and far infrared radiations to test banana drying. The dried banana slices had lower hardness and greater crispness than commercially available ones. Another methodology for drying longan, an exotic fruit (Somjai *et al.*, 2009) [17] in two phases was investigated: SHS followed by 70 °C hot air drying. They concluded that SHS at 180 °C was optimum for drying longan with higher retention of nutrients. As compared to drying with hot air, SHS offered dried durian chips of excellent quality in terms of colour and rehydration ratio (Jamradloedluk *et al.*, 2007) [18]. The effect of LPSHS drying on Indian gooseberry was tested by Methakhup *et al.*, (2005) [19]. The samples seemed to have maximum ascorbic acid retention and maintain the colour better than hot air drying. The novel drying method has emerged as an intriguing method for rapid stripping away more than 50% of the initial water content in less than 10 minutes at temperature 150 or 170 °C.

There seems to be currently no results on drying of apple slices with SHS. According to Mujumdar (2007), academic and research organisations must promote emerging technologies in order to establish appropriate justification for expenditures and investments in food industries. The purpose of this study was to investigate temperature (70, 90 °C), absolute pressure (0.5, 0.8 bar) and flow rate (0.1, 0.3 m^3/h) of SHS on drying of apple. The viability of SHS as a drying medium on drying characteristics and physical attributes attributes namely volume, apparent density, shrinkage, colour and rehydration ratio and colour were examined.

Materials and Methods

Raw material

Fresh apples of Red Delicious variety were procured from the reputed supermarket (Coimbatore) and stored at refrigerated temperature of 4 °C. The apples were washed with potable water and peeled using food grade stainless steel knife. Apple slices of 2 mm thickness were pre-treated with a solution of 5% citric acid (w/v) and 1% ascorbic acid (w/v) in order to prevent browning effects. The slices were then rinsed with cold potable water before the drying studies.

Drying experiment

For the drying experiments, low-pressure superheated steam drying unit developed in the Department of Food Process Engineering, AEC&RI, TNAU, Coimbatore was used. The dryer utilized superheated steam as the drying medium at temperature range of 70 and 90 °C. The absolute pressure of the steam was 0.5 and 0.8 bar. The flow rate of superheated steam was maintained at 0.1 and 0.3 m^3/h. The apple slices were uniformly spread on the sample trays. The experimental design of the study having three factors two levels each is shown in Table 1. The influence of these factors was tested against various responses namely drying characteristics, apparent density, porosity, shrinkage, rehydration ability and colour value.

Table 1: Design of experiment

Independent variables	Level		Dependent variables
SHS temperature (°C)	70	90	Drying characteristics Apparent density (g/cm^3) Porosity (Ɛ) Rehydration Ratio Shrinkage (%) Colour value
SHS pressure (kPa abs.)	0.5	0.8	
SHS flow rate (m^3/h)	0.1	0.3	

Moisture content

Moisture content of the sample was determined by vacuum oven method (AOAC, 1975) [1]. 10 g of sample was accurately weighed and dried in a vacuum oven at 70 °C under a pressure of ≤ 100 mm Hg. The moisture content was calculated by the following expression (Canet, 2016) [2] and expressed on dry basis (d.b.):

$$\text{Moisture content} = \frac{w1-w2}{w2} \times 100,\ \%\ \text{d.b.} \qquad (1)$$

where,
W_1 – weight of sample before drying, g
W_2 – weight of sample after drying, g

Volume and Apparent Density

Sample volume measurements were made using Pycnometer, *n*-heptane being the working liquid. The apparent density (ρ) was readily obtained by this method. Average value of three samples was noted and measurements were made in triplicate. Volume and apparent density of both fresh and dried apple slices were calculated with the equations:

$$V = \frac{(Mpnh-Mp]-[Mpnhs-Mp-Ms]}{\rho nh} \qquad (2)$$

$$\rho_d = \frac{(mass\ of\ sample\ in\ air)}{V} \qquad (3)$$

where,
M_{pnh} – mass of Pycnometer filled with *n*-heptane, g
M_p – mass of empty Pycnometer, g
M_{pnhs} – mass of Pycnometer filled with *n*-heptane + sample, g
M_s – mass of sample, g
P_{nh} – density of *n*-heptane, kg/m^3

Shrinkage

Three samples were used for measuring shrinkage of each experimental condition. The shrinkage (S) values of samples were expressed as percentage change in volume (V_f) to the original sample volume (V_i).

$$S = \frac{(Vi-Vf)}{Vi} \times 100 \qquad (4)$$

Porosity

During the drying process, porosity of product increases with the removal of moisture and volatiles present in it. Porosity (Ɛ) is the ratio between volume of air (V_a) present in the sample to overall volume (V) (Lewis, 1987) [7].

$$\mathcal{E} = \frac{Va}{V} \quad (5)$$

It is expressed as a function of apparent density (ρb) and particle density (ρa) and takes the form:

$$\mathcal{E} = 1 - \frac{\rho b}{\rho a} \quad (6)$$

Rehydration ratio

Rehydration ratio (R) of the samples was estimated by dipping dried samples in hot boiling water 100 °C for 10 minutes. The samples were drained thereby their volume before and after dipping were measured using Pycnometer. It was calculated as:

$$R = \frac{Vf}{Vi} \quad (7)$$

Where V_i and V_f are volume of dried apple slices before and after hot water immersion, respectively.

Colour

Colour value of the apple slices before and after each drying treatment was measured using a Hunter Lab Colour Meter, that provides *L*, *a* and *b* colour scale values. *L* value indicates the lightness or darkness parameter, *a* value the redness or greenness and *b* value the yellowness or blueness parameter. The surface colour parameter of apple slices were measured (5 measurements per fruit) and the values averaged. Measurements were made on upper surface of the sample using white tile as a reference.

Statistical analysis

Experimental data were analyzed using Analysis of Variance (ANOVA) by Minitab 19.1.1.0 software. The Tukey's test was performed to establish multiple comparisons of mean values. Mean value was considered to be significantly different when $p \leq 0.05$. Modelling of responses with respect to predictors was carried out using SPSS software version 16.0.

Results and discussion

Drying characteristics of apple

The heat-sensitive material namely apple, had an initial moisture content of about 545% d.b. was dried in 130 min duration in the convective dryer using LPSHS as drying medium. Figure 1shows the change in mass of the samples with respect to drying time for LPSHS drying.

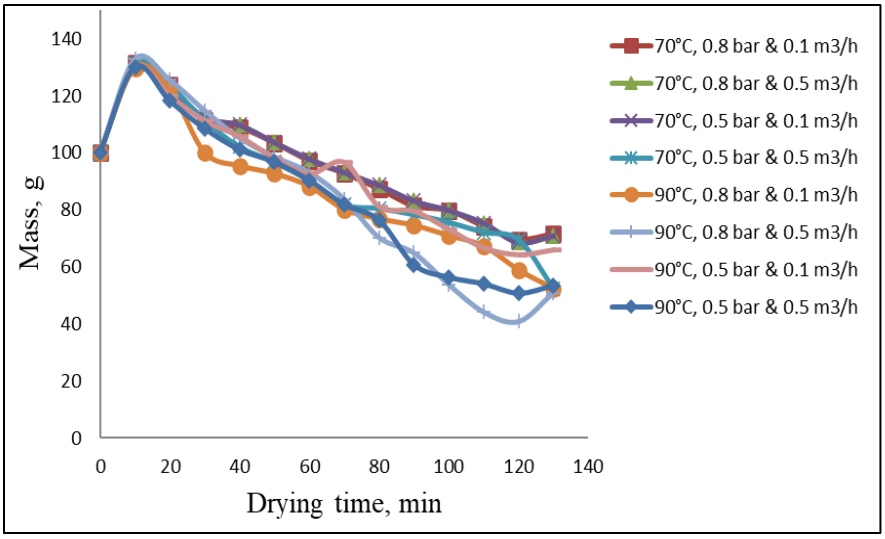

Fig 1: Drying curve of apple slices undergoing LPSHS drying

The drying curves of apple slices showed decrease in temperature during first few minutes probably due to initialization of the dryer. Drying as expected, started about 5 min after which the sample mass was recorded initially. It was seen in the Figure 2 that all samples were found to gain a small amount of moisture (30 g approximately) during first 10 min of drying process. As a matter of fact, this phenomenon is typical with respect to superheated steam drying (Tang *et al.*, 2000; Mujumdar (2000) [8, 9]. Nonetheless, condensation of steam during start-up of the drying process is rather negligible when the operating pressure is low. When drying at 70 and 90 °C, the moisture gain in samples was about 2.3 and 1.5%, respectively. Restoration time, the time by which original mass of sample has returned to its original value (Iyota *et al.*, 2001) [10] was 19 and 12 min for drying at 70 and 90 °C at 0.8 and 0.5 bar, respectively. The final moisture content of 108% (d.b.) was obtained when dried at 90 °C, 0.5 bar in 130 min duration time.

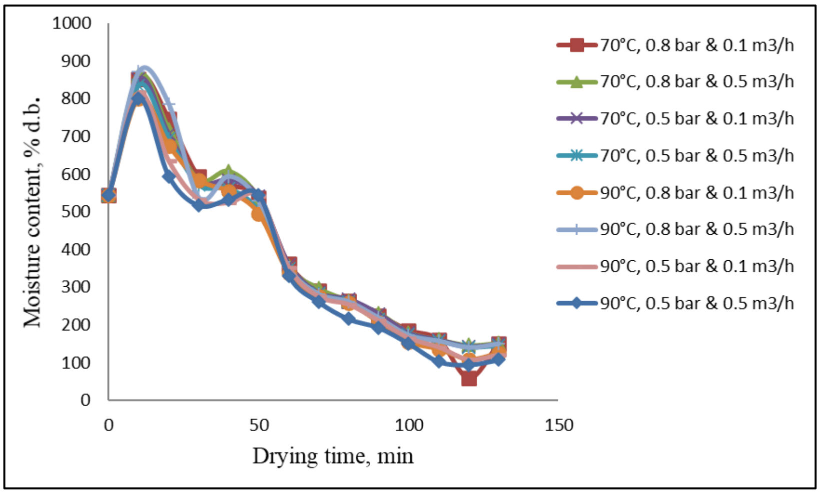

Fig 2: Drying time Vs Moisture content of apple slices

It can be noted from Figure 4 that the influence of temperature on drying rate was higher than that of pressure during LPSHS drying, particularly at high drying temperature (90 °C). The consequence of operating pressure was less evident at low temperature, 70 °C. This may possibly due to actuality that the thermal properties of superheated steam were affected to a larger extent by temperature. It was noticeable from Fig 2 that the moisture content decreased rapidly 545 % to 105% d.b. from at a high temperature (90 °C) than at low temperature (70 °C). For instance, increase in drying medium temperature from70 to 90 °C lead to reduction in drying time of about 45 and 32%, respectively. Furthermore, it was noted that the moisture content of sample decreased quickly at low pressure 0.5 bar by reason of moisture being evaporated in sample at low temperature. Decrease in pressure from 0.8 to 0.5 bar led to a reduction in drying time by 12 and 20%, respectively.

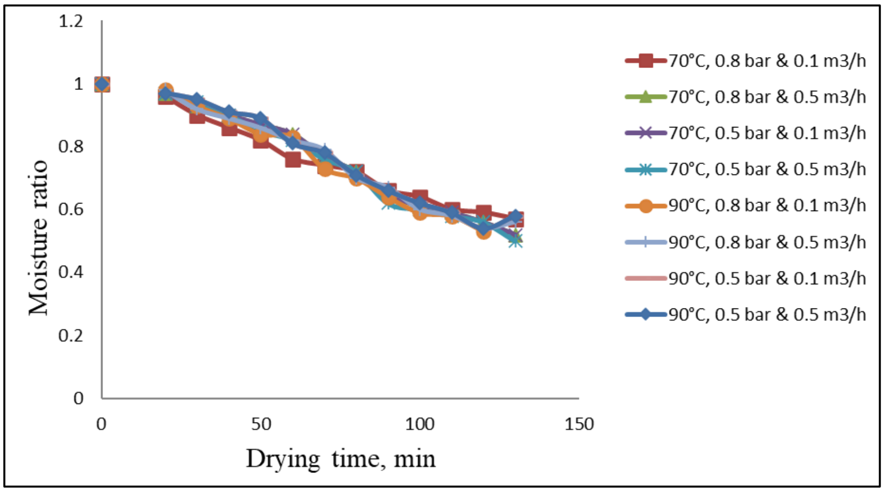

Fig 3: Drying time Vs Moisture ratio

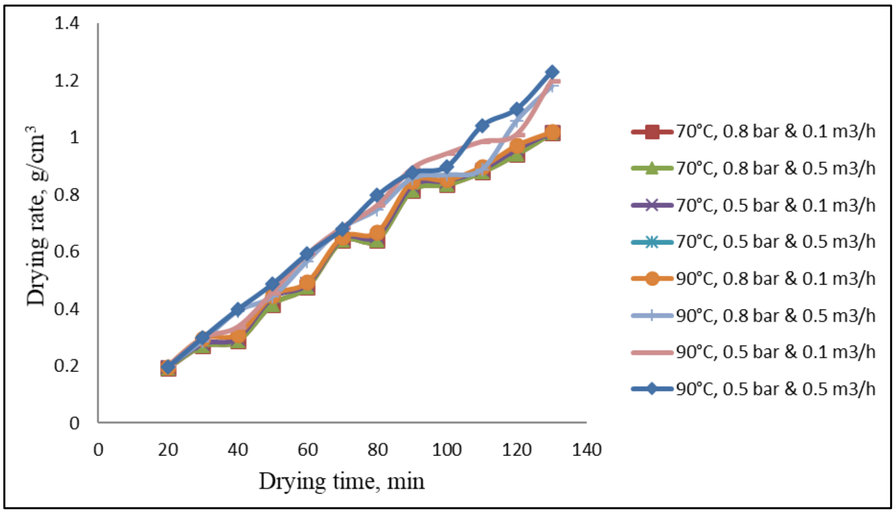

Fig 4: Drying time Vs Drying rate

The moisture ratio of samples with respect to drying time and drying rate with respect to drying time is shown in Figure 3 and Figure 4, respectively. It clearly shows that the moisture ratio and drying rate were higher at higher drying temperature. Another crucial problem encountered during LPSHS drying was that at lower operating temperature (70 °C), pressure (0.8 bar) and steam flow rate (0.1 m^3/h), there was an enormous amount of steam condensation inside the pipe work and drying chamber. Steam condensation on the sample surface during initial phase, contributes to longer drying time.

Physical attributes of apple slices dried using LPSHS

Effect of dryer operating parameters on the physical attributes of LPSHS dried apple slices namely apparent density, volume, porosity, shrinkage rehydration ability were investigated. Table 2 illustrates the grouping information of responses using Tukey Method with 95% confidence interval (n=8).

Table 2: Tukey Pairwise Comparison of mean values and grouping

S. No	Factor	Mean±StDev	Grouping	95% CI
1.	Volume	0.0888 ±0.003	E	-0.043, 0.220
2.	Apparent density	1.4375±0.032	C	1.305, 1.569
3.	Porosity	0.8275±0.065	D	0.695, 0.959
4.	Rehydration ratio	4.907±0.336	B	4.776, 5.039
5.	Shrinkage	91.00±0.225	A	90.875, 91.139

Pooled StDev = 0.183853

The volume and apparent density of apple undergoing LPSHS was found to moderately decrease and increase, respectively. The volume of samples dried at 70 °C, 0.8bar pressure at steam flow rate of 0.1m^3/h was 0.09±0.01 g/cm^3 and those dried at 90 °C, 0.5 bar and 0.5 m^3/h was 0.093±0.04 g/cm^3. Results confirmed the inverse relationship existing between volume and apparent. It was observed that volume of dried apple slices was inversely proportional to apparent density i.e., apple with low apparent density had larger volume as expected. The apparent density was found to have increasing value of 1.52±0.06 g/cm^3 at drying temperature of 90 °C and steam flow rate of 0.5 m^3/h. The change in these properties may be due to increase in operating pressure as pressure effects the percentage of void space developed in final dried product. It was in accordance to the results given by (Krokida *et al.*, 2000) [11] that compared density of dried carrot undergoing convective hot air, freeze, microwave and osmotic drying. It was concluded in the study that the operating pressure crucially influenced the volume and density of dried product. Also, by lowering the operating pressure, the structural collapse of dried food can be prevented.

Shrinkage

Unlike the apparent density, shrinkage of dried product was directly correlated to volume of dried samples. The percentage shrinkage of sample dried in SHS showed only slight variation from that of the original one. The samples dried at temperature of 70 °C at 0.5 bar pressure had lower shrinkage of 90.7% than those dried at 90 °C at 0.5 bar was 91.23%. Reports specify that SHS drying has the potential to reduce degree of shrinkage in product due to vapour evolution inside the product. Thereby, the product becomes more porous in nature (Seyed-Yagoobi *et al.*, 1999) [12]. Uniform shrinkage pattern was seen in dried apple slices as SHS under reduced pressure.

The apple slices dried using SHS had a better rehydration capacity. The rehydration ratio was 5.23 for samples dried at 90 °C, 0.5 bar & 0.5 m^3/h whereas it was 4.47 for those dried at 70 °C, 0.8 bar & 0.1 m3/h. The rehydration ability is closely related to the shrinkage pattern of the dried samples. Drying with SHS at reduced pressure avoids the formation of dense layers thereby enhances the adsorption of water inside pore spaces.

Colour

Although a dispersion of ‘*L*’ values was observed**,** the mean value remained close to 6 (almost constant). The ‘*a*’ value remained constant at the beginning of drying. It started to increase after a period of 10 and 15 min at 70 and 90 °C, respectively. This indicates that the redness-greenness value is closely associated to temperature. The apple slices were in +a (redness) area after drying. The ‘*b*’ value linearly increased from the beginning of drying process. It was found to increase rapidly at low temperature. Further, it remained in yellowness area. Slight variation indicated a mild yellowing in colour. An increase in ‘*a*’ and ‘*b*’ colour values was evident. It shall be correlated to non-enzymatic browning reactions. At the end of drying process, browning of edges was seen. It was due to maillard or caramelization reaction.

Modelling of experimental data

Curve fitting is the most powerful data analysis tool for drying related studies. It examines the relationship between one or more independent and dependent variables. The main aim of fitting the experimental data is to determine the best fit model relating the predictors and responses. SPSS provides curve estimation regression models namely linear, logarithmic, inverse, quadratic, cubic, power, compound, S-curve, logistic, growth and exponential models.

SPSS provides curve estimation regression models namely linear, logarithmic, inverse, quadratic, cubic, power, compound, S-curve, logistic, growth and exponential models

S. No.	Name of the regression model	Equation of the model
1.	Linear	$Y = b_0 + (b_1 * t)$
2.	Logarithmic	$Y = b_0 + (b_1 * \ln(t))$
3.	Inverse	$Y = b_0 + (b_1/t)$
4.	Quadratic	$Y = b_0 + (b_1 * t) + (b_2 * t^{\wedge 2})$
5.	Cubic	$Y = b_0 + (b_1 * t) + (b_2 * t^{\wedge 2}) + (b3 * t^{\wedge 3})$

6.	Compound	$\ln(Y) = \ln(b_0) + (\ln(b_1 * t)$
7.	Power	$\ln(Y) = \ln(b_0) + (b_1 * \ln(t))$
8.	S-curve	$\ln(Y) = b_0 + (b_1/t)$
9.	Growth	$\ln(Y) = b_0 + (b_1 * t)$
10.	Exponential	$\ln(Y) = \ln(b_0) + (b_1 * t)$

Model summary

Volume of LPSHS dried apple slices

The data obtained for change in volume of dried apple slices was fitted in various regression models as shown in Figure 5. The values were found to have a best fit in cubic model with R^2 value of 0.955. The R, adjusted R square and standard error of estimate for the model was found to be 0.977, 0.921 and 0.004, respectively. There was a significant change in volume with *p value* 0.004 (p<0.05).

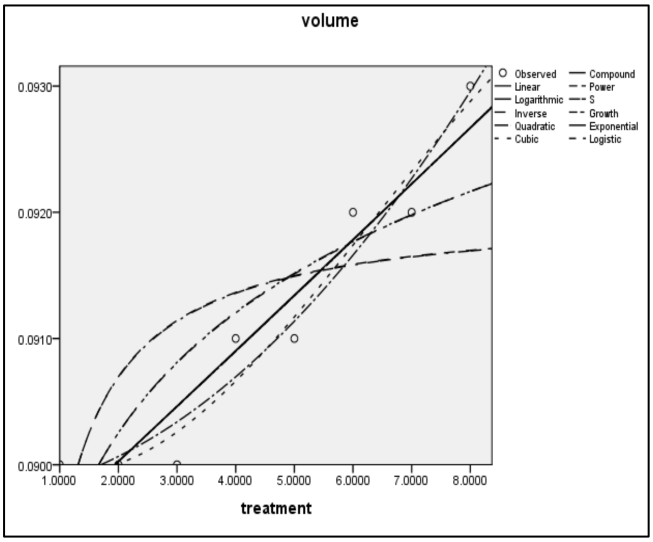

Fig 5: Model fitting of volume of dried apple slices

Density of LPSHS dried apple slices

The data obtained for change in volume of dried apple slices was found to have a best fit in quadratic model with R^2 value of 0.98. The R, adjusted R square and standard error of estimate for the model was found to be 0.90, 0.794 and 0.019, respectively. There was a significant change in volume with *p value* 0.002 (p< 0.05). The experimental values obtained for change in density of samples fitted in regression models were shown in Figure 6.

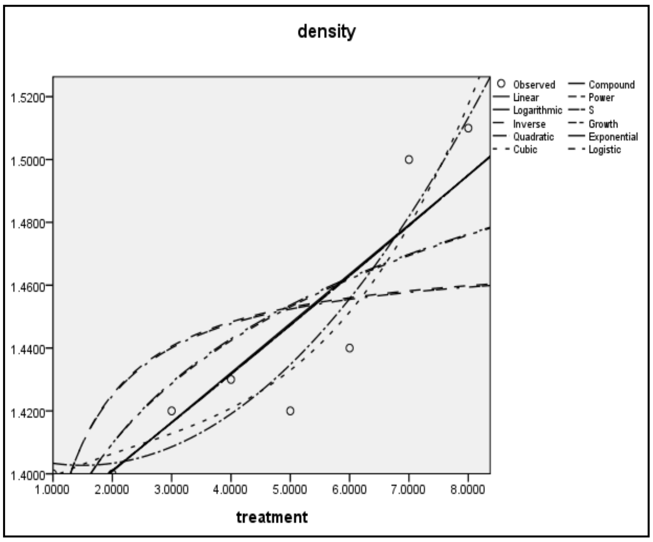

Fig 6: Model fitting of density of dried apple slices

Porosity of LPSHS dried apple slices

The porosity values of dried samples had a best fit in linear model with R^2 value of 0.97. The R, adjusted R square and standard error of estimate for the model was found to be 0.98, 0.746 and 0.122, respectively. There was a significant change in volume with *p value* 0.004 (p< 0.05). The experimental values obtained for change in density of samples fitted in regression models were shown in Figure 7.

Rehydration ratio of LPSHS dried apple slices

The values obtained for change in rehydration ratio and shrinkage shown in Figure 8 and 9 was found to have best fit in linear models with R^2 values of 0.9 and 0.93, respectively. Also, there was a significant difference in rehydration ability and shrinkage with respect to drying treatments p value 0.001 (p<0.05).

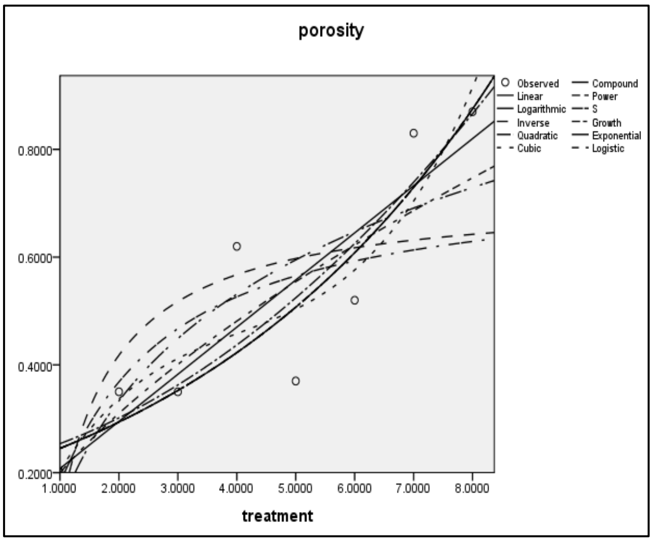

Fig 7: Model fitting of porosity of dried apple slices

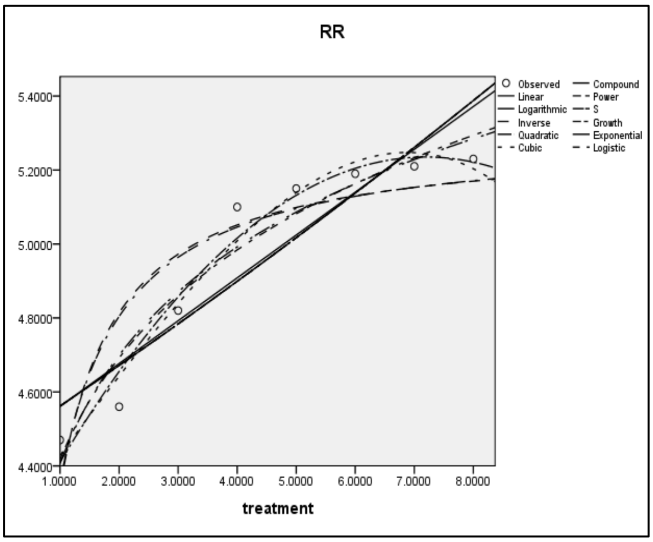

Fig 8: Model fitting of Rehydration Ratio of dried apple slices

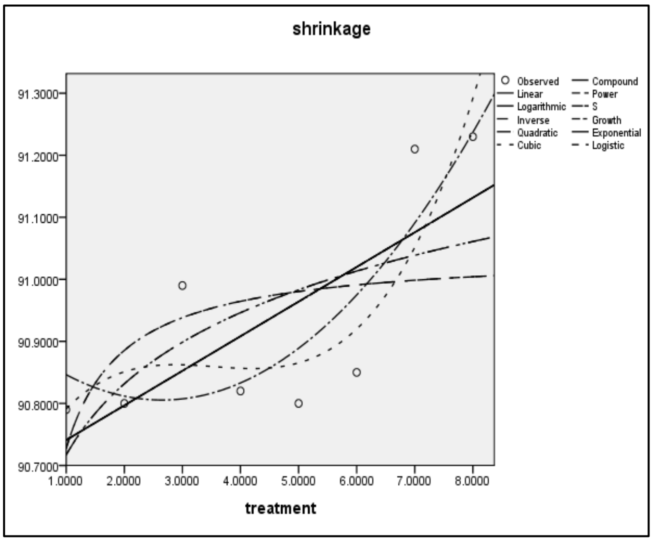

Fig 9: Model fitting of shrinkage of dried apple slices

ROC curve

The Receiver Operating Characteristic (ROC) curve is a plot of sensitivity of values Vs 1-specificity. The value ranges from 0 to 1. The model values of volume and density falls within right corner of the plot shown in Figure 10. It is an indication that the experimental data obtained during drying of apple slices have high sensitivity and high specificity values.

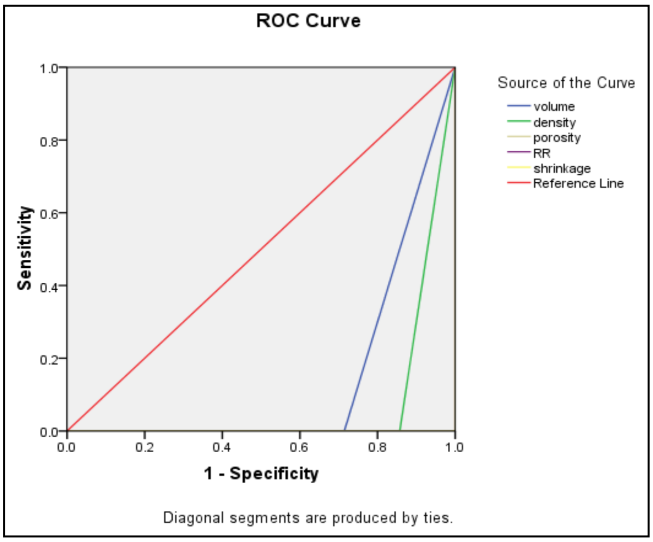

Fig 10: ROC curve of LPSHS dried apple slices

Conclusion

Detailed experimental investigation of the low-pressure superheated steam drying showed that, against lower drying rate due to poor convective heat transfer under lower operating pressure, the process was found to give superior quality final dried apple slices. It was noted that the effect of superheated steam temperature was more significant compared to that of operating pressure. The operating pressure and temperature affected the drying characteristics in a typical manner. The fruit slices dried under high temperature 90 °C, low pressure 0.5 bar had high drying characteristics. Whereas, physical attributes of samples exposed to a low temperature of 70 °C and low pressure of 0.5 bar had better results. The volume, porosity (Ɛ), rehydration ratio and percentage shrinkage of LPSHS dried samples were 0.09 g/cm^3, 0.87, 5.23 and 91%, respectively. The steam flow rate did not show a significant effect on both drying characteristics as well as physical attributes on the model fruit material. This particular drying method yielded apples with better rehydration ability and higher porosity over the studied operating parameters. Hence, low-pressure superheated steam drying is found to be a promising technology for the preparation of Ready to Eat (RTE) fruits as a snack food.

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