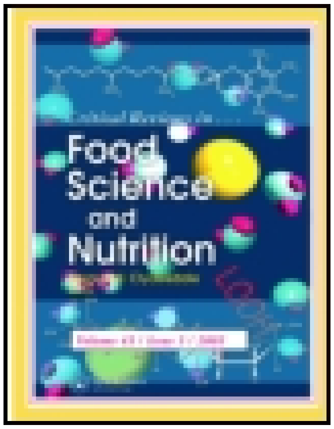


Critical Reviews in Food Science and Nutrition
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/bfsn20

# Recent developments in superheated steam processing of foods - A review

Alfy Anto [a], Kiran Bv [a], Jeevitha Gc [a] & H. Umesh Hebbar Ph.D. [a]
[a] CFTRI, FE, Mysore, 570 020, India
Accepted author version posted online: 27 Aug 2014.

To cite this article: Alfy Anto, Kiran Bv, Jeevitha Gc & H. Umesh Hebbar Ph.D. (2014): Recent developments in superheated steam processing of foods - A review, Critical Reviews in Food Science and Nutrition, DOI: 10.1080/10408398.2012.740641

To link to this article: http://dx.doi.org/10.1080/10408398.2012.740641

**Recent developments in superheated steam processing of foods - A review**

Alfy Anto, Kiran BV, Jeevitha GC, H. Umesh Hebbar, Ph.D.*

CFTRI, FE, Mysore, 570 020 India

Corresponding author: Dr. H. Umesh Hebbar, Ph.D., CFTRI, Food Engineering, Principal Scientist, Mysore, 570020 India. Email: hebbar@cftri.res.in

**Abstract**

Although the use of superheated steam has been known for quite a long time, only in recent past it has emerged as a viable technology for food processing. Superheated steam having higher enthalpy can quickly transfer heat to the material being processed, resulting in its rapid heating. The major advantages of using superheated steam for food processing are better product quality (color, shrinkage, and rehydration characteristics), reduced oxidation losses and higher energy efficiency. This review provides a comprehensive overview of recent studies on the application of superheated steam for food processing operations such as drying, decontamination and microbial load reduction, parboiling and enzyme inactivation. The review encompasses aspects such as effect of superheated steam processing on product quality, mathematical models reported for superheated steam drying and future scope of application in food processing. Recent studies on process improvisation wherein superheated steam is used at low pressure, in fluidized bed mode, sequential processing with hot air/infrared and in combination with micro water droplets have also been discussed.

***INTRODUCTION***

Even though the concept of superheated steam processing was originally proposed more than 100 years ago, only in the recent past it has gained importance and emerged as a viable and potential technology for food processing. Superheated steam is obtained by supplying additional sensible heat to steam to rise its temperature above the saturation point at a given pressure. Elimination of case hardening, higher energy efficiency and reduction in oxidative reactions due to oxygen free environment are some of the advantages of superheated steam processing (Mujumdar, 2007). Also, the drop in superheated steam temperature during processing will not result in its condensation (normally the case with saturated steam), as long as the temperature is higher than the saturation temperature at the processing pressure. This could be contributing to higher drying rate normally observed with superheated steam. The condensation at the initial stages of drying due to drop in temperature could be a favourable factor in some cases like drying of paddy, as steam condensation promotes starch gelatinization, resulting in higher head rice yield. The moisture that is evaporated during processing need not be exhausted, as it becomes part of the drying medium (Tang and Cenkowski, 2000). In order to make superheated steam processing economical, the exhaust steam is collected and either used for other applications or the latent heat is recovered by condensing the steam. By condensing and collecting the exhaust steam, dust and expensive or toxic compounds may be collected instead of releasing them into the environment and thus the risk of these hazards can be mitigated (Mujumdar and Law, 2010). The limitations of superheated steam processing technique include relatively higher capital cost, complexity of the equipment, and high temperature of processed materials resulting in quality degradation, particularly for heat sensitive material (Deventer and Heijmans, 2001; Kudra and Mujumdar, 2002).

In the recent years, a number of studies on the application of superheated steam for various food processing operations have been reported. The extensive literature survey carried out in this work indicated that the majority of these reports are on drying of food products (Li et al., 1999; Tang et al., 2000; Tang and Cenkowski, 2000; Caixeta et al., 2002; Markowski et al., 2003; Huang et al., 2004; Nathakaranakule et al., 2007; Nimmol et al., 2007; Suvarnakuta et al., 2011). The other applications reported are enzyme inactivation (Pronyk et al., 2005; Sotome et al., 2009; Satou et al., 2010; Head et al., 2011), decontamination (Pronyk et al., 2006; Cenkowski et al., 2007; Kondijoyan and Portanguen, 2008) and microbial load reduction (Shull and Ernst, 1962; Nygaard and Hostmark, 2008; Head et al., 2008) of foods. Recently, process improvisations such as superheated steam processing under low pressure, fluidized bed heating, in combination with infrared radiation and with water droplets have been attempted by researchers to improve product quality and energy efficiency. This review critically evaluates the recent applications of superheated steam for drying, decontamination and microbial load reduction, enzyme inactivation and parboiling of various food materials.

***DRYING***

During superheated steam drying, the drying takes place through direct contact between superheated steam and the product to be dried. Superheated steam has heat transfer properties superior to air at the same temperature and above the ‘inversion temperature’ (160-200ºC for evaporation of water), superheated steam yields better results, as compared to dry air. Minimum resistance to mass transfer (material surface to steam) and higher moisture mobility within the product (due to higher temperature) are responsible for improving superheated steam drying (SSD) in constant rate period and falling rate period, respectively.

Mujumdar et al. (2007) summarised the product related factors (sensitivity to temperature and oxygen, moisture content, thermal resistance and taste/aroma) and process related factors (other uses of steam, environmental emissions from dryers, combustion/explosion hazards and cost of thermal energy) contributing to the feasibility of superheated steam drying. The principles, advantages and limitations, as well as diverse applications of super heated steam drying technologies have been reviewed in a few papers and books (Kumar and Mujumdar, 1990; Mujumdar, 1992; Kudra and Mujumdar, 2001 and 2009; Karimi, 2010). Beeby and Potter, (1985) reported that the feature of energy saving in SSD makes the technique a desirable alternative and strict laws regarding environmental pollution offer another incentive to SSD.

SSD is broadly classified in to three categories, based on the operating pressure, i.e., low pressure, near atmospheric pressure and high pressure. Low pressure dryers are being operated at sub atmospheric pressures (5-30 kPa) and recently, this technique was employed (Elustondo et al., 2001; Mujumdar et al., 2000; Devahastin et al., 2004) to handle heat sensitive products, as it provides the opportunity to operate at lower temperatures. The near atmospheric pressure dryers operated at normal atmospheric pressure are used in various modes such as fluidized bed, fixed bed, pneumatic, spray or impingement drying (Sagar and Kumar, 2010). Reports are available on use of high pressure dryers operating at a pressure range of 5-25 bar for drying of peat and beet pulp. Some of the recent studies reported on SSD are discussed in the following sections and the key findings of these works are summarized in Tables 1, 2, 3 and 4.

***Drying of meat and fish products***

*Zousoon*

Zousoon is a pan fried pork product of intermediate moisture (2-12%) consumed in Taiwan and China. A study reported by Huang et al. (2004) explored the use of superheated steam as a way to process pork bundles in an oxygen free environment to inhibit lipid oxidation. Samples were pan-fried or processed in superheated steam at 150°C then packaged in cans and stored for one year. Sensory evaluation (for off-odours) after the storage period showed that superheated steam samples are better than pan-fried samples. Lipid analysis indicated that superheated steam was effective in suppressing lipid oxidation and had greater stability as compared to pan-fried zousoon.

*Chicken meat*

Nathakaranakule et al. (2007) compared and evaluated different drying techniques for chicken meat, which was aimed as an ingredient for ready-to-eat noodle. Two multi-stage drying techniques, namely, SSD in the first stage followed by heat pump drying in the second stage (SSD-HP), and SSD in the first stage followed by hot air drying in the second stage (SSD-AD), were proposed. The effects of superheated steam temperature and moisture content of chicken at the end of the first-stage drying on the drying kinetics and quality of the dried product viz. colour, shrinkage, rehydration ability were evaluated. The results were also compared with only superheated steam drying. SSD-HP was found to be the most suitable drying method for drying chicken as an ingredient for ready-to-eat noodle. The SEM (Scanning electron microscopy) images showed that chicken dried by combined method (SSD-HP and SSD-AD) was better in terms of retaining collagenous tissues, which were completely broken and hydrolyzed into gelatin in the case of only SSD (Figure 1).

*Fish press cake*

Borquez et al. (2008) conducted drying tests for mackerel press-cake with hot air (80-170°C) as well as superheated steam (146-185°C) in a pilot impingement cylindrical dryer developed by the authors. Feed rate and residence time of solids were studied experimentally as a function of dryer inclination for hot air and superheated steam as drying media. Drying rates and heat and mass transfer coefficients were found to increase at shorter residence times and higher medium temperatures and authors concluded that superheated steam processing for shorter period (typically for 7.0 to 13.5 s) would minimize the loss of omega-3 fatty acids.

***Drying of fruits***

*Drying of banana slices*

A concept of combining LPSSD with far infrared radiation (LPSSD + FIR) was studied by Nimmol et al. (2007), as a novel drying technology for heat sensitive product such as banana. The effect of temperature and pressure of drying medium on drying kinetics and product quality (color, shrinkage, rehydration behaviour, microstructure and texture) were investigated and compared with combined vacuum and far infrared drying (vacuum + FIR). It was observed that LPSSD + FIR took longer drying time than vacuum + FIR at almost all drying conditions except at the highest drying temperature tested (90°C). Although, the drying time of LPSSD + FIR at 90ºC was the shortest and dried banana slices were crispy, the product color was dark. LPSSD + FIR drying at 80°C was suggested as the best drying condition amongst the conditions tested in the study, as it had acceptable product quality including porous structure compared to those dried by vacuum + FIR (Figure 2).

Leonard et al. (2008) investigated the effect of different drying methods such as LPSSD (80 and 90°C at 7 kPa) and vacuum drying with and without FIR on structure of banana slice. The X-ray microtomography technique coupled with 3D image analysis was used to determine total pore volume and size distribution of dried banana slices. The results were also compared with those of products dried by LPSSD without FIR. At the same drying temperature, the application of FIR resulted in an increase in slice porosity. Combination of FIR increased the porosity in LPSSD (32%) and vacuum (37%) dried slices due to higher internal pressure gradients caused by increased slice temperature. Authors observed that at higher temperature (90°C), the porosity of slices dried at by LPSSD was higher than that of vacuum dried under both the drying conditions (with and without FIR heating). This was attributed to higher temperature attained by the slices at the initial stages of LPSSD.

An intermittent drying scheme, one of the possible methods to reduce the energy consumption of the process was explored for LPSSD and vacuum drying of banana chips (Thomkapanich et al., 2007). In this study, the effect of intermittent supply of energy and vacuum at various intermittency values of on and off periods (10:5, 10:10 and 10:20 min in the case of intermittent supply of energy and 5:0, 5:5 and 5:10 min in case of intermittent supply of vacuum) at the on period setting temperatures of 70, 80 and 90°C on the drying kinetics and heat transfer behaviour of banana chips was studied. Although, the overall drying rate of intermittent temperature LPSSD did not significantly differ from that of continuous LPSSD, the net drying time was significantly shorter, leading to high energy saving (up to 65%). The effect of intermittent temperature on quality was not significant except the higher ascorbic acid retention, especially at longer tempering periods (Table 5). On the other hand intermittent pressure processing led to higher degradation of ascorbic acid.

*Mangosteen rind*

Mangosteen (*Garcinia mangostana* L.) is a tropical fruit and is known as queen of fruits in Asia. Suvarnakuta et al. (2011) studied the effect of drying methods and conditions on retention as well as antioxidant activity of xanthones in mangosteen rind. Mangosteen rind was subjected to hot air drying, vacuum drying and LPSSD (7 kPa) at 60, 75 and 90°C. The results showed that the drying methods significantly affect the degradation of xanthones and their antioxidant activity. Either hot air drying or LPSSD at 75°C was proposed as an appropriate drying technique and conditions, as they retained higher amounts (72-78%) of xanthones in dried mangosteen rind.

*Longan*

Longan (*Dimocarpus longan* L) is a subtropical fruit commonly grown in China, Taiwan, Indonesia, Thailand and Vietnam. Somjai et al. (2009) developed a model for longan without stone drying using a two-stage SSD followed by hot air drying (SSD + HAD). The experiments were conducted at 120, 140, 160, and 180°C followed by hot air at 60 and 70°C. The superheated steam and hot air temperatures in each stage of drying affected the drying kinetics and dried product quality viz. color, shrinkage and microstructure. The overall drying rate of longan dried by SSD + HAD depended on the temperature of the air more than that of steam. The color of SSD + HAD dried longan was better as compared to SSD, while this process showed no improvement in terms of shrinkage. Considering both product quality and drying time, two stage drying with superheated steam at 180°C followed by hot air at 70°C was the optimal drying condition for drying longan without stone.

*Indian gooseberry*

Methakhup et al. (2005) studied LPSSD (65 and 75°C at 7, 10 and 13 kPa) of Indian gooseberry flake and compared the drying kinetics and product quality degradation with that of vacuum drying at the same conditions. While vacuum drying required shorter drying time (nearly 50% less), low pressure superheated dried flakes had higher (5-10%) retention of ascorbic acid and color.

***Drying of vegetables***

*Carrot*

Hiranvarachat et al. (2008) studied the drying kinetics, isomerisation kinetics and antioxidant activities of β-carotene in carrots cubes dried by different methods. It was found that vacuum drying and LPSSD (60-80°C at 7 kPa) led to more conversion of all trans-β-carotene to 13-cis-β-carotene and also resulted in lesser degradation of β-carotene than hot air drying. Carrots undergoing LPSSD had higher antioxidant activity than those subjected to other drying treatments. LPSSD at 60°C was the best treatment to preserve β-carotene and antioxidant activities in carrot. In another study (Devahastin et al., 2004) it was observed that appearance and the textural properties of dried and rehydrated carrot cubes by LPSSD (Figure 3) were better (shrinkage, color and rehydration characteristics) than that of vacuum dried. It was observed that the effect of operating pressure was less significant than that of steam temperature in LPSSD.

*Potato*

Iyota et al. (2001) determined the drying kinetics, surface conditions and colour changes of dried raw potato slices undergoing SSD and hot air drying. Authors observed that the samples dried by superheated steam were glossier and there were no ‘remaining’ starch granules on the surface. On the other hand, starch gelatinization of the samples dried by hot air occurred more slowly than in the case of SSD. Mujumdar and Devahastin, (2008) studied the SEM images of potato slices dried by superheated steam and hot air and concluded that superheated steam dried slices were better (more porous) compared to hot air dried. Tang and Cenkowski (2000) compared the dehydration characteristics, temperature histories, drying rates and overall moisture diffusivities of cylindrical potato samples exposed to superheated steam and hot air at three different temperatures (125, 145 and 165°C). The temperature of the drying medium had a greater effect on the drying rate, overall moisture diffusivity and consequently drying time for SSD than for the hot air drying. Increasing the temperature form 125 to 145°C decreased the drying time by nearly 60 and 24% for superheated steam and hot air, respectively. A constant rate drying period was observed only with superheated steam at 125 and 145°C.

Caixeta et al. (2002) also reported drying of potato chips in impinging jets of superheated steam (115, 130, and 145°C) and compared the performance with hot air drying at the same conditions. The objective of the study was to produce low-fat potato chips with the desired texture, color and ascorbic acid retention. The superheated steam impingement drying process of potato chips was characterized by constant rate and falling rate periods, while that of air drying had only falling rate period. Superheated steam dried potato chips had more shrinkage, higher bulk density, lower porosity, and lighter colour at the same conditions as compared to that dried by hot air. Higher retention of ascorbic acid and softer texture was obtained in superheated steam processed potato chips. The textural characteristics of superheated steam dried chips were closer to that of commercial potato chips.

The effect of the degree of starch retrogradation, slice thickness and final moisture content on the texture of potato chips dried by low pressure superheated steam drying (LPSSD) was investigated by Kingcam et al. (2008). Potato slices (1.5, 2.5 and 3.5 mm thick) were pre-treated with different methods (blanching and then freezing for 24 h, blanching and then repeated freezing/thawing either for 3 or 5 cycles) to study the effect of these pre-treatment methods on the degree of starch retrogradation. The potato slices were then dried by LPSSD at 90°C and absolute pressure of 7 kPa to three levels of final moisture content (1.5%, 2.5% and 3.5% db). Authors reported that various pre-treatment methods affected the drying rate while initial thickness had an influence on the hardness of chips. Final moisture content did not have any significant impact on hardness and toughness. Higher degrees of starch retrogradation led to an increase in the hardness and toughness of dried chips, which was attributed to higher degree of crystallinity. However starch retrogradation did not show any significant effect on the crispness of the chips.

In another work, Pimpaporn et al. (2007) studied the effect of various pretreatments and drying temperatures on the quality of low pressure superheated steam dried potato chips. The objective of the study was to explore the possibility of employing LPSSD as an alternative technique to conventional deep fat frying in order to produce low fat snack product. Potato chips were subjected to various pretreatments such as (a) blanching, (b) combined blanching and freezing, (c) blanching followed by immersion in glycerol solution and freezing and (d) combined blanching, immersion in monoglyceride solution and freezing before drying at different temperatures (70, 80 and 90°C) and at an absolute pressure of 7 kPa. The quality of the dried chips was evaluated in terms of color, texture (hardness, toughness and crispness) and microstructure. In terms of the drying behaviour and the dried product quality, LPSSD at 90°C with combined blanching and freezing pretreatments was proposed as the most favourable conditions for drying potato chips. Moreira, (2001) reported drying of potato chips employing impingement drying technique, using hot air or superheated steam as medium. Impingement drying with superheated steam produced potato chips with less colour deterioration and nutritional losses (ascorbic acid) than drying with hot air.

***Drying of milk products***

*Drying of paneer*

Shrivastav and Kumbhar (2010) conducted drying experiments on paneer (1.0 and 1.5 $cm^3$ cubes) at 62, 72 and 82°C and 10, 14 and 18 kPa absolute pressures with superheated steam and evaluated the textural quality of product. Hardness, adhesiveness, gumminess and chewiness increased with increase in temperature and decreased with increase in pressure. However, springiness and cohesiveness decreased with increase in temperature and pressure. Results indicated that paneer dried under low pressure superheated steam and rehydrated had similar textural properties as that of fresh paneer (Table 6).

***Drying of cereals, beans and other products***

*Spent grains*

An empirical equation with regression-determined coefficients was developed by Tang et al. (2005) to describe thin-layer drying of brewers spent grain (BSG) and distillers spent grain (DSG) using superheated steam (110-180ºC at 5 different steam velocities). Unlike in hot-air drying, not only steam temperature but also steam velocity influenced the drying rate of BSG and DSG in superheated steam. At 145°C, an increase in steam velocity from 0.3 to 1.1 m/s reduced the drying time by half for both spent grains. Increasing the SSD temperature from 110 to 180°C decreased the starch content by 14.5 and 11.5% for BSG and DSG, respectively at a steam velocity of 0.66 m/s. Drying to the equilibrium in 145°C at a superheated steam velocity of 0.66 m/s resulted in decrease of starch content by 22-23% for DSG as compared with that in the non-dried material. The partial gelatinization of starch and formation of amylose-lipid complexes or resistant starch were the probable reasons cited for the decrease in starch content. The SSD parameters had no effect on β-glucan, pentosan, and protein contents in the dried samples.

*Paddy*

Taechapairoj et al. (2003) carried out fluidised bed paddy drying using superheated steam and compared the performance of hot air based fluidized bed drying reported in literature. The mechanism of mass transfer in superheated steam fluidized bed drying was strongly controlled by internal moisture movement in the kernel and a two-series exponential equation was proposed to explain its movement. The head rice yield from SSD was more sustainable and had higher values than those obtained from the hot air drying. Whereas in the case of white rice, the colour of grain turned darker, making it of poorer quality. In addition, the percentage of white belly kernels decreased with increase in the initial moisture content, providing relatively higher head rice yield. Authors suggested that in order to maintain good head rice yield the high moist paddy should not be dried to lower than 18%.

Rordprapat et al. (2005) reported a comparative study of fluidized bed paddy drying using superheated steam and hot air. The physical properties such as, head yield, whiteness and white belly, viscosity of rice flour and microstructure of rice kernel were analyzed. The steam condensation during initial few minutes of SSD was reported to be responsible for lower drying rates as compared to hot air drying. However, the steam condensation promoted the starch gelatinization, resulting in higher head rice yield. Higher degree of Maillard reaction was responsible for lower whiteness value, though the percentage of white belly did not vary much compared to hot air drying. Measured pasting properties indicated that gelatinization occurred more in paddy dried by superheated steam.

*Soybean*

The drying characteristics and inactivation of urease enzyme in soybean using superheated steam and hot air fluidized bed was investigated by Prachayawarakorn et al. (2006). The effective diffusion coefficient, increased with increased drying temperatures (120-150 ºC) and moisture content. Furthermore, it depended on the type of heating medium, with lower moisture diffusion for soybean dried by superheated steam. This was attributed to the operating temperature being lower than the inversion temperature. Inactivation of the urease enzyme in both the media showed difference in rate with the rate of inactivation increasing, as the temperature and moisture content increased. Authors concluded that in order to get rid of urease enzyme and simultaneously preserve its nutritional qualities (protein solubility and lysine content) fluidized bed drying can be operated at a lower temperature (below 135°C) with superheated steam as compared to hot air (135-150°C).

*Tortilla chips*

Pronyk et al. (2005) reported the work of Li et al. (1999) on processing of tortilla chips using impinging jets of superheated steam and hot air at temperatures of 115, 130, and 145°C. The effect of superheated steam processing on product quality was evaluated based on parameters such as shrinkage, crispness, starch gelatinization, and microstructure. Compared to hot air drying, superheated steam processing resulted in higher drying rates and more starch gelatinization at equivalent temperatures and convective heat transfer coefficients. Higher steam temperatures resulted in less shrinkage, higher modulus of deformation (crispness) and also porous product. However, at higher steam temperatures there was less starch gelatinization and the pasting properties of tortilla chips had an increased ability to absorb water. In another work (Moreira, 2001), impingement drying of tortilla chips, using hot air or superheated steam as medium has been reported. At higher temperatures (above 130°C), tortilla chips dried faster with superheated steam, as compared to hot air (at the same conditions).

*Noodles*

Markowski et al. (2003) reported the application of superheated steam for the preparation of instant noodles. Asian noodles were partially cooked when dried at high temperatures (up to 150ºC) using superheated steam, creating an instant noodle which eliminated the necessity of cooking in oil. When noodles were processed at relatively lower temperatures of 110ºC and 120ºC, textural parameters such as recovery, adhesiveness, and gumminess were better. However, there was a negative effect on other textural properties namely, maximum cutting stress, resistance to compression and surface firmness. The breaking strength of the noodles was adversely affected and colour of the noodles turned brown at higher temperatures (above 130ºC). The differential scanning calorimetry showed that starch was modified during superheated steam processing and affected its ability to swell when cooked. Even though, this study indicated that superheated steam processing could be a potential method to produce commercially acceptable instant noodles, authors concluded that further studies are needed to optimize the processing conditions to have good overall product quality.

***Drying of spices and herbs***

*Coriander and pepper seeds*

Kozanoglu et al. (2006) studied low pressure superheated steam (90-110°C at 40-66 kPa) fluidized bed drying of coriander and pepper seeds. The moisture gain in the initial period of the process was avoided by supplying additional heat. Both coriander and pepper seeds had higher drying rates and lower final moisture content when operating temperature was increased. For a given temperature, lower operating pressure resulted in higher degree of superheating and improved the drying rate. The study indicated that fluidized bed drying using superheated steam can facilitate lower temperature operation (90-110°C), if the operating temperature is lower, as compared to conventional fluidized bed drying (125-170°C).

*Basil leaves*

Drying of Basil leaves using low pressure superheated steam was compared with conventional hot air (50, 60 and 70°C) drying (Barbieri et al., 2004). Results showed that the original aroma profile of basil (especially methyl cinnamate, 1, 8-cineole, linalool and methyl chavicol, which are considered to be characteristic of basil aroma) was retained more (80-83%)

in the LPSSD (Figure 4 and 5) and air dried product showed a significant variation (reduction by 45-92%) in the relative proportions of aroma compounds.

***Drying of edible Chitosan film***

Mayachiew and Devahastin (2010) studied the effects of various drying methods and conditions such as ambient drying, hot air drying (40°C), vacuum drying and LPSSD (70, 80 and 90°C) at 10 kPa on the residual total phenolic content (TPC) of edible chitosan films enriched with Indian gooseberry extract (1-3/100g). There was no significant loss (2-4%) of residual TPC in the case of ambient and hot air drying. However, LPSSD films had slightly higher residual TPC (80-87%) than the vacuum dried films (76-85%). The addition of extract to the chitosan reduced the swelling of the films, which is attributed to increase in cross-linkage. Swelling of the films is reported to be more in case of ambient and hot air drying when compared to vacuum and LPSSD. The residual TPC, degree of swelling and functional group interaction were affected by drying methods and conditions. Ambient drying, low temperature hot air drying and LPSSD at 70°C resulted in chitosan films with less intermolecular interaction, higher degree of swelling as well as release of TPC than by other drying methods and conditions. The results indicated that drying methods and conditions may be used to engineer chitosan films for controlled release of antioxidants in food packaging applications. In another work Mayachiew et al. (2010) studied the effect of above mentioned drying methods on antimicrobial activity of edible chitosan film enriched with galangal extract (126, 252 and 378 mg/g film) against *Staphylococcus aureus.* Ambient drying and hot air drying resulted in films with higher antimicrobial activity and higher degree of swelling due to lower intermolecular interaction compared to LPSSD at 70°C and 10 kPa. However, LPSSD performed better as compared to vacuum drying under similar conditions.

***MATHEMATICAL MODELLING OF DRYING***

Wu et al. (1987) proposed a numerical model to study the effectiveness of various drying media like superheated steam, humid air and dry air for wedge shaped food products. The model showed that the superheated steam exhibits higher heat transfer rates than other fluids. The evaporation rates were also higher for superheated steam than for dry air or humid air when the fluid temperature was more than the inversion temperature (~275ºC).

Martinello et al. (2003) developed a fixed bed mathematical model to simulate the SSD of fresh parsley (*Petroselinum Cripsum*). The simulation model developed using mass and energy conservation equations for solid and steam phases was used to analyze the influence of different process variables [bed height (thin layer, 2 and 10 cm), operating pressure (0.07-0.17 kgf/cm$^2$), steam velocity (5-12 m/s) and temperature (70-100°C)] on moisture content of the material. An acceptable agreement between experimental and theoretical moisture content values was obtained.

Sa-adchom et al. (2011) developed a semi-empirical model for estimating the effective diffusion coefficient ($D_{eff}$) and for predicting the evolution of the moisture content and the center temperature of sliced pork during superheated steam drying. The model based on mass and energy balance equations was divided into heating up, constant drying rate and falling drying rate periods. The predicted results were compared with the experimental data of SSD of seasoned and unseasoned pork with slice thickness of 1 and 2 mm at a drying temperature of 140°C. The comparison results showed that the developed model could estimate the ranges of the $D_{eff}$ value of pork fairly well ($R^2$ = 0.809-0.985) and could reasonably predict the evolution of the moisture content of the sliced pork. The predicted centre temperature of the sliced pork agreed well in the constant drying rate period and after the drying time of 10 min.

Drying characteristics, selection of analytical model and development of artificial neural network (ANN) models of 1 $cm^3$ paneer at LPSSD were studied by Shrivatsav and Kumbhar (2010). Effects of steam temperature and pressure on drying rates were determined. Page's model had higher coefficient of determination (0.997) and lower SD (0.0043) compared to that of generalized exponential and logarithmic models in all the cases. Second degree polynomial, non linear regression analysis resulted in a good agreement of defined model by changing the values of temperature and corresponding pressure. Optimized ANN models were developed for all data set and the correlation coefficient for all data set was more than 0.98.

Taechapairoj et al. (2006) developed a mathematical model of paddy drying in superheated steam fluidized bed dryer to predict moisture content and temperature. The model was developed based on mass and energy balance. The operating parameters set in the model development included superheated steam temperature, bed depth and superficial superheated steam velocity. The numeric calculations from the model were in agreement with experimental investigations for different operating conditions. The validated model was then used to examine the effect of operating conditions on drying behaviour and gelatinization of paddy. The simulated results showed that the time required for complete gelatinization and evaporating water was shortened by increasing superficial superheated steam velocity and temperature, and decreasing bed depth. The bed depth of 15 cm and temperature of 180°C was recommended from the simulations in order to obtain higher productivity of parboiled rice.

In the work reported by Elustondo et al. (2001), mathematical expression to calculate the drying rate of foodstuffs (shrimps, banana, apple, potato and cassava) dried with low pressure superheated steam was developed. The equation was based on a theoretical drying mechanism, which assumed that water removal is carried out by evaporation in a moving boundary making the vapour to flow through the dry layer built, as drying proceeds. A simplified expression having only two parameters that are linked to physical characteristics such as thermal properties and boiling point rise was derived and was found to be a good fit for the conditions employed. In another work, Elustondo et al. (2002) showed that drying with superheated steam has the characteristic that at given steam velocity and temperature there exists an optimum working pressure at which the drying rate is maximum. It was found that for all other conditions given, the maximum drying rate is a linear function of pressure.

Ducept et al. (2002) explored computational fluid dynamics (CFD) study for conceiving, designing and analyzing superheated steam spray dryer. The CFD model was validated by comparing experimental and numerical particle residence time distribution (RTD) for two different operating conditions of steam (12, 40 kg/h) and feed (5 and 13 kg/h) flow rates. A very high specific rate of evaporation (50 kg/h $m^3$) obtained with superheated steam as heating medium showed that it allows a smaller chamber and thereby reduces the price.

Suvarnakuta et al. (2007) proposed the use of a simple three dimensional liquid diffusion based model to predict the evolutions of the moisture content and temperature of a product undergoing LPSSD. The effect of the product shrinkage was also included directly in the model and the effect of this on the predictability of the model was shown. The model was able to predict the heat and mass transfer behaviour as well as the change in β-carotene content of carrot cube reasonably well over a range of moisture content when accurate values of the heat transfer coefficient were used. The use of more realistic boundary conditions and inclusion of terms that can take into account hydrostatic pressure gradients which may exist within the product during drying were suggested by the authors to improve the performance of the model.

***DECONTAMINATION AND MICROBIAL LOAD REDUCTION***

The use of superheated steam as a processing medium can reduce or eliminate microbial load on foods, can solubilize and extract contaminants such as spores, mycotoxins and odours in addition to thermal degradation. A few studies reported on decontamination and microbial load reductions using superheated steam are discussed in the following sections.

Pronyk et al. (2006) studied the efficacy of superheated steam processing of wheat kernels for decontamination of *Fusarium* mycotoxin deoxynivalenol (DON). Contamination of wheat with DON is a concern to the ethanol industry as it is stable during processing and gets concentrated in the spent grains, which are potentially a valuable feedstock. Superheated steam at four processing temperatures (110, 135, 160 and 185°C), three steam velocities (0.65, 1.3 and 1.5 m/s) and processing times (2-15 min) was used to treat wheat kernels naturally contaminated with DON (15.8 ppm). With the increase in temperature, the kernel had toasted odour and the surface attained brown colour. Superheated steam processing increased the friability of the kernels in all the processing conditions which in turn can reduce the energy cost and time during milling. The kernels processed at 185°C and 1.3 m/s exhibited significant reduction in DON levels (52%) after 6 min processing. Processing at lower temperature (110 and 135ºC) and velocity variation did not affect the DON reduction. Authors concluded that reduction in DON is not due to washing affect or water solubilisation, but due to thermal degradation. The pre-steaming of kernels with saturated steam in fact increased the DON retention.

In another study by Cenkowski et al. (2007), the effects of superheated steam on grains contaminated with DON and *Geobacillus stearothermophilus* spores was reported. The studies were carried out at processing temperatures between 110 and 185°C for three steam velocities of 0.65, 1.3 and 1.5 m/s. The results showed reductions in DON concentration up to 52% at 185°C for about 6 min of processing time. Thermal degradation was the dominant factor in the destruction of DON and pre-processing such as washing with wet steam did not have any significant additional effect on DON reduction. The Z-value for *G. stearothermophilus* spores exposed to superheated steam at higher temperatures (130-175°C) was determined to be 28.4°C. The initial condensation of steam on the surface of a product contaminated with spores may play a role in increased reduction of spores. Authors concluded that use of superheated steam is beneficial, if product is to be dried apart from reducing the contaminants in food, as both are taking place simultaneously during superheated steam processing. The survivor curve for *G. stearothermophilus* processed with superheated steam is shown in Figure 6.

Graphical procedure for comparing thermal death of *Bacillus stearothermophilus* spores in saturated and superheated steam was reported by Shull and Ernst (1962). The authors used a jacketed steam sterilizer in which the superheated steam was produced at the beginning by transfer of heat from the steam heated jacket to saturated steam entering the vessel. Measurements of spore inactivation and temperature revealed the presence of superheat in surface layers of fabrics being processed at 121ºC. The higher temperature (by nearly 8°C) of the fabric surfaces was attributed to absorption of excess heat energy from superheated steam. The rate of spore destruction in superheated steam region was found to be less than in saturated steam at the same temperature. The higher resistance of spores to superheated steam at lower temperatures could be one of the reasons for observed lower degree of spore destruction. In this study, authors emphasised the necessity for control of superheat in design and operation of steam sterilizers to obtain desired results.

Kondjoyan and Portanguen (2008) investigated the effectiveness of superheated steam in the decontamination of poultry skin. The temperature of the steam delivery tube was set either at 200 or 500°C leading to the jet temperatures of 160-180°C and 400-450°C, respectively. The surface of poultry skin was inoculated with about $10^7$ cfu/cm$^2$ *Listeria innocua* and treated with either superheated steam or saturated steam up to 1 min. Superheated steam was found to be more efficient than saturated steam leading to an average reduction of more than 5 $\log_{10}$cfu/cm$^2$ after 30 s of treatment. This study showed that the average differences between the superheated and non-superheated steam treatments are very significant between 20 and 30 s of heating and not significant either in the initial stages (below 20 s) or at longer processing durations (above 30 s).

Nygaard and Hostmark (2008) investigated the microbial inactivation of SSD of fish meal in a pilot scale fluidized bed dryer (~10 kg input material) and compared the performance with hot air as heating medium. The exposure time required for 90% reduction in population (D-values) of the surrogate organisms *Clostridium sporogenes* and *Escherichia Coli* at 300°C were 0.33 and less than 0.10 min, respectively. The corresponding D-values obtained during hot air drying at the same temperature were 54 and 1.12 min. The D-values for spores of the thermophile *G. stearothermophilus* were 3.54 and 228 min for superheated steam and boiling water processing, respectively. The results indicated that the superheated steam processing can be effectively used for inactivating micro organisms.

Head et al. (2008) studied the effect of processing with superheated steam on *G. stearothermophilus* ATCC 10149 spores. Inoculum levels of 3 and 6 $\log_{10}$ CFU/g was mixed with sterile sand and exposed to superheated steam at 105-175 °C with different heating and cooling periods (Protocol A: heating 2 times for a duration of 5 min each with intermediate cooling for 15 min; Protocol B: heating 3 times for a duration of 5 min each with intermediate cooling for 15 min). A mean z-value of 25.4°C was obtained for both inoculum levels for processing temperatures between 130 and175°C. Spore response to superheated steam treatment depended on inoculum size. Authors concluded that superheated steam treatment may be effective for reduction in viability of thermal resistant bacterial spores, provided treatments are separated by intermittent cooling periods or very high superheated steam temperatures (160-175ºC). Table 7 shows the percent reduction of *G. stearothermophilus* spores processed with superheated steam at different temperatures for 10 or 15 minutes. The literature reports on application of superheated steam for decontamination and microbial load reduction are summarized in Table 8.

***PARBOILING***

Parboiling of paddy is a hydro-thermal process aimed at improving milling, nutritional and organoleptic attributes of rice. The drying method is the key factor influencing the milling quality of parboiled rice (Bhattacharya and Swamy, 1967). Several drying methods such as sun drying, hot air drying, vacuum drying and SSD have been used for drying parboiled rice (Bhattacharya, 1985; Soponronarit et al., 2004). Superheated steam shows great potential to replace the hot air, particularly when used with starch-based materials. When using this as medium, both steaming and drying stages, required for the traditional method, are incorporated into a single stage. The works reported in this area are summarized in Table 8.

Soponronnarit et al. (2006) studied the superheated steam fluidized-bed drying of parboiled brown rice to determine the optimum parboiling process. The influence of soaking temperature (70-90°C) and time (0.5-2.0 h), steaming temperature (120-160°C), and bed depth (8-12 cm) on the physical properties such as head rice yield, whiteness and white belly, rice flour viscosity and starch granule microstructure of brown rice were compared with hot air dried grains under the similar conditions. During the first few minutes, the drying rates were lower for SSD as compared to that of hot air due to an initial steam condensation. The effect of bed depth and soaking time of grain on drying rate was not significant. Due to complete gelatinization, superheated steam dried brown rice had higher head rice yield and lesser white belly kernel than that dried by hot air. Whiteness of hot air dried brown rice was found to be more than that of superheated steam. Peak viscosity, breakdown viscosity and final viscosity (FV) of rice starch dried by superheated steam and hot air was lower than that of reference rice, while pasting temperature was found to be higher. Due to the lower values of FV and setback viscosity, cooked rice obtained from superheated steam dried brown rice showed higher hardness than hot air dried and reference rice. SEM images of rice starch processed at the same temperature (140°C) showed complete gelatinization in case of superheated steam while gelatinization was incomplete for hot air dried (Figure 7).

The effect of processing conditions such as soaking, steaming and drying on the quality of parboiled non-glutinous, short grain, japonica (koshihikari) brown rice was reported by Hebbar et al. (2008). The pre soaked rice was steamed using normal steam, superheated steam and mixture of superheated steam and water micro droplets (SHS + WMD) to gelatinize the starch. Forced convective drying (oven drying) of steamed rice using air at a moderate temperature (38 ± 1°C) was attempted as an alternative to conventional shade drying. The study showed that the method of drying has a significant effect on the quality of parboiled rice. Parboiling resulted in browning of grains while the head yield was very high (> 95%) for all parboiling conditions. Superheated steam processing resulted in higher amount of moisture loss as compared to SHS + WMD processing at same steaming temperature. SHS + WMD (115°C) processed rice samples were dried in 4.0-4.5 h and it did not differ significantly from superheated steam processed at the same temperature (115°C). Processing at 125°C with SHS + WMD resulted in a length to width ratio (1.76-1.78), which was almost same as that of normal steam processed grains. Hardness of SHS + WMD and superheated steam processed grains were higher by 10-20%, as compared to rice steamed by normal steam.

### *ENZYME INACTIVATION*

#### *Brown rice*

Satou et al. (2010) attempted superheated steam treatment (125–300°C and 0.25-2 min at steam flow rate of 53 kg/h) of brown rice (cultivar Koshihikari BL) to stabilize or improve its storage quality. Regardless of the superheated steam processing conditions, residual lipase activity was found to be almost constant at about 5% of that of untreated brown rice. Lipoxygenase was completely inactivated by superheated steam processing at 125°C for 1 min. The starch damage was not significant when superheated steam temperature was below 150°C. These results showed that superheated steam treatment at a lower temperature and for a short time can inactivate the enzyme in brown rice, without influencing starch quality.

***Oat groats***

Heat treatment is vital part of oat processing and is mainly carried out to extend shelf life by inactivating enzymes which cause rancidity, besides reducing bacterial counts, and to produce a desirable toasted aroma and flavour (Pronyk et al., 2005). Processing for 7.5 min at 120°C was sufficient to inactivate peroxidase to the desired level. The increase in viscosity was not as high as that of kiln dried oat, probably due to incomplete gelatinization. Processing of oat groats with superheated steam as an alternative to kiln drying for stabilizing was reported by Head et al. (2011). The study mainly focused on aspects related to product quality. Both superheated steam processed (110°C for 10-14 min) and commercially processed groats remained shelf-stable up to 26 weeks when stored at 21°C and 38°C. No substantial changes were reported in color, cold paste viscosity, free fatty acid contents and sensory attributes. Superheated steam processed groats released lower amounts (2 µg/g) of hexanal as compared to that (7-9 µg/g) of processed commercially.

***Potato***

Sotome et al. (2009) proposed a novel technique of combining superheated steam with water droplets for enzyme inactivation of potato. A heating system using superheated steam (115°C) and a spray of hot water micro droplets (WMD) was developed to prevent drying of food material during superheated steam heating. Blanching of potato was examined with the new system (SHS + WMD), superheated steam and hot water (100ºC). In SHS + WMD heating, a mixture of SHS at 115°C, 2.46 kg/h flow rate and hot water at 0.54 kg/h was used. Potato tissue processed with hot water became soft and brittle, and its brightness and chromatic quality decreased due to absorption of water and dissolution of solid content to the water. These quality changes were prevented in SHS + WMD and superheated steam heating. Heat transfer by superheated steam was enhanced by the presence of WMD, presumably because the water layer formed on the potato by condensation of superheated steam was stirred and its thermal resistance was decreased by collisions of WMD with the potato. The mass of potato processed with SHS + WMD was almost constant during the heating, while the relative mass of potato processed with superheated steam decreased 3.3% with 16 min of heating. For potato cylinder heating, SHS + WMD exhibited a higher heat transfer rate than superheated steam. It was proposed that water droplets enhanced the heat transfer of superheated steam by stirring the water layer on the potato sample formed by steam condensation. The colour values, especially the Lightness (L*) were better for SHS + WMD, as compared to SHS and hot water blanching (Table 9). Taking account of these results, the authors concluded that SHS + WMD could reduce the blanching time for small pieces of fruit and vegetables. All the studies reported on superheated steam enzyme inactivation have been summarized in Table 8.

### *CONCLUSIONS AND FUTURE SCOPE*

A comprehensive and selective overview presented on recent studies of the applications of superheated steam in food industry indicated that it is one of the potential methods for heat processing of food materials. Most of the reports on drying of high moisture content materials like fruits, vegetables and meat products indicated that operation at relatively lower temperatures, i.e., 110-140ºC is preferable from the product quality point of view. A few reports have suggested that hybrid mode drying involving superheated steam and other drying methods such as hot air or FIR are superior compared to superheated steam alone. Intermittent drying with superheated steam could also be explored to have energy efficiency. The review indicated that impingement drying or LPSSD drying is one of the probable methods for drying of thin products like chips or noodles and obtain product with lower fat content. Better retention of color and nutrients were reported in most of these studies as compared to conventional drying. However, the factors such as lesser starch gelatinization at high temperatures, higher shrinkage and lower porosity observed in some studies on drying of chips are to be addressed in order to further improve the product quality. The studies on decontamination and microbial load reduction showed that superheated steam can be used as a processing medium effectively for this purpose. However, higher processing temperature needed to achieve the desired results could be factor that needs to be viewed also from product quality point of view. There are only a few reports on the application of superheated steam for parboiling. The review indicated that there was no significant change in superheated steam processed rice quality (head rice yield, color, and texture) compared to conventional drying or steaming. Further studies are needed to arrive at any logical conclusion on efficacy of superheated steam for parboiling. The reports on enzyme inactivation indicated that superheated steam can be used to inactivate enzymes to the desired level without significantly changing product quality. Use of mixture of superheated steam with micro-droplets of water could be an option for processing high moisture content materials like vegetables.

Superheated steam processing comply with new trends on energy efficiency and low environmental impact, therefore they have a high potential for industrial application in the near future. However, both laboratory and pilot scale studies to generate scientific and engineering data and to establish the superiority of this technique in terms of energy efficiency, product quality and processing cost needs to be established. The current concerns on energy efficiency and claims for clean processes generate a new setting for further R & D in innovative superheated steam processing technology. The focus should be more on development of equipment with improved efficiency, as there are only a few equipment manufacturers who develop custom built superheated steam based processing equipment. More extensive studies are needed in developing LPSSD processes, to handle heat sensitive food products. As hybrid processing systems are found to be efficient, further studies should focus on the combination of processes, which could be either simultaneous (superheated steam and IR, superheated steam with water droplets) or stage wise (superheated steam followed by conventional process) processing. Mathematical modelling is another area that needs greater attention for better understanding of heat and mass transfer during superheated steam processing to widen the scope of application of superheated steam in food processing.

*ACKNOWLEDGEMENTS*

The corresponding author wish to thank UNU-Kirin, Japan for UNU-Kirin Fellowship follow-up grant for supporting this work. The authors wish to thank Director, CFTRI, and Head, Food Engineering, CFTRI for their kind support and encouragement.

***REFERENCES***

Barbieri, S., Elustondo, M., and Urbicain, M. (2004). Retention of aroma compounds in basil dried with low pressure superheated steam. *J. Food Eng.* **65**: 109-115.

Beeby, C. and Potter, O. E. (1985). Steam drying. *Proceeding of 4$^{th}$ International Drying Symposium*, May 5-8, Kyoto, Japan.

Bhattacharya, K. R. and Indudhara Swamy, Y. M. (1967). Conditions of drying parboiled paddy for optimum milling quality. *Cereal Chem.* **44**: 592–600.

Bhattacharya, K. R. (1985). Parboiling of rice. **In**: *Rice-Chemistry and technology*, pp. 289–348. Juliano, B.O. Ed., AAOCC, St. Paul, M.N.

Borquez, R. M., Canales, E. R., and Quezada, H. R. (2008). Drying of Fish Press-Cake with Superheated Steam in a Pilot Plant Impingement System. *Drying Technol*. **26**: 290–298.

Caixeta, A. T., Moreira, R., and Castell-Perez, M. E. (2002). Impingement drying of potato chips. *J. Food Proc. Eng.* **25**: 63–90.

Cenkowksi, S., Pronyk, C., Zmidzinska, D., and Muir, W. E. (2007). Decontamination of food products with superheated steam. *J. Food Eng.* **83**: 68-75.

Devahastin, S., Suvarnakuta, P., Soponronnarit, S., and Mujumdar, A. S. (2004). A comparative study of low-pressured superheated steam and vacuum drying of a heat-sensitive material. *Drying Technol*. **22**: 1845-1867.

Deventer, V. H. C. and Heijmans, R. M. H. (2001). Drying with superheated steam. *Drying Technol.* **19**: 2033-2045.

Ducept, F., Sionneau, M., and Vasseur, J. (2002). Superheated Steam Dryer: Simulations and Experiments on Product Drying. *Chem. Eng. J.* **86**: 75-83.

Elustondo, D. M., Elustondo, M. P., and Urbicain, M. J. (2001). Mathematical modeling of moisture evaporation from foodstuffs exposed to sub atmospheric pressure superheated steam. *J. Food Eng.* **49**: 15-24.

Elustondo, D. M., Mujumdar, A. S., and Urbicain, M. J. (2002). Optimum operating conditions in drying foodstuffs with superheated steam. *Drying Technol.* **20**: 381-402.

Hebbar, U. H., Hossen, S. M., Itaru Sotome, I., Makiko Takenaka, M., Seiichiro Isobe, S., and Okadome, H. (2008). Effect of processing conditions on the quality of parboiled brown rice. *Jpn. J. Crop Sci*. **77** (Special issue 2): 326-327.

Head, D. S., Cenkowski, S., Holley, R., and Blank, G. (2008). Effects of superheated steam on *Geobacillus stearothermophilus* spore viability. *J. Appl. Microbiol.* **104**: 1213-1220.

Head, D., Cenkowski, S., Arntfield, S., and Henderson, K. (2011). Storage stability of oat groats processed commercially with superheated steam. *LWT -Food Sci.Technol.* **44**: 261-268.

Hiranvarachat, B., Suvarnakuta, P., and Devahastin, S. (2008). Isomerisation kinetics and antioxidant activities of β-carotene in carrots undergoing different drying techniques and conditions. *Food Chem.* **107**: 1538-1546.

Huang, T., Ho, C., and Fu, H. (2004). Inhibition of lipid oxidation in pork bundles processing by superheated steam frying. *J. Agric. Food Chem.* **52**: 2924-2928.

Iyota, H., Nishimura, N., Onuma, T., and Nomura, T. (2001). Drying of sliced raw potatoes in superheated steam and hot air. *Drying Technol.* **19**: 1411–1424.

Kingcam, R., Devahastin, S., and Chiewchan, N. (2008). Effect of starch retrogradation on texture of potato chips produced by low pressure superheated steam drying. *J. Food Eng.* **89**: 72–79.

Karimi, F. (2010). Applications of superheated steam for the drying of food products. *Int. Agrophysics*. **24**: 195-204.

Kondjoyan, A. and Portanguen, S. (2008). Effect of superheated steam on the inactivation of *Listeria innocua* surface inoculated onto chicken skin. *J. Food Eng.* **87**: 162-171.

Kozanoglu, B., Vazquez, A. C., Chanes, J. W., and Patin, J. L. (2006). Drying of seeds in a superheated steam vacuum fluidized bed. *J. Food Eng.* **75**: 383–387.

Kudra, T. and Mujumdar, A. S. (2001). *Advanced drying technologies*. Dekker press, New York.

Kudra ,T. and Mujumdar, A. S. (2002). *Advanced drying technologies*. Dekker Press, New York.

Kudra, T. and Mujumdar, A. S. (2009). *Advanced drying Technologies*. 2nd Ed., CRC Press, Boca Raton, FL.

Kumar, P. and Mujumdar, A. S. (1990). Superheated steam drying—a bibliography. *Drying Technol.* 81: 195–205.

Leonard, A., Blacher, S., Nimmol, C., and Devahastin, S. (2008). Effect of far infrared radiation assisted drying on microstructure of banana slices. *J. Food Eng.* **85**: 154-162.

Li, Y. B., Seyed-Yagoobi, J., Moreira, R. G., and Yamsaengsung, R. (1999). Superheated steam impingement drying of tortilla chips. *Drying Technol.* **17**: 191- 213.

Markowski, M., Cenkowski, S., Hatcher, D. W., Dexter, J. E., and Edwards, N. M. (2003). The effect of superheated-steam dehydration kinetics on textural properties of Asian noodles. *Trans ASAE*. **46**: 389–395.

Martinello, M. A., Mattea, M. A., and Crapiste, G. (2003). Superheated steam drying of parsley: A fixed bed model for predicting drying performance. *Lat. Am. Appl. Res.* **33**: 333-337.

Mayachiew, P. and Devahastin, S. (2010). Effects of drying methods and conditions on release characteristics of edible chitosan films enriched with Indian gooseberry extract. *Food Chem.* **118**: 594-601.

Mayachiew, P., Devahastin, S., Mackey, B. M., and Niranjan, K. (2010). Effects of drying methods and conditions on antimicrobial activity of edible chitosan films enriched with galangal extract. *Food Res. Int.* **43**: 125-132.

Methakhup, S., Chiewchan, N., and Devahastin, S. (2005). Effects of drying methods and conditions on drying kinetics and quality of Indian gooseberry flake. *LWT- Food Sci. Technol.* **38**: 579–587.

Moreira, G.R. (2001). Impingement drying of foods using hot air and superheated steam. *J. Food Eng.* **49**: 291-295.

Mujumdar, A.S. (2000). Superheated steam drying-technology of the future. **In**: *Mujumdar's Practical Guide to Industrial Drying*, pp. 115–138. Devahastin, S., Ed., Exergex, Brossard, Canada.

Mujumdar, A. S. and Devahastin, S. (2008). Fundamental Principles of Drying. **In**: *Guide to Industrial Drying − Principles, Equipments and New Developments*, Mujumdar, A.S., Ed., Three S Colors Publications, Mumbai, India.

Mujumdar, A. S. and Law, C. L. (2010). Drying technology: Trends and applications in postharvest processing. *Food Bioproc. Technol.* **3**, 843-852.

Mujumdar, A. S. (1992). Superheated Steam Drying of Paper: Principles, Status and Potential. **In**: *Drying of Solids.* Mujumdar, A. S., Ed., International Science Publisher, New York.

Mujumdar, A. S. (2007). Superheated steam drying. **In**: *Handbook of Industrial Drying*. Mujumdar, A. S., Ed., CRC Press, Boca Raton, FL.

Nathakaranakule, A., Kraiwanichkul, W., and Soponronnarit, S. (2007). Comparative study of different combined superheated-steam drying techniques for chicken meat. *J. Food Eng.* **80**: 1023–1030.

Nimmol, A. C., Devahastin, B. S., Swasdisevi, A. T., and Soponronnarit, S. (2007). Drying of banana slices using combined low-pressure superheated steam and far-infrared radiation. *J. Food Eng.* **81**: 624–633.

Nygaard, H. and Hostmark, O. (2008). Microbial Inactivation during superheated steam drying of Fish Meal. *Drying Technol.* **26**: 220-230.

Pimpaporn, P., Devahastin, S., and Chiewchan, N. (2007). Effects of combined pretreatments on drying kinetics and quality of potato chips undergoing low-pressure superheated steam drying. *J. Food Eng.* **81**: 318-329.

Prachayawarakorn, S., Prachayawasin, P., and Soponronnarit, S. (2006). Heating process of soybean using hot-air and superheated-steam fluidized-bed dryers. *LWT- Food Sci. Technol.* **39**: 770-778.

Pronyk, C., Cenkowski, S., and Abramson, D. (2006). Superheated steam reduction of deoxynivalenol in naturally contaminated wheat kernels. *Food Cont.* **17**: 786-796.

Pronyk, C., Cenkowski, S., and Muir, W. E. (2005). Current status of superheated steam drying and processing. *Proceedings of 3rd International American conference on drying,* August 21-23, Montreal, Canada.

Rordprapat, W., Nathakaranakule, A., Tia, W., and Soponronnarit, S. (2005). Comparative study of fluidized bed paddy drying using hot air and superheated steam. *J. Food Eng.* **71**: 28-36.

Sa-adchom, P., Swasdisevi, T., Nathakaranakule, A., and Soponronnarit, S. (2011). Mathematical model of pork slice drying using superheated steam. *J. Food Eng.* **104**: 499-507.

Sagar, V. R. and Kumar, S. P. (2010). Recent advances in drying and dehydration of fruits and vegetables: A review. *J. Food Sci. Technol.* **47**: 15-26.

Satou, K., Takahashi, Y., and Yoshii, Y. (2010). Effect of Superheated Steam Treatment on Enzymes Related to Lipid Oxidation of Brown Rice. *Food Sci. Technol. Res*. **16**: 93 – 97.

Shrivastav, S. and Kumbhar, B. K. (2010). Textural profile analysis of paneer dried with low pressure superheated steam. *J. Food Sci. Technol.* **47**: 355–357.

Shull, J. J. and Ernst, R. R. (1962). Graphical procedure for comparing death of *Bacillus stearothermophilus* spores in saturated and superheated steam. *J. Appl. Microbiol.* **10**: 452-457.

Somjai, T., Achariyaviriya, S., Achariyaviriya, A., and Namsanguan, K. (2009). Strategy for longan drying in two stage superheated steam and hot air. *J. Food Eng.* **95**: 313-321.

Soponronarit, S., Taechapairoj, C., and Prachayawarakorn, S. (2004). New technique producing parboiled rice. *J. R. Inst. Thai.* **29**: 78–86.

Soponronnarit, S., Nathakaranakule, A., Jirajindalert, A., and Taechapairoj, C. (2006). Parboiling brown rice using super heated steam fluidization technique. *J. Food Eng.* **75**: 423–432.

Sotome, I., Takenaka, M., Koseki, S., Ogasawara, Y., Nadachi, Y., Okadome, H., and Isobe, S. (2009). Blanching of potato with superheated steam and hot water spray. *LWT- Food Sci. Technol.* **42**: 1035 - 1040.

Suvarnakuta, P., Chweerungrat, C., and Devahastin, S. (2011). Effects of drying methods on assay and antioxidant activity of xanthones in mangosteen rind. *Food Chem.* **125**: 240-247.

Suvarnakuta, P., Devahastin, S., and Mujumdar, A. S. (2007). A mathematical model for low-pressure superheated steam drying of a biomaterial. *Chem. Eng. Proc.* **46**: 675–683.

Taechapairoj, C., Prachayawarakorn, S., and Soponronnarit, S. (2003). Modelling of parboiled rice in superheated steam fluidized bed. *J. Food Eng.* **76**: 411-419.

Tang, Z. and Cenkowski, S. (2000). Dehydration dynamics of potatoes in superheated steam and hot air. *Canadian Agric. Eng.* **42**: 43–49.

Tang, Z., Cenkowski, S., and Izydorczyk, M. (2005). Thin-layer drying of spent grains in superheated steam. *J. Food Eng.* **67**: 457–465.

Tang, Z., Cenkowski, S., and Muir, W. E. (2000). Dehydration of sugar-beet pulp in superheated steam and hot air. *Trans ASAE*, **43**: 685–689.

Thomkapanich, O., Suvarnakuta, P., and Devahastin, S. (2007). Study of intermittent low-pressure superheated steam and vacuum drying of a heat-sensitive material. *Drying Technol.* **25**: 205–223.

Wu. C. H., Davis, D. C., Chung, J. N., and Chow, L. C. (1987). Simulation of wedge-shaped product dehydration using mixtures of superheated steam and air in laminar flow. *Numer. heat transf.* **11**: 109-123.

***FIGURE LEGENDS***

**Figure 1** SEM images of longitudinal section of chicken dried by (a) SS at 120°C, (b) SSD-AD at 120ºC & 55ºC and (c) SSD-HP at 160ºC & 55ºC (from Nathakaranakule et al., 2007).

**Figure 2** SEM images showing cross section of banana slices dried by (a) LPSSD-FIR at 80°C, (b) vacuum-FIR at 80°C, (c) LPSSD-FIR at 90°C and (d) Vacuum-FIR at 90°C (from Nimmol et al., 2007).

**Figure 3** Photographs of carrot cubes dried by LPSSD and vacuum drying (from Devahastin et al., 2004).

**Figure 4** Composition profile of fresh and LPSSD dried samples (from Barbieri et al., 2004).

**Figure 5** Composition profile of fresh and air dried samples (from Barbieri et al., 2004).

**Figure 6** Survivor curve for *G. stearothermophilus* spores (initial inoculation of $10^3$ cfu/g) processed with superheated steam at different temperatures. Symbols represent means of three trials. Vertical bars represent standard deviations of the means (from Cenkowski et al., 2007).

**Figure 7** SEM images of cross section of soaked rice starch dried by (a) hot air and (b) superheated steam (from Soponronnarit et al., 2006).

**Table 1** Superheated steam drying of meat & fish products and fruits

| Product | Drying conditions | Remarks | References |
|---|---|---|---|
| Meat & Fish products | | | |
| Zousoon | SHS, 150°C | Better in terms of 'off-odours', effective in suppressing lipid oxidation and had greater stability as compared to pan-frying. | Huang et al. (2004) |
| Chicken meat | Combining with high pressure or air drying | SSD-HP was found to be the most suitable drying method. | Nathakaranakule et al. (2007) |
| Fish press cake | 146-185°C | High moisture and lesser loss of omega-3 fatty acids. | Borquez et al. (2008) |
| Fruits | | | |
| Banana slices | LPSSD-FIR and Vacuum -FIR at 80-90°C | LPSSD-FIR drying at 80°C was better, as product was more porous compared to those dried by vacuum-FIR. | Nimmol et al. (2007) |
| | LPSSD-FIR & LPSSD at 80, 90°C | Far infrared radiation was found to modify the structure of the dried bananas by increasing their final porosity. | Leonard et al. (2008) |
| | Intermittent LPSSD and vacuum drying at 70, 80 and 90°C | Net drying time was significantly shorter leading to higher ascorbic acid retention. | Thomkapanich et al.(2007) |
| Mangosteen rind | LPSSD at 60-90°C | LPSSD at 75°C was proposed as an appropriate drying technique as it retained higher amounts of xanthones. | Suvarnakuta et al. (2011) |
| Longan | SSD+HAD, 120-180°C followed by HAD at 60-70°C | Two-stage drying with superheated steam at 180°C followed by hot air at 70°C was better. | Somjai et al. (2009) |
| Indian gooseberry | LPSSD, 65,75°C, 7-13 kPa | LPSSD samples had higher (5-10%) retention of ascorbic acid and color. | Methakhup et al. (2005) |

SHS: Superheated steam; LPSSD: Low pressure superheated steam drying; FIR: Far infrared radiation; HAD: Hot air drying

**Table 2** Superheated steam drying of vegetables and milk products

| Product | Drying conditions | Remarks | References |
|---|---|---|---|
| Vegetables | | | |
| Carrot | LPSSD, 60-80°C, 7kPa | LPSSD at 60°C was the best treatment to preserve β-carotene and antioxidant activity. | Hiranvarachat et al. (2008) |
| Potato | SHS | Samples dried by SHS were glossier and there were no 'remaining' starch granules on the surface & starch gelatinisation rate was higher. | Iyota et al. (2001) |
| | SHS | They concluded that SHS is better compared to HAD. | Mujumdar and Devahastin, (2008) |
| | SHS, 125-165°C | Increase in drying temperature decreased the dehydration time by 60%. | Tang and Cenkowski (2000) |
| | Impingement drying above 130ºC | Less colour deterioration and vitamin C losses. | Moreira (2001) |
| | SHS, 115-145°C | Higher retention of ascorbic acid and closer in texture to the commercial potato chips than the air dried. | Caixeta et al. (2002) |
| | LPSSD at 90°C, 7 kPa | The various pre-treatment methods were found to have an obvious effect on the rates of moisture reduction of the samples. | Kingcam et al. (2008) |
| | LPSSD at 70- 90°C, intermittent processing | Ascorbic acid retention was higher with intermittent temperature processing than intermittent pressure processing. | Thomkapanich et al. (2007 |
| | LPSSD at 70-90°C, 7 kPa, pre-treated slices | LPSSD at 90°C with combined blanching and freezing pre-treatments was better. | Pimpaporn et al. (2007) |
| Milk products | | | |
| Paneer | LPSSD, 62-82°C, 10-18 kPa | Hardness, adhesiveness, gumminess and chewiness increased with increase in temperature and decreased with increase in pressure. | Shrivastav and Kumbhar (2010) |

LPSSD: Low pressure superheated steam drying; SHS: Superheated steam

**Table 3** Superheated steam drying of grains, beans & other products and Spices & Herbs and edible Chitosan film

| Product | Drying conditions | Remarks | References |
|---|---|---|---|
| Grains & Beans & other products | | | |
| Spent grains | SHS, 110-180°C | Unlike in hot-air drying, not only steam temperature but also steam velocity influenced the drying rate of brewers spent grain and distillers spent grain. | Tang et al. (2005) |
| Paddy | SHS, 120-160°C, bed height of 8–12 cm | Head rice yield was higher than those obtained from the hot air drying, whereas the colour of white rice turned darker. | Taechapairoj et al. (2006) |
| | SHS, 150°C, bed depth of 10 cm | Head rice yield & gelatinisation of superheated steam dried paddy was higher. | Rordprapat et al. (2005) |
| Soybean | SHS, 120-150ºC | Inactivation of urease enzyme was faster for soybean dried in superheated steam than hot air. | Prachayawarakorn et al. (2006) |
| Tortilla chips | SHS, 115-145ºC | At 145°C, there was less shrinkage and higher crispness and higher drying rates. | Pronyk et al. (2005) |
| | Impingement drying above 130ºC | Chips dried faster in superheated steam compared to hot air drying. | Moreira (2001) |
| Noodles | SHS, 110-150°C | At 150°C, noodles become partially cooked, eliminating additional cooking in oil. | Markowski et al. (2003) |
| Spices & Herbs | | | |
| Coriander & pepper seeds | LPSSD-Fluidized bed, 90-110°C, 40 kPa, | Both seeds had higher drying rates and lower final moisture content when operating temperature was increased. | Kozanoglu et al. (2006) |
| Basil leaves | LPSSD, 50-70°C | The original aroma profile of basil was retained more. | Barbieri et al. (2004) |
| Edible Chitosan film | | | |
| Enriched with gooseberry extract | LPSSD, 70-90°C, 10 kPa | LPSSD at 70°C resulted in films with less intermolecular interaction, higher degree of swelling and release of TPC. | Mayachiew and Devahastin (2010) |
| Enriched with galangal extract | LPSSD 70-90°C, 10 kPa | Ambient as well as hot air drying resulted in films with higher antimicrobial activity and higher degree of swelling compared to LPSSD. LPSSD performed better as compared to vacuum drying under similar conditions. | Mayachiew et al. (2010) |

LPSSD: Low pressure superheated steam drying; SHS: Superheated steam

**Table 4** Mathematical modelling of superheated steam based processes

| Product | Model type | Objective | References |
|---|---|---|---|
| Parsley | Fixed bed drying model | To analyze the influence of different process variables [bed height, 2 cm and 10 cm), operating pressure 0.07-0.17 kgf/cm$^2$), steam velocity (5-12 m/s) and temperature (70-100°C)] on moisture content of material. | Martinello et al. (2003) |
| Pork | Semi-empirical model based on mass and energy balance | For estimating the effective diffusion coefficient ($D_{eff}$) value and predicting the evolution of the moisture content and the center temperature of sliced pork. | Saadchom et al. (2011) |
| Paneer | Artificial neural network model | Drying characteristics of 1 cm$^3$ paneer dried using low pressure superheated steam. | Shrivatsav and Kumbhar (2010) |
| Paddy | Fluidized bed drying model based on mass and energy balance | To predict moisture content and temperature of paddy. | Taechapairoj et al. (2006) |
| Shrimps, banana, apple, potato and cassava | Based on a theoretical drying mechanism | To calculate the drying rate of foodstuffs being dried with low pressure superheated steam was developed. | Elustondo et al. (2001) |
| Model system | Linear equation | To show that the relationship between maximum drying rate and pressure can be established through a linear equation. | Elustondo et al. (2002) |
| - | CFD model solving heat, mass and momentum balance equation | To conceive and analyze superheated steam spray dryer. | Ducept et al. (2002) |
| Carrot | Three dimensional liquid diffusion based model | To predict the evolutions of the moisture content and temperature of a product undergoing low pressure superheated steam. | Suvarnakuta et al. (2007) |

CFD: Computational fluid dynamics

**Table 5** Ascorbic acid retention of banana chips dried by intermittent temperature and pressure (from Thomkapanich et al., 2007)

| Drying method | Temp. (°C) | Intermittent temperature drying | | Intermittent pressure drying | |
|---|---|---|---|---|---|
| | | Intermittency (on:off, min) | Ascorbic acid retention (%) | Intermittency (on:off, min) | Ascorbic acid retention (%) |
| LPSSD | 70 | Continuous drying | N/A* | Continuous drying | N/A |
| | | 10:5 | N/A | 5:0 | N/A |
| | | 10:10 | N/A | 5:5 | N/A |
| | | 10:20 | N/A | 5:10 | N/A |
| | 80 | Continuous drying | 53.14 ± 2.79 | Continuous drying | 53.14 ± 2.79 |
| | | 10:5 | 62.09 ± 1.94 | 5:0 | 47.74 ± 2.21 |
| | | 10:10 | 65.09 ± 2.07 | 5:5 | 41.60 ± 2.62 |
| | | 10:20 | 63.99 ± 0.52 | 5:10 | 30.05 ± 2.42 |
| | 90 | Continuous drying | 41.33 ± 2.76 | Continuous drying | 41.33 ± 2.76 |
| | | 10:5 | 52.78 ± 2.40 | 5:0 | 37.04 ± 1.70 |
| | | 10:10 | 64.46 ± 4.39 | 5:5 | 31.20 ± 3.17 |
| | | 10:20 | 55.78 ± 2.55 | 5:10 | 25.76 ± 1.89 |
| Vacuum | 70 | Continuous drying | N/A | Continuous drying | N/A |
| | | 10:5 | N/A | 5:0 | N/A |
| | | 10:10 | N/A | 5:5 | N/A |
| | | 10:20 | N/A | 5:10 | N/A |
| | 80 | Continuous drying | 40.75 ± 2.73 | Continuous drying | 40.75 ± 2.73 |
| | | 10:5 | 44.63 ± 3.73 | 5:0 | 37.78 ± 0.41 |
| | | 10:10 | 44.94 ± 2.47 | 5:5 | 31.67 ± 0.89 |
| | | 10:20 | 55.37 ± 2.73 | 5:10 | 29.14 ± 2.53 |
| | 90 | Continuous drying | 37.76 ± 2.63 | Continuous drying | 37.76 ± 2.63 |
| | | 10:5 | 44.10 ± 0.80 | 5:0 | 33.20 ± 1.42 |
| | | 10:10 | 54.04 ± 1.53 | 5:5 | 30.47 ± 2.14 |
| | | 10:20 | 58.35 ± 3.01 | 5:10 | 21.82 ± 1.82 |

N/A* - Final moisture content was not achieved; LPSSD: Low pressure superheated steam drying

**Table 6** Comparison of textural properties of fresh and rehydrated paneer (from Shrivastav and Kumbhar, 2010)

| Properties | 1 $cm^3$ paneer | | 1.5 $cm^3$ paneer | |
|---|---|---|---|---|
| | Fresh | Rehydrated | Fresh | Rehydrated |
| Hardness, g | 168.2 | 203.0 to 392.5 | 157.9 | 177.9 to 213.5 |
| Adhesiveness, g/s | –2.919 | –0.360 to –1.901 | –4.405 | –2.32 to –3.01 |
| Springiness, mm | 0.851 | 0.751 to 0.816 | 0.768 | 0.734 to 0.752 |
| Cohesiveness | 0.658 | 0.609 to 0.642 | 0.576 | 0.472 to 0.521 |
| Gumminess | 110.780 | 130.4 to 241.9 | 91.507 | 72.2 to 99.9 |
| Chewiness | 94.372 | 106.3 to 189.5 | 53.195 | 57.4 to 79.5 |
| Resilience (n = 3) | 0.248 | 0.73 to 0.214 | 0.194 | 0.118 to 0.152 |

**Table 7** Percent reduction of *Geobacillus stearothermophilus* spores processed with superheated steam (SHS) at different temperatures compared with results from Protocol A or B at 3 $\log_{10}$ CFU $g^{-1}$ and at 6 $\log_{10}$ CFU $g^{-}1$ (from Head et al., 2008).

| SHS temperature(°C) | Protocol A | Continuous SHS 10 min | Protocol B | Continuous SHS 15 min |
|---|---|---|---|---|
| a) 3 log10 CFU $g^{-1}$ | | | | |
| 105 | 94.7 ± 1.9 | 94.9 ± 0.3 | 98.4±0.4 | 96.4 ± 0.9 |
| 130 | 88.5 ± 1.3 | 82.0 ± 3.8 | 92.9±1.4 | 87.3 ± 0.7 |
| 145 | 85.9 ± 0.3 | 76.7 ± 3.6 | 93.7±0.1 | 83.7 ± 3.3 |
| b) 6 log10 CFU $g^{-1}$ | | | | |
| 105 | 77.9 ± 0.9 | 64.1 ± 4.4 | 80.9±1.3 | 60.5 ± 1.9 |
| 130 | 84.0 ± 3.8 | 70.3 ± 2.9 | 89.0±1.7 | 65.5 ± 4.4 |
| 145 | 84.9 ± 0.8 | 44.4 ± 20.3 | 95.6±1.3 | 71.2 ± 2.2 |

Protocol A: 2 exposures to SHS for 5 min with cooling for 15 min in between

Protocol B: 3 exposures to SHS for 5 min with cooling for 15 min in between

**Table 8** Literature reports on superheated steam based processes for decontamination and microbial load reduction, parboiling and enzyme inactivation

| Product | Processing conditions | Remarks | References |
|---|---|---|---|
| Decontamination and microbial load reduction | | | |
| Wheat | SHS, 110-185°C, 0.65-1.5 m/s | Significant reduction in DON levels were seen at 160 and 185ºC which were not seen at 110 and 135ºC and the effect of velocity was not significant. | Pronyk et al. (2006) |
| Grains | SHS, 110-185°C, 0.65-1.5 m/s | Reductions in DON concentration up to 52% at 185°C. | Cenkowski et al. (2007) |
| Poultry skin | SHS, 400-450°C | More bacterial inactivation efficient than saturated steam leading to an average reduction of more than 5 $\log_{10}$cfu/cm$^2$. | Kondjoyan and Portanguen, (2008) |
| Fish meal | SHS | The D-values for spores of the thermophile *G. stearothermophilus* were lower compared to hot air processing. | Nygaard and Hostmark, (2008) |
| *G.stearotherm-ophilus* | SHS, 105-175°C | Effective for reduction in viability of thermally resistant bacterial spores possible, if treatments are separated by intermittent cooling periods or very high superheated steam temperatures (160-175ºC). | Head et al. (2008) |
| Parboiling | | | |
| Paddy | 120-160°C, bed depth (8-12 cm) | Head rice yield of paddy was higher than that dried by hot air. But the values of whiteness were lower. | Soponronnarit et al. (2006) |
| Brown rice | SHS+WMD | Japonica rice processed using SHS+WMD at 115°C did not differ significantly from superheated steam processing. At 125°C rice higher length to width ratio. | Hebbar et al. (2008). |
| Enzyme inactivation | | | |
| Brown rice | SHS, 125–300°C | At low temperature and for a short time processing was sufficient to inactivate the enzyme without changing starch quality. | Satou et al. (2010) |
| Oat groats | SHS, 120°C | Processing for 7.5 min was sufficient to inactivate peroxidase. | Pronyk et al. (2005) |
| | SHS, 110°C | A lower amount of hexanal was released as compared to that of processed commercially. | Head et al. (2010) |
| Potato | SHS+WMD, 115ºC | SHS+WMD reduced the blanching time for fruit and vegetables. | Sotome et al. (2009) |

SHS: Superheated steam, WMD: Water micro droplets; DON: Deoxynivalenol

**Table 9** Changes in colour of potato samples caused by the heating processes (from Sotome et al., 2009)

| Heating time(min) | Heating media | L* | a* | b* |
|---|---|---|---|---|
| 0 | - | 73.36±1.17 | -2.46±0.09 | 22.63±0.41 |
| | SHS+WMD[#] | 61.82±0.94 | -5.22±0.12 | 13.61±0.43 |
| 11 | SHS[*] | 61.86±1.24 | -5.40±0.11 | 12.32±0.94 |
| | Hot water | 55.08±0.71 | -5.07±0.06 | 11.37±0.45 |
| | SHS+WMD | 63.67±0.54 | -5.82±0.06 | 11.04±0.25 |
| 16 | SHS | 63.56±0.65 | -4.54±1.11 | 11.60±0.65 |
| | Hot water | 55.66±0.56 | -5.52±0.20 | 9.72±0.64 |

*SHS – Superheated steam

#WMD-Water micro droplets

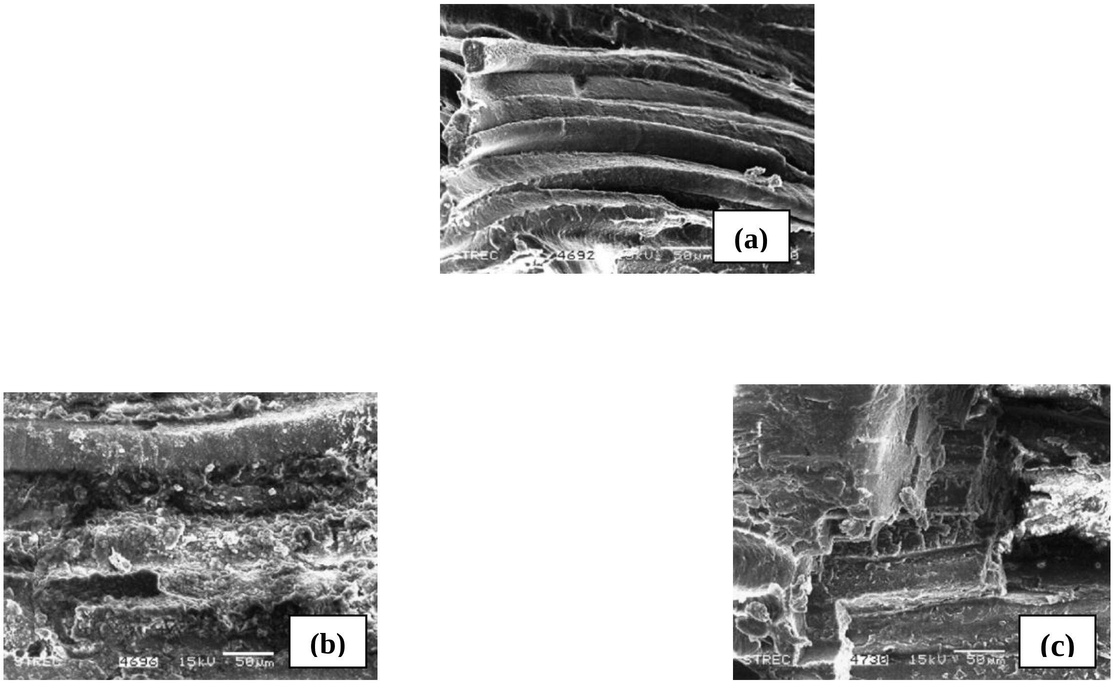


**Figure 1** SEM images of longitudinal section of chicken dried by (a) SS at 120°C, (b) SSD-AD at 120ºC & 55ºC and (c) SSD-HP at 160ºC & 55ºC (from Nathakaranakule et al., 2007).

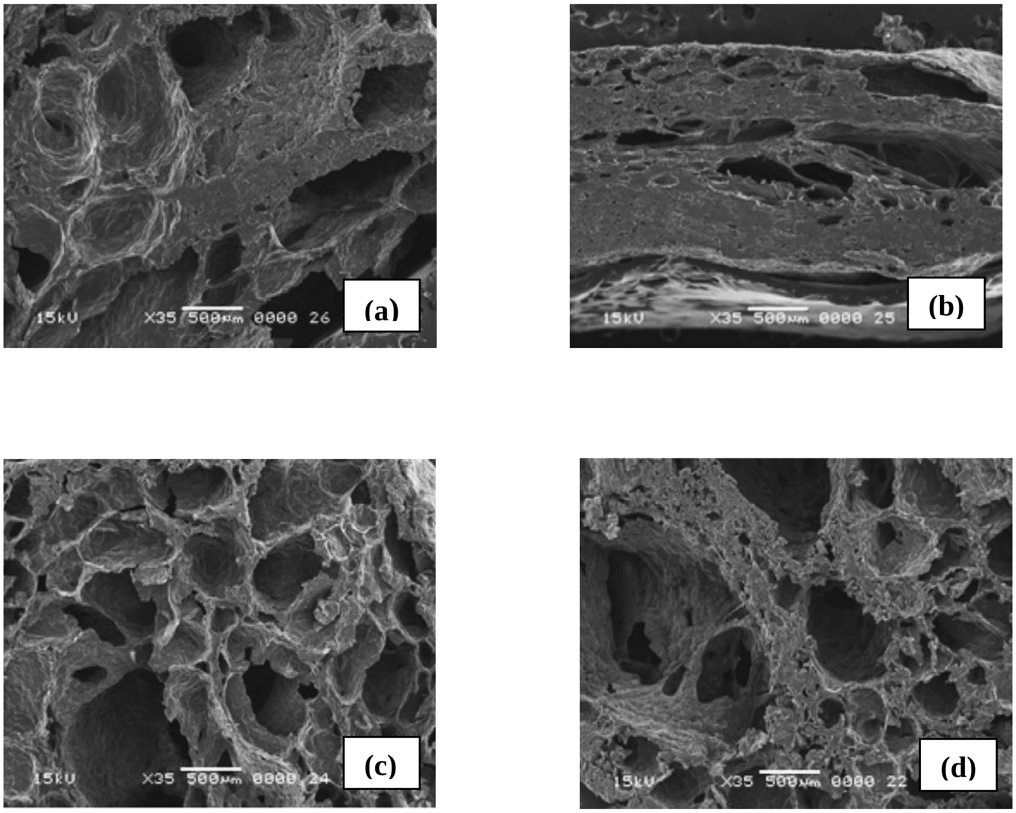


**Figure 2** SEM images showing cross section of banana slices dried by (a) LPSSD-FIR at 80°C, (b) Vacuum-FIR at 80°C, (c) LPSSD-FIR at 90°C and (d) Vacuum-FIR at 90°C (from Nimmol et al., 2007).

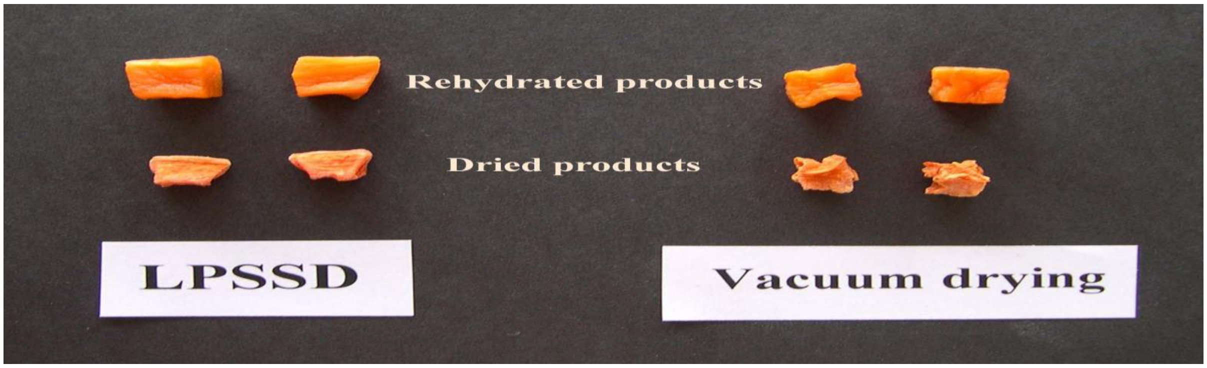


**Figure 3** Photographs of carrot cubes dried by LPSSD and vacuum drying (from Devahastin et al., 2004).

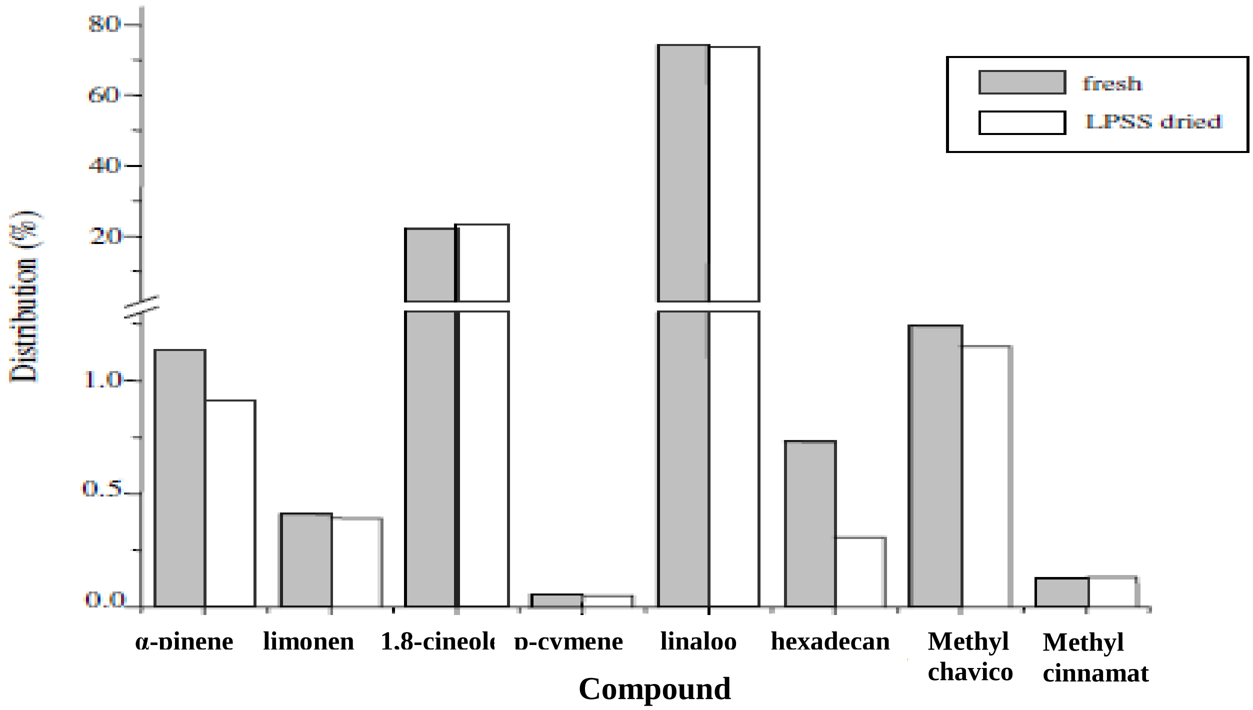


**Figure 4** Composition profile of fresh and LPSSD dried samples (from Barbieri et al., 2004).

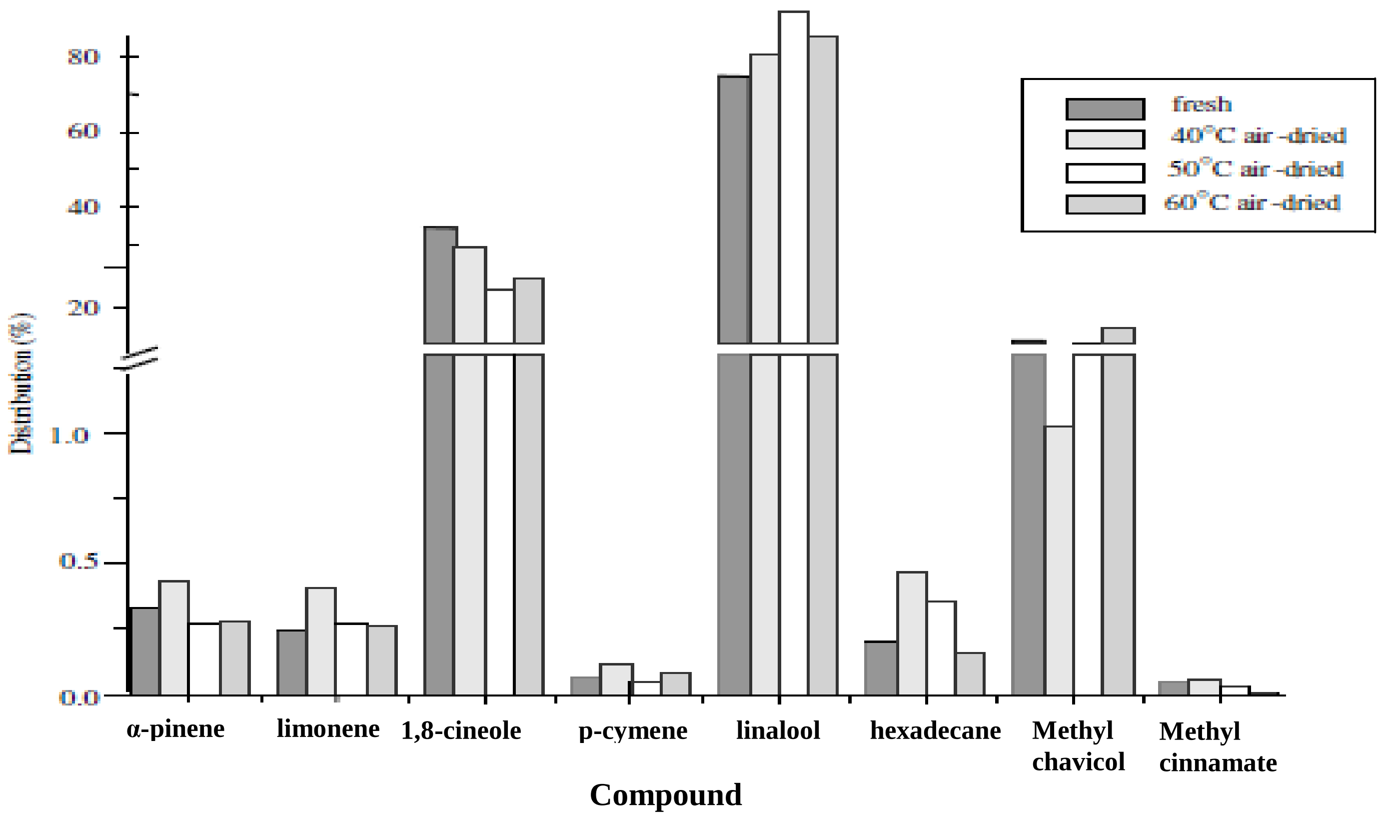


**Figure 5** Composition profile of fresh and air dried samples (from Barbieri et al., 2004).

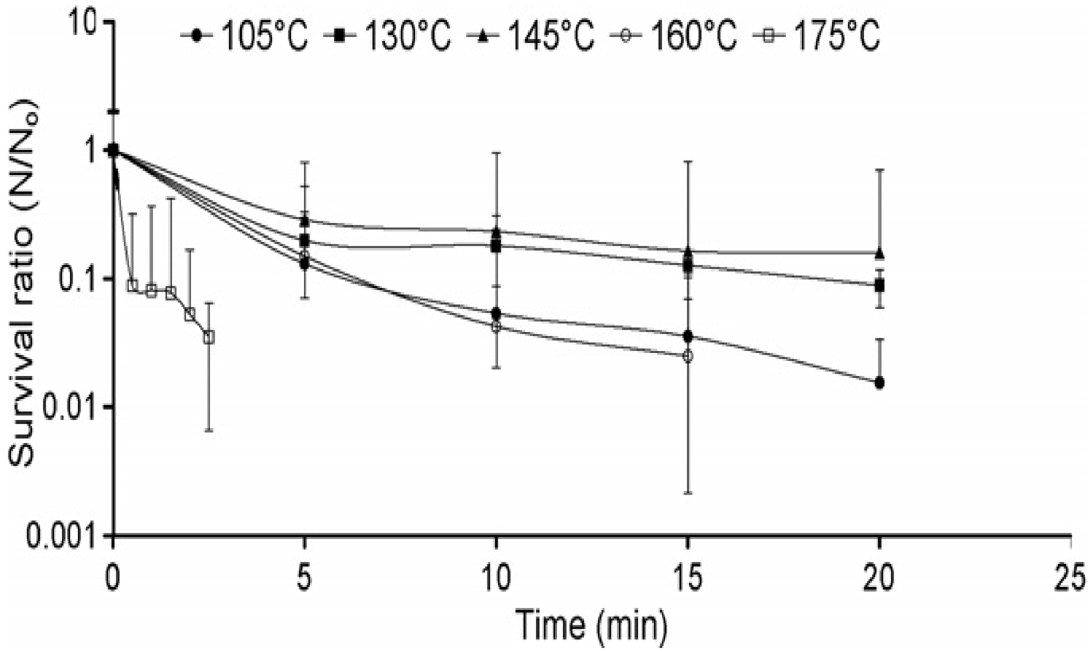


**Figure 6** Survivor curve for G. *stearothermophilus* spores (initial inoculation of $10^3$ cfu/g) processed with superheated steam at different temperatures. Symbols represent means of three trials. Vertical bars represent standard deviations of the means (from Cenkowski et al., 2007).


**Figure 7** SEM images of cross section of rice starch dried by (a) hot air and (b) superheated steam (from Soponronnarit et al., 2006).