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Superheated Steam Drying of Potato Slices under Low Pressure conditions

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ABSTRACT: Superheated steam drying is an innovative, novel technology with high potential benefits compared to conventional hot-air drying. The approach is becoming more common, particularly in drying of food materials. A study was conducted to explore the influence of the air-less drying method for vegetables. Drying studies of potato were conducted in a convective batch dryer with superheated steam at low pressure as a drying medium. Experiments were conducted at drying temperature 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. Potato slices dried at 90°C, 0.5 bar pressure were found to have an enhanced drying rate of 0.1 to 1.5 g/min with reduced drying time of about 130-150 min. In terms of quality attributes, samples exposed to a lower temperature level of 70°C and low pressure of 0.5 bar had promising results. The volume, porosity (ε), rehydration ratio and percentage shrinkage of the dried samples were 0.09 g/cm^3, 0.8, 5.3 and 91%, respectively. The colour value in terms of redness increased with increasing drying temperature. It was found that dried potato slices with a mild cooked flavour and unchanged shape, better texture and colour can be obtained by this method.

Keywords: superheated steam, low pressure, potato, drying, quality.

INTRODUCTION

Fresh vegetables are perishable commodities with enormous commercial and industrial importance. They are processed in order to increase shelf life and preserve the quality attributes. Potato (*Solanum tuberosum*) is a significant crop belonging to Solanaceae family. They are beneficial vegetable holding high energy value, dietary fiber, bio-active phyto- chemicals, vitamins and minerals. It offers a potential benefit for using as a functional ingredient (Brinley *et al.,* 2008). Due to shifting food patterns, the demand and consumption of the vegetable has expanded in recent years. In developed countries, more than half of the cultivated vegetables are used as processed food products. They are mostly consumed as dried, smoked, fried snack food. Global markets for processed potato products have been expanding in recent years. On the other hand, potatoes have a lower shelf-life as a result of deterioration due to humidity, temperature and microbial growth. Dehydration of potato results in two sorts of products, namely dehydrated vegetable and snack food, which are used for a variety of applications.

Drying is an ancient and commonly adopted postharvest food preservation technique involving couple heat and mass transfer phenomena. It has a strong influence in improving postharvest handling, packaging, transportation and further food processing practices. Being considered as an essential postharvest unit operation for food processing industries, it remains to be an incessant research area. Conventional drying methods have been applied for processing and preservation of horticultural commodities, both commercially and industrially. Most of the conventional drying techniques affect the final product quality attributes and are energy and time consuming. They offer heat for drying by conduction associated with poor heat transfer rate. During thermal processing of fruits and vegetables, the micro-structure is damaged. The damage includes loss of cell membrane integrity, function and cell wall degradation (Carbonell *et al.*, 2006). All of these alterations have a significant impact on texture, which is a significant factor affecting the quality of the dried food material.

A new concept of utilizing superheated steam pressure as a drying medium by reducing the pressure below atmospheric level is emerging for heat-sensitive food materials. It has more advantages when compared to conventional superheated steam drying at atmospheric pressure (Devahastin *et al.*, 2004). Sub-atmospheric pressure superheated steam drying is a novel, air-less technology known for producing high quality dried food materials. The unique advantages of this drying include energy saving when steam is recycled, better pollution control by reduced exhaust gas emission, inert steam prevents explosion hazard, high heat transfer co-efficient with reduced drying time, Furthermore, it prevents oxidation of food products.

Consumers' resistance to chemical additives in food preservation is increasing. As a result, the fast-food industry is rapidly continuing to expand, showing the potential for use of additive-free dehydrated vegetables as a part of soups and rehydrated mixtures (Maskan, 2001). There is a huge demand for fat free or low-fat snack food products (Garayo and Moreira, 2002). It has been the driving force of snack food processing industries all over the world (Moreira, 2001). Hence, drying with low-pressure superheated steam will be a possible alternative for the manufacture of oil-free potato chips with desirable quality characteristics. Several works have been conducted on hot air drying of potato with different geometries. It was found that quality degradation in terms of colour, shrinkage, nutritional and organoleptic characteristics (Wang and Brennan, 1995). Krokida *et al.* (2001) reported excess browning and in terms of colour, increase in yellowness and redness in hot air dried potato. Higher retention of vitamin C content and lower rehydration capacity with higher shrinkage during conventional hot air drying of potato (Khraisheh *et al.*, 2004).

Different pre-treatments are required on the vegetable which could have a significant impact on the ultimate product quality. In the food industry, blanching of fruits and vegetables is a common practice. The vegetables should indeed be blanched before drying to have a ready-to-eat (RTE) snack food. Blanching causes loss in soluble solids, enzyme denaturation, removal of air from tissue, hydrolysis, dissolution of structural polymers namely pectin and starch gelatinization (Mate *et al.*, 1998). The steam condensation during initial drying process results in simultaneous blanching of vegetables. It is indeed an added advantage of this particular drying process. As a result, blanched vegetables have different internal structure than the unblanched ones. The structural modifications are likely to have an impact on the drying process as well as the dried product's value.

In food processing industry, pre-treatment with calcium has shown to improve the firmness of dehydated fruits and vegetables. Its capacity to bond with pectin has been linked to calcium's role in promoting cell stiffness. When fresh-cut items are treated with calcium compounds, the hardness of the flesh can be improved (Moraga *et al.*, 2009). Some researchers have reported that the pre-treatment reduces tissue damage and improves the rehydration capacity of dried products (Sham *et al.*, 2001; Deng and Zhao, 2008).

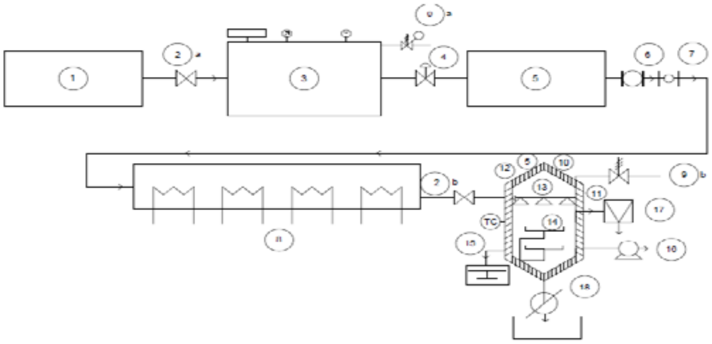
MATERIALS AND METHODS

A. Raw materials

Fresh potato was selected as the model heat sensitive material for the study. The potatoes used for the experiments were procured from a reputed supermarket (Coimbatore) and stored at cold storage temperature of 10±5°C. They were washed with potable water, outer skin were peeled off and then sliced to 2 mm uniform thickness. The potato slices were subjected to pre-treatment in order to prevent discolouration caused by browning effects. They were dipped in a solution of 0.5% calcium chloride for a period of 10 min (Wang *et al.*, 2010). The samples were taken from solution, rinsed and the excess moisture was blotted out using tissue paper. The pre-treated potato slices were used for the drying studies.

B. Experimental set-up

A schematic diagram of the superheated steam dryer operating at reduced pressure is shown in Fig. 1. The custom designed dryer could be used for drying 5 kg of fresh horticultural commodity. The major components of the dryer consists of a double jacketed stainless steel drying chamber insulated with glass wool, electric boiler, superheated steam generator and a vacuum pump to maintain vacuum in the drying chamber. The area of the drying chamber was 42 × 56 cm^2. It has two removable perforated stainless steel sample holders with 8 mm grid. An electric boiler with 25-30 kg/h capacity of generating saturated steam feeds the drying system. Saturated steam was generated at 4 bar pressure with corresponding temperature of 150°C.



(1) water tank; (2 a, b) globe valve; (3) electric boiler; (4) pressure regulating valve; (5) superheated steam generation unit; (6) moisture separator; (7) steam totalizer; (8) heating element; (9 a, b) pressure safety valve; (10) drying chamber; (11) insulation; (12) steam inlet; (13) steam distribution pipe line; (14) sample tray; (15) load indicator; (16) vacuum pump; (17) vacuum breaker; (18) condenser.

Fig. 1. A schematic diagram of the sub-atmospheric pressure superheated steam dryer.

Steam at its saturated state along with moisture was passed to the separating unit to make it as dry steam. The dry steam was converted into superheated state by means of constant-enthalpy process. A pressure regulator was used to control the flow of superheated steam in to the pipe line assembly. The flow rate of the SHS was set to 0.1 and 0.3 m^3/h. The pressure, temperature and flow rate were monitored using a vortex type flow meter along with a steam totalizer (Cosmo Technologies, Model: SFC-146). The steam carrying the evaporated moisture from the product is passed through the condenser.

C. Drying curve measurement

A batch of 100 g fresh potato slices were placed in perforated stainless steel sample holding trays of dimension (35 cm × 35 cm). Homogeneous drying was ensured inside the drying chamber by means of T-type thermocouple. Load cells were placed below the trays and connected to a load indicator for determination of continuous moisture loss during the drying process.

E. Dryer operating conditions

Fresh samples were dried utilizing superheated steam as a drying medium at a temperature range of 70 & 90°C and at absolute pressure levels of 0.5 and 0.8 bar, respectively. The flow rate of superheated steam was maintained at 0.1 and 0.3 m^3/h. The experimental design of the study having three factors with 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 (DOE).

Independent variables	Level		Dependent variables
Temperature (°C)	70	90	Drying characteristics Apparent density (g/cm^3) Porosity (Ɛ) Rehydration Ratio Shrinkage (%) Colour value Texture
Pressure (bar)	0.5	0.8	
Steam flow rate (m^3/h)	0.1	0.3	

Moisture content. The moisture content of the sample was determined by hot-air oven method (AOAC, 1984). Measurements were repeated 3 times and the relative standard deviation was 3%. It was dried till consecutive weights recorded. Moisture content was calculated by the following expression and expressed on per cent 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

Measurement of 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 the method given by Elustondo *et al.*, (2002). Average value of three samples was noted and measurements were made in triplicate. Volume and apparent density of both fresh and dried samples were calculated with the equations:

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

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

where,

M_{ph} – mass of Pycnometer filled with *n*-heptane, g

M_p – mass of empty Pycnometer,

M_{phs} – 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 measurement

Shrinkage of the fresh and dried samples was measured by the method reported by Elustondo *et al.*, (2002). All measurements were made in triplicate. It is expressed as percentage change in volume (V_f) to the original sample volume (V_i) and calculated as:

$$\text{Shrinkage} = \frac{(V_i - V_f)}{V_i} \times 100 \qquad (4)$$

Porosity. Porosity (Ɛ) is the ratio of volume of air (V_a) present in the sample to overall volume (V) (Lewis, 1987).

$$\varepsilon = \frac{V_a}{V} \qquad (5)$$

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

$$\text{Porosity} = 1 - \frac{\rho_b}{\rho_a} \qquad (6)$$

Colour measurement. Colour value of the samples was measured using colour flex meter (Hunter Associates Laboratory, USA, model: 45/0°). The Hunter parameters namely, *L* (lightness/darkness), *a* (redness/greenness), *b* (yellowness/blueness) were measured. Colour changes were calculated using the equations:

$$\Delta L = \frac{L-L*}{L*}\ ;\ \Delta a = \frac{a-a*}{a*}\ ;\ \Delta b = \frac{b-b*}{b*} \qquad (7)$$

where,

L, *a*, *b* = lightness, redness and yellowness of dried sample

*L**, *a**, *b** = initial sample values of lightness, redness and yellowness

Rehydration capacity. Rehydration capacity of the samples was estimated by dipping dried samples in hot boiling water at 100°C for 10 minutes. The samples were drained thereby their mass before and after dipping were measured. Rehydration ratio (R) expresses the ability of dried sample to absorb water (Lewicki, 1998) and calculated as:

$$\text{Rehydration ratio} = \frac{m_f}{m_i} \qquad (8)$$

where, m_i and m_f are mass of dried apple slices before and after hot water immersion, respectively.

Texture analysis. Texture of samples was evaluated by compressive test using a digital sclerometer (Parisa Technology, Mumbai, India). The test was conducted by applying direct force to the sample which was placed on the rigid base plate. A cylindrical needle with pressure diameter of 3.5 mm was inserted at a constant speed till it cracked the sample. Maximum compression force of the sample was used to relate the texture in terms of hardness (Moreno-Perez., 1996).

Statistical analysis. All the experimental data were analyzed using Analysis of Variance (ANOVA) by Minitab 19.1.1.0 software. The Tukey's test was performed in order to establish multiple comparison of mean values. Mean value was considered to be significantly different when $p \leq 0.05$.

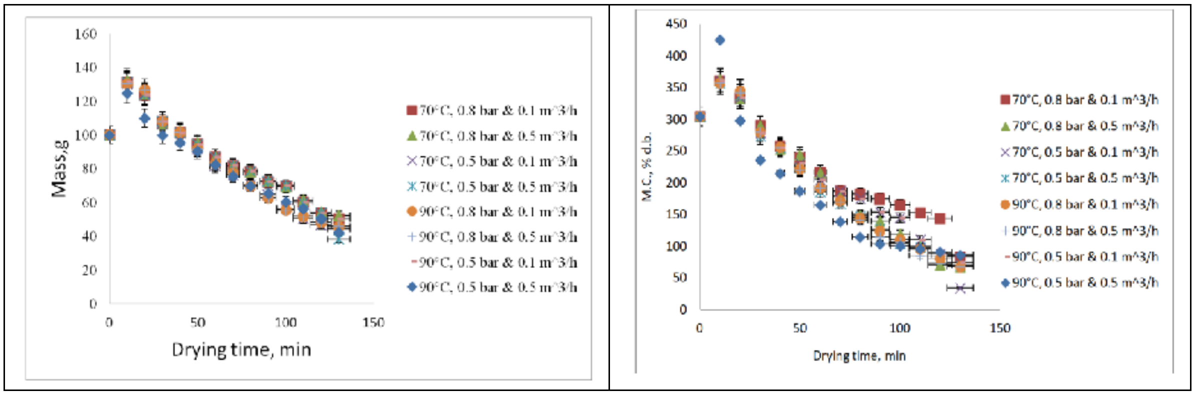
RESULTS AND DISCUSSION

A. Drying characteristics

The heat-sensitive material was subjected to drying experiments in the developed batch-type dryer with superheated steam at reduced pressure as drying medium. The samples were exposed to combination of temperate, pressure and steam flow rate levels as shown in Table 3. Potato slices with initial moisture content of about 305% d.b. was dried to about 70% d.b. in about 120 to 180 min. The dryer was pre-heated to a temperature range of 50-70°C by blowing hot-air into the chamber. This was done in order to address the commonly encountered condensation problem in steam dryers. It takes about 20 min for initialization of the drying process. From the Fig. 1 (a), a small amount of moisture gain (20-30 g approximately) during first few minutes of the drying process was observed. Nevertheless, steam condensation during start-up of the process is negligible at low operating pressure (Tang *et al.,* 2000). Steam condensation on the product accounts for blanching which is considered to be advantageous over other conventional methods. The restoration phase in which original mass of sample returns to original value was around 25 and 10 min for drying at 70 and 90°C respectively.

At higher drying temperature of 90°C, the drying rates were observed to be higher than at 70°C. The effect of pressure on was uncertain at low temperature (70°C). It is more likely due to the fact that the thermal characteristic of steam is highly influenced by temperature rather than pressure. An increase in SHS temperature from 70 to 90°C led to a deduction in drying time of about 29 and 12% respectively. The moisture content of samples reduced rapidly at a lower pressure (0.5 bar). Furthermore, a reduction of drying time by 11 and 23% was achieved in case of drying at reduced pressure at 0.5 and 0.8 bar, respectively. Implementing the drying process with superheated steam at high pressure (0.8 bar) had a serious problem. It was unable to dry the sample to moisture content below 70% d.b. as there was an enormous quantity of steam condensation in drying chamber. The condensation period was more than 20 min.

The moisture ratio data of samples with respect to drying time shows that the moisture ratio and drying rate were higher at high drying temperature (70°C) and low operating pressure (0.5 bar). Steam flow rate was found to be insignificant with respect to drying characteristics at $p<0.05$. 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 in utilizing superheated steam at low pressure as a drying medium.



(a) (b)

Fig. 2. Drying characteristics curve of potato slices (a) drying time Vs mass (b) drying time Vs moisture content.

Quality characteristics of potato slices. The effects of dryer operating parameters on the physical characteristics of potato slices were investigated. The grouping information of dependent variables using Tukey method at 95% confidence interval (n=8) is shown in Table 3.

Table 3: Tukey pairwise comparison of mean values and grouping.

Sr. No.	Factor	Mean±StDev	Grouping	95% CI
1.	Volume	1.07 ±0.02	C	0.04, 0.22
2.	Apparent density	1.5±0.03	D	1.30, 1.57
3.	Porosity	0.8±0.05	E	0.70, 1.00
4.	Rehydration ratio	5.0±0.03	B	4.8, 5.04
5.	Shrinkage	91.00±0.2	A	90.7, 91.2

Pooled St. Dev = 0.18385

Volume and apparent density. The effect of operating temperature, pressure and steam flow rate on varying physical attributes namely apparent density, volume, rehydration ability and porosity were investigated. The values are shown in Fig. 2. Volume of the dried sample was observed to be inversely proportional to the apparent density. The potato slices dried at low temperature had low apparent density of 1.4 g/cm^3 with volume reduction. The operating pressure was found to significantly influence the volume and apparent density of the samples with p value < 0.05. The major reason for this is that the operating pressure has an impact on the percentage air pores in the final dried samples (Krokida and Maroulis, 2000). In this case, the operating temperature was found not to have effect on the volume and apparent density of the final product. The decrease in operating pressure from 0.8 to 0.5 bar had a decrease in volume from 0.093 to 0.09 cm^3, respectively. Inversely, the apparent density increased for samples dried at 90°C and 0.5 bar. It was noted that reducing the pressure during superheated steam drying prevented the structural collapse of the potato slices.

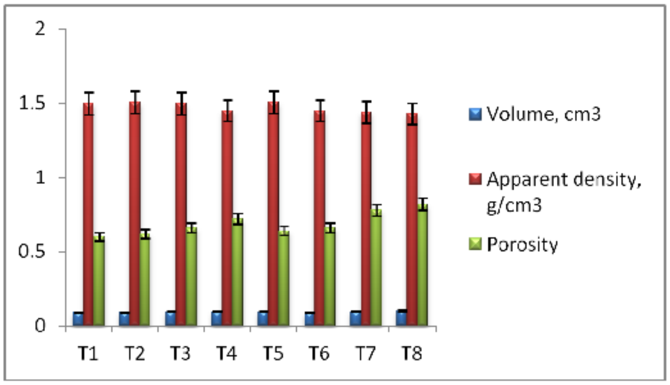


Fig. 3. Volume, apparent density and porosity of potato slices underwent different drying treatment.

Shrinkage. The result of shrinkage values of potato slices exposed to sub-atmospheric pressure superheated drying is shown in Fig. 3. The shrinkage was observed to have a direct correlation with the volume of the dried sample. The percent shrinkage in potato slices dried using superheated steam drying showed a slight variation from that of the fresh ones. The samples dried at lower temperature of 70°C at 0.5 bar pressure had lower shrinkage of 90.8% than those dried at 90°C at 0.5 bar was 91.2%.

Unlike conventional drying methods, the superheated steam drying brings about a vapour evolution from inside of the material which expands into cells. Hence, it leads to porous dried final product (Seyed-Yagoobi *et al.,* 1999). The drying temperature was found to significantly influence the shrinkage value of the dried product ($p<0.05$). The drying temperature directly influences the shrinkage property of dried samples. The high drying temperature (90°C) generates higher moisture gradient within the product thereby resulting in higher degree of shrinkage. The effect of operating pressure on shrinkage was not significant in this study.

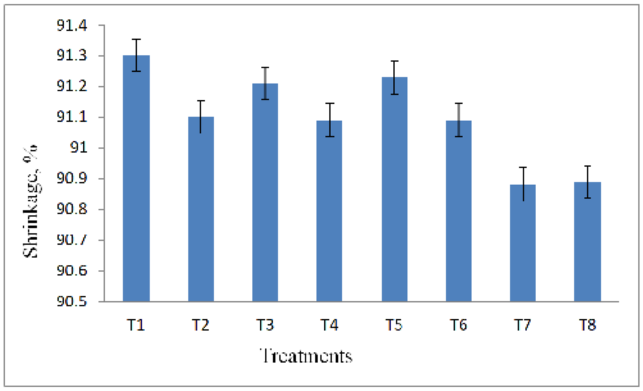


Fig. 4. Shrinkage of potato slices underwent drying at different treatment combinations.

Rehydration capacity. The potato slices dried using superheated steam at reduced pressure had a better rehydration capacity. The results are shown in Fig. 5. The rehydration ratio was 5.2 for samples dried at 90°C, 0.5 bar & 0.5 m^3/h whereas it was 4.5 for those dried at 70°C, 0.8 bar & 0.1 m^3/h. The rehydration ability is closely related to the shrinkage pattern of the dried samples. Drying with SHS at low pressure avoids the formation of dense layers thereby enhances the adsorption of water inside the pore spaces. It was also observed that there is a negative relationship between shrinkage and rehydration property of the dried samples.

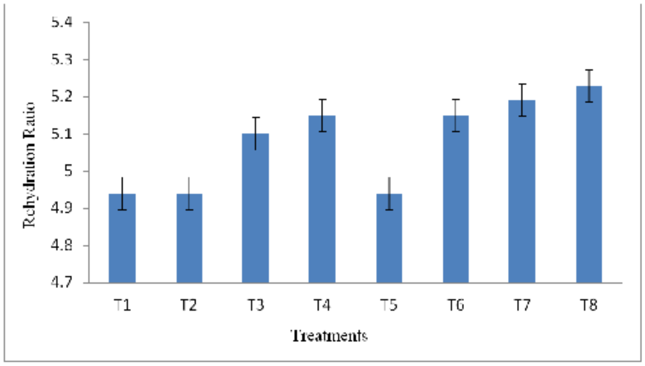


Fig. 5. Rehydration ratio of potato slices underwent drying at different treatment combinations.

Colour. The changes in colour value of potato slices in terms of colour difference namely Δ*L*, Δ*a* and Δ*b* are shown in Table 3. The steam condensation during initial drying contributes to simultaneous blanching. As the enzymes are destroyed during blanching, the colour changes in dried samples were due to Maillard reactions. The drying temperature and pressure did not significantly affect Δ*L* (lightness) value ($p<0.05$). With respect to change in redness (Δ*a*) of dried samples, drying pressure, steam flow rate and their interactions had no significant influence ($p<0.05$) on this parameter. The dried potato samples were found to be red than the fresh ones. Higher drying temperature (90°C), led to increase in Δ*a* value of 1.4 to 1.7. The change in redness value at 90°C was significantly higher than at 70°C. Due to leaching out of reducing sugars, which seem to be the substrate of Maillard process, blanching reduced the Δ*a* value. Similar results were reported by Pedreschi *et al*., (2005). The Δ*b* value, of samples was not influenced by the drying temperature. The samples did not have a stable yellowness values and not significantly different ($p<0.05$).

Table 3: Effect of drying temperature, pressure and steam flow rate on hardness and colour changes of potato slices.

T.No.	Treatment combinations	Peak force, N	Δ*L*	Δ*a*	Δ*b*
T_1	70°C, 0.8 bar & 0.1 m^3/h	7.86±0.06	-0.55±0.01	1.02±0.01	-0.5±0.02
T_2	70°C, 0.8 bar & 0.5 m^3/h	5.25±0.02	-0.02±0.01	0.62±0.01	-0.79±0.05
T_3	70°C, 0.5 bar & 0.1 m^3/h	5.76±0.05	-0.11±0.05	0.52±0.04	0.90±0.01
T_4	70°C, 0.5 bar & 0.5 m^3/h	5.58±0.1	-0.10±0.02	0.71±0.04	0.67±0.01
T_5	90°C, 0.8 bar & 0.1 m^3/h	4.97±0.05	-0.72±0.04	1.7±0.02	-0.7±0.03
T_6	90°C, 0.8 bar & 0.5 m^3/h	4.63±0.01	-0.4±0.01	1.4±0.02	-0.15±0.02
T_7	90°C, 0.5 bar & 0.1 m^3/h	2.83±0.02	-0.3±0.02	1.46±0.05	0.29±0.03
T_8	90°C, 0.5 bar & 0.5 m^3/h	2.81±0.01	-0.41±0.01	1.4±0.04	-0.15±0.02

Texture. Texture of the dried samples is shown in Table 3. It is expressed in terms of hardness and maximum breaking force of the sample. In potato, blanching brings about gelatinization of starch causing tissue softening. It reduced the hardness of the dried sample. The hardness value of potatoes dried at temperature of 70°C was about 5-7 N and at 90°C was about 2-4 N. Samples with less hardness was observed at low temperature (70°C). The samples had better surface characteristics when dried at low temperature. Similar findings were reported by Mujumdar (1995). It was observed that the drying temperature and pressure significantly affected hardness of the potato slices ($p<0.05$). Different steam pressure and flow rate did not affect the hardness of samples.

CONCLUSION

The detailed experimental investigation of the superheated steam drying under low conditions showed that, the process produced superior quality final dried potato slices. It was noted that the effect of superheated steam drying temperature was more significant when compared to that of the operating pressure. The operating pressure and temperature affected the drying characteristics in an exponential manner. The vegetable slices dried under high temperature 90°C, low pressure of 0.5 bar had higher drying characteristics. Whereas, the physical attributes of samples exposed to low temperature of 70°C and low pressure of 0.5 bar had better results. The steam flow rate did not show any significant effect on both drying characteristics as well as physical attributes of the model vegetable material. This particular drying method yielded potatoes with better rehydration ability and higher porosity over the studied operating parameters. Hence, this drying method is found to be promising for the preparation of Ready to Eat (RTE) potato slices as a snack food.

FUTURE SCOPE

As only limited research works has been conducted on superheated steam drying under reduced pressure conditions, there is a huge scope for studying the drying behaviour of various heat-sensitive biomaterials.

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