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REVIEW ARTICLE

Recent advances in drying and dehydration of fruits and vegetables: a review

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Abstract Fruits and vegetables are dried to enhance storage stability, minimize packaging requirement and reduce transport weight. Preservation of fruits and vegetables through drying based on sun and solar drying techniques which cause poor quality and product contamination. Energy consumption and quality of dried products are critical parameters in the selection of drying process. An optimum drying system for the preparation of quality dehydrated products is cost effective as it shortens the drying time and cause minimum damage to the product. To reduce the energy utilization and operational cost new dimensions came up in drying techniques. Among the technologies osmotic dehydration, vacuum drying, freeze drying, superheated steam drying, heat pump drying and spray drying have great scope for the production of quality dried products and powders.

Keywords Superheated steam drying · Heat pump drying · Fruits and vegetable dehydration · Freeze drying · Spray drying · Pulsed electric field

Introduction

Fruits and vegetables are important sources of essential dietary nutrients such as vitamins, minerals and fibre. Since the moisture content of fresh fruits and vegetables is more than 80%, they are classified as highly perishable commodities (Orsat et al. 2006). Keeping the product fresh is the best way to maintain its nutritional value, but most storage techniques require low temperatures, which are difficult to maintain throughout the distribution chain. On the other hand, drying is a suitable alternative for post harvest management especially in countries like India where exist poorly established low temperature distribution and handling facilities. It is noted that over 20% of the world perishable crops are dried to increase shelf-life and promote food security (Grabowski et al. 2003). Fruits, vegetables and their products are dried to enhance storage stability, minimise packaging requirements and reduce transport weight. Nonetheless, in India hardly any portion of perishables are dried which leads to enormous loss in terms of money and labour besides steep rise in prices of commodities during the off season.

The preservation of fruits and vegetables through drying dates back many centuries and is based on sun and solar drying techniques. The poor quality and product contamination lead to the development of alternate drying technologies (Bezyma and Kutovoy 2005). The most applicable method of drying includes freeze, vacuum, osmotic, cabinet or tray, fluidized bed, spouted bed, Ohmic, micro wave and combination thereof (George et al. 2004). Except for freeze drying, applying heat during drying through conduction, convection and radiation are the basic techniques used to force water to vapourise, while forced air is applied to encourage the removal of vapour. A large number of food and biomaterials are dehydrated in a variety of units with diverse processing conditions. The choice of drying method depends on various factors such as the type of product, availability of dryer, cost of dehydration and final quality of desiccated product. Energy consumption and quality of dried products are other critical parameters in the selection of a drying process. To reduce the use of fossil fuel, electrical energy is an alternate source of energy for drying applications especially where electricity is generated by a renewable energy source such as hydro power or wind power (Raghavan and Orsat 1998, Raghavan et al. 2005). Keeping these in view, the present review is focussing on recent developments in drying and dehydration and future scope for better drying.

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Drying of fruits and vegetables

Drying of fruits and vegetables has been principally accomplished by convective drying (Nijhuis et al. 1998). There are a number of studies that have addressed the problems associated with conventional convective drying. Some important physical properties of the products have changed such as loss of colour (Chua et al. 2000), change of texture, chemical changes affecting flavour and nutrients and shrinkage (Mayor and Sereno 2004). Besides, convective drying gives little scope for prior rehydration to further processing after drying for a minimal quality (Khraisheh et al. 2004). The high temperature of the drying process is an important cause for loss of quality. Lowering the process temperature has great potential for improving the quality of dried products (Nindo et al. 2003, Beaudry et al. 2004). However in such conditions, the operating time and the associated cost become unacceptable. To reduce the operational cost different pre-treatments and new method of low temperature and low energy drying methods are evolved. A brief review of recent development (past 15 years) will be discussed in the following sections.

Osmotic dehydration (OD)

Osmosis is known as a partial dehydration process. Although it does not remove enough moisture to be considered as a dried product, the process has the advantage of requiring little energy. It works well as a pre-treatment prior to drying by other methods. The application of OD to fruits and to a lesser extent to vegetables, has received attention in recent years as a technique for production of intermediate moisture foods or as a pre-treatment prior to drying in order to reduce energy consumption or heat damage (Jayaraman and Gupta 1992).

Some aspects of osmotically dehydrated fruits have been reviewed by various workers with reference to osmotic agents and their concentration (Bolin et al. 1983), temperature (Le Maguer 1998), sample to solution ratio (Conwoy et al. 1983), agitation of fruit in syrup (Hawkes and Flink 1978), sample size and shapes (Islam and Flink 1982, Lerici et al. 1985), osmotic agents (Lenart and Flink 1984), material type (Talens et al. 2000), pre-treatment (Fito et al. 2001), size and shape (Lerici et al. 1985), temperature and concentration (Lazarides et al. 1995, Sagar and Kumar 2007), dehydration method and physico-chemical changes (Conwoy el aI 1983, Lenart and Flink 1984, Le Maguer 1998, Kumar et al. 2006).

Nsonzi and Ramaswamy (1998) modelled the mass transfer process with respect to moisture loss and solids gain. They stated that even though the moisture loss and solids gain occurred at the same time, the rate of moisture loss was much higher than the rate of solids gain. The advantage of OD is its lower energy use and lower product thermal damage since lower temperatures used allow the retention of nutrients (Shi et al. 1997). Lenart (1996) described the main advantages of using OD as the reduction of process temperature, sweeter taste of dehydrated product, reduction of 20–30% energy consumption and shorter drying time. Sagar and Kumar (2007) in OD of guava slices found that higher sugar concentration (60^0B) and temperature (60°C) increase the water loss from the produce and solid gain into the osmosed guava slices.

The driving force for the diffusion of water from the tissue into the solution is provided by higher osmotic pressure of hypertonic solution. The rate of mass transfer during OD is generally low. Techniques to improve mass transfer are partial vacuum (Rastogi and Raghava Rao 2004), ultra high hydrostatic pressure (Rastogi and Niranjan 2008), high intensity electrical field pulses (Rastogi et al. 1999), super critical CO_2 treatment (Tedjo et al. 2002) and prior to OD processing and using centrifugal force (Azura et al. 1996).

Vacuum

The reduction in pressure causes the expansion and escape of gas occluded into pores. When the pressure is restored, the pores can be occupied by the osmotic solution, increasing the available mass transfer surface area. The effect of vacuum application during OD is explained on the basis of osmotic transport parameter, the mass transfer co-efficient and the interfacial area (Rastogi and Raghava Rao 2004). Vacuum pressure (50-100 mbar) is applied to the system for shorter time to achieve the desired result.

High hydrostatic pressure

It is observed that application of high hydrostatic pressure damages the cell wall structure which leads to significant changes in the tissue architecture, leaving the cells more permeable, resulting in increased mass transfer rates during OD (Rastogi and Niranjan 2008).

Pulsed electric field (PEF)

The PEF treatment has been reported to increase the permeability of plant cells. PEF treatment-induced cell damage, resulted in tissue softening, which in turn resulted in a loss of turgor pressure, leading to a reduction in compressive strength. The increase in permeability of potato (Azura et al. 1996) and carrot (Rastogi et al. 1999) tissues by PEF treatment resulted in improved mass transfer during OD. The effective diffusion coefficients of water and solute increased exponentially with electric field strength. The increase in effective diffusion coefficient can also be attributed to an increase in cell wall permeability, which facilitated the transport of water and solute. Taiwo et al. (2002) studied the effect of PEF and other pre-treatments on OD of apple slices. It was concluded that PEF treatment increased water loss, which was attributed to increased cell membrane permeability. The effect of PEF treatment on solid gain was minimal. Lai and Sharma (2005) reported that PEF pre-treatment (number of pulses 100, pulse width 840 µs, field strength 2.67 kV/cm, 1 Hz; specific energy input 3.58 kJ/kg) resulted in higher moisture loss and solid gain in mangoes during subsequent OD. Ade-Omowaye et al. (2003) compared the quality characteristics of PEF-pre treated and osmotically-treated red paprika with osmotic treatment at higher temperature. The retention of ascorbic acid and carotenoids was higher for PEF pre-treated and osmotically-treated paprika. Drying time of PEF-pre treated paprika was reduced by 25%. Taiwo et al. (2003) studied the influence of high intensity electric field pulses and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. Rehydration rate increased with temperature but higher rehydration capacity values were obtained at low temperatures (24°C and 45°C).

Super critical CO_2

This emerged as an attractive unit operation for the processing of food and biological material. The critical point of CO_2 gas is at 304.17 K and 7.38 MPa (Tedjo et al. 2002). The combination of pressure and temperature as process parameters makes it possible to vary the solvent of the medium within certain ranges as desired without having to change the composition of solvent. This treatment will not improve the water loss but favour solid gain.

Ultrasound

Acoustic streaming can affect the thickness of boundary layer which exists between stirred fluid and solid. Cavitation, a phenomenon produced by the sonication, consists of the formation of bubbles in the liquid which can collapse and generate localised pressure fluctuation. This ultimately increases the mass transfer of osmotic treatment. The rate of transfer depends on pressure and frequency of the wave produced by sonication (Raghavan et al. 2005).

Centrifugal force

Azura et al. (1996) applied a centrifugal force (64 g) during OD and obtained enhanced mass transfer of 15%. But prior work in variables like solvent, solute, plant tissue, permeability of tissue, mass transfer rate and solid gain are necessary to make the unit operation more successful.

Microwave heating

Microwave technology uses electromagnetic waves that pass through material and cause its molecules to oscillate generating heat. Microwave heating generates heat within the material and heats the entire volume at about the same rate. Microwave technology can be combined with conventional heating and drying units and is easily automated. The overall ratio of moisture loss to solid gain was higher in microwave assisted OD than in conventional OD (Xian-Ju et al. 2007).

Heat pump drying

The use of heat pumps for drying has been studied since the early 1950s; though the idea was mechanically feasible, it was not economically attractive due to the low fuel prices prevailing at that time. But the high fuel costs of the early 1970s revived the interest in use of heat pumps for drying due to the deemed energy savings. Conventional dryers would heat the air by using high quality energy (such as electricity or fuels) and vent a stream of moist, hot air at the exhaust, which represented a significant quantity of low-grade energy being lost from the process. In order to reduce this loss, heat pumps were introduced to the systems to recover the latent heat of evaporation of water lost in the exhaust from the dryer. By placing the evaporator of a heat pump in the exhaust stream , the air leaving the dryer is cooled (thereby recovering the sensible heat component) and then dehumidified (to recover the latent heat) by the refrigerant. The heat thus added to the refrigerant is then rejected at the condenser of the heat pump to the stream of air entering the dryer, thus raising its temperature. When the air leaving the dryer is recirculated, the added benefit of dehumidification of the drying air is also realised, increasing its potential to achieve better drying.

Hogan et al. (1983) studied heat pump assisted grain drying and concluded that the systems were useful due to their lower energy consumption in comparison with electrically heated units. Essentially, heat pumps were used to reduce the energy consumption of dryers and it is now universally agreed that heat pump dehumidifier (HPD) assisted drying systems do have energy savings (Queiroz et al. 2004, Seco et al. 2004). One of the main advantages of HPD drying is the retention of quality and its successful application to drying highly valued heat sensitive materials.

Kohayakawa et al. (2004) describe a study in which mango slices were dried in a HPD dryer and the energy consumption of this system was compared with a hypothetical electrically heated dryer. It is reported that the HPD dryer has an advantage of 22 to 40% reduction in the power consumption. Hawlader et al. (2006) dried apple, guava and potato pieces in a HPD dryer using nitrogen and carbon dioxide to replace air. The evacuation during drying seemed to benefit the final colour of the products, which showed lesser browning. Besides, the porosity and rehydration characteristics of the product were superior compared with material dried under vacuum. Gabas et al. (2004) studied drying of apple cylinders in a heat pump dryer and compared it with products obtained from an electrically heated dryer. The HP dryer used 40% less energy compared with the electrical heater and at a faster rate of drying. Alves-Filho et al. (2004) dried green peas in a fluidised bed heat pump dryer under atmospheric freeze-drying conditions and obtained products with high levels of rehydration ability, floatability and desirable colour characteristics. Uddin et al. (2004) compared heat pump drying with microwave and freeze drying of guava, mango and honeydew melon.

They suggested that microwave application be coupled with heat pump drying for better results such as faster drying rate, lower shrinkage, and better appearance of the product and low cost of the process.

Microwave drying

Microwave drying uses electrical energy in the frequency range of 300 MHz to 300 GHz, with 2,450 MHz being the most commonly used frequency. Microwaves are generated inside an oven by stepping up the alternating current from domestic power lines at a frequency of 60 Hz up to 2,450 MHz. A device called the magnetron accomplishes this (Orsat et al. 2005). The use of microwave energy for drying has been demonstrated to have a moderately low energy consumption (Tulasidas et al. 1995a). The volumetric heating and reduced processing time make microwaves an attractive source of thermal energy. Since microwaves alone cannot complete a drying process, it is recommended to combine techniques, such as forced air or vacuum, in order to further improve the efficiency of the microwave process (Chou and Chua 2001).

When the material couples with microwave energy, heat is generated within the product through molecular excitation. The critical next step is to immediately remove the water vapour. A simple technique for removing water is to pass air over the surface of the material hence combining processes to form what is called "microwave convective drying". The air temperature passing through the product can be varied to shorten the drying time. In order to control the product's temperature, either power density (Watts/g of material) or duty cycle (time of power on/off) must be controlled (Changrue et al. 2004). It is mainly in the falling rate period that the use of microwaves can prove most beneficial. As the material absorbs the microwave energy, a temperature gradient occurs where the centre temperature is greater, forcing the moisture out (Erle 2005). It is clear that the drying takes place in the falling rate period (Soysal et al. 2006). The dielectric loss factor of a material is a measure of the ability of material to dissipate electric energy. It is important to realise that dielectric properties are specific only for a given frequency and materials' properties. The dielectric properties change as a function of temperature and moisture, hence the uniformity of moisture and drying temperature govern the uniformity of the drying process (Meda and Raghavan 2004).

Use of microwave energy in drying offers reduced drying times and complements conventional drying in later stages by specifically targeting the internal residual moisture (Osepchuk 2002). The drying of banana slices with microwave demonstrated that good quality dried products can be achieved by varying power density and duty cycle time. In dried carrots, quality improvement was found in colour, shrinkage and rehydration property (Wang and Xi 2005). The quality of raisins dried by microwave was superior to hot air dried samples in colour, damage, darkness, crystallised sugar, stickiness and uniformity (Tulasidas et al. 1995b).

Superheated steam drying

Drying with superheated steam (SS) in the absence of air in a medium composed entirely of steam. The ability of SS to dry food material is due to the addition of sensible heat to raise its temperature above the corresponding saturation temperature at a given pressure. It is not necessary to exhaust the evaporated water from the produce until the pressure develops beyond certain limit. After that excess steam will be released. The great advantage is that recycling of drying method is possible, provided additional sensible heat is added. Besides, any conventional convection and conduction dryer could be easily converted to use superheated steam (Tatemoto et al. 2007). Fixed bed, fluidized bed, flash, impingement, pneumatic and spray dryers are using superheated steam technology for quality drying of produces.

SS fluidized drying

Trials indicate that SS drying could be effectively used for many products like corn starch, potato starch and for making other by products. However, particles that are too large or fine produces are impossible to dry in a fluidised bed. The model was developed based on diffusivity theory and uses a number of assumptions. Among them are: i) condensation of water vapour on samples occurs below the boiling point of water, ii) all of the heat transferred into the sample surface is used for evaporation when the sample temperature is equal to the boiling point, iii) boiling point of water changes the pressure in the local point of sample, iv) overall heat transfer coefficient on the sample surface includes thermal radiation from the drying medium and v) drying process is complete when the temperature of sample is higher than the boiling point of water (Tatemoto et al. 2007).

Impingement drying with SS

Though it is mainly used in paper industries, in the food industry, air impingement is used for baking and cooking of products such as potato chips, pizza, cookies and flat breads (Rahman and Labuza 1999). Low fat potato chips can be prepared by this method. SS processed potato chips retained more vitamin C and were better in texture than air dried samples. It is observed that mass transfer was following Ficks law of diffusion and heat transfer within potato was considered to follow Fouriers law of conduction (Leeratamark et al. 2006). However, attention should be given to the effect of SS impingement drying on product quality including shrinkage, crispness and microstructure.

SS flash drying

Food products sensitive to high temperature have a high potential to be processed with SS flash drying when processing is under vacuum. Pneumatic or flash drying is a process in which the transported gas changes into SS. It is mainly used to dry organic compounds like lignite, bark, peat and pulp (Okos et al. 1992).

Freeze drying

Freeze drying of biological materials is one of the best methods of water removal which results in final product of the highest quality. Freeze drying is sublimation of ice fraction where water passes from solid to gaseous state. Due to very low temperature all the deterioration activity and microbiological activity are stopped and provide better quality to the final product. Recently the market for organic products is increasing. Therefore, the use of freeze drying of fruits and vegetables is not only increasing in volume but also diversifying (Brown 1999). Freeze drying seems to be better preservation method over other dehydration methods such as air or drum drying (Hsuch et al. 2003). Nonetheless, freeze drying of small fruits (strawberry) received particular attention by several researchers (Paakkonen and Mattila 1991, Hammami and Rene 1997, Shishegarha et al. 2002). Strawberry dried at 20°C retained better quality than at 60°C. The product mostly collapses i.e. loss in structure, reduction in pore size and shrinkage at higher temperature (Hammami and Rene 1997). Paakkonen and Mattila (1991) have found that low processing temperature improved the sensory quality of dried fruits.

Spray drying (SD)

The SD is a well known industrial technology used extensively on a large scale for drying and powdering heat sensitive materials from liquid foods. The overall objective in SD is to get the most rapid liquid removal with minimal negative impact on the product, without damaging the surrounding environment at the lowest capital and operating costs (Hall 1996). By using heat, SD efficiently transforms a dilute fluid suspension into a dry powder and renders good quality to final powder (Masters 1991). SD process comprises of 4 basic steps (Masters 1991, Filkova and Majumdar 1995): i) atomisation, ii) contact between drop lets and hot gas, iii) water evaporation and iv) gas-powder separation. Uniformity of drop size and homogeneity of spray jet are important considerations in designing nozzle. Pneumatic two-fluid nozzle, pressure nozzle and cone nozzle are most commonly used. Drying through SD may either in single stage, 2 or 3 stages. Pneumatic nozzle type driers mostly worked with single stage drying. Two-stage system comprises of the spray dryer followed by a vibro-fluidized bed system. Three stage processes improve the properties of dried powder by instant reconstitution because the fluid bed works as a dryer-agglomerator, controlling particle agglomeration (Master 2004).

Vacuum drying

Vacuum drying is an important process for heat sensitive materials. The process of vacuum drying can be considered according to physical condition used to add heat and remove water vapour. Low temperature can be used under vacuum for certain methods that might discolour or decompose at high temperature. A comparison of drying technologies in review by Khin et al. (2005) showed that freeze drying, vacuum drying and osmotic dehydration are considered too costly for large scale production of commodity.

Hybrid drying/Combination drying

Hybrid drying techniques are becoming common since the combined technology receives the benefits of individual process. Combination drying systems were tested by Feng et al. (1999). The number of combinations possible is vast and as technology continues to improve more will be developed. Adding a micro wave system to a spouted bed system combines the benefits offered by each technology. The microwave action decreases drying time while the fluidization produce by the spouting system improves drying uniformity, thus reducing the burning. Thermal-vacuum dryer intended for drying agricultural products can be manufactured with cheap and widely used materials such as wood or plastic.

Chou and Chua (2001) reviewed new hybrid drying technologies for heat sensitive food. Donsi et al. (1998) showed the combination of hot air drying and freeze drying increased the quality of dehydrated fruits and vegetables. Kumar et al. (2001) showed the combination process produced dehydrated carrot and pumpkin having similar quality as freeze dried products. The drying time and total energy consumption was favourably 50% lower than freeze drying alone.

High initial cost, loss of aroma, degradation of texture are some of the disadvantages of microwave drying. Combination drying with an initial conventional drying process followed by a finish microwave or microwave vacuum process has proven to reduce drying time while improving product quality and minimising energy requirements (Erle 2005, Soysal et al. 2006).

Microwave convection and microwave vacuum drying

Since the boiling point of water gets reduced at lower pressures, vacuum can be applied to microwave drying to improve product quality. There have been numerous studies on the application of vacuum to microwave drying. Drouzas and Schubert (1996) investigated vacuum-microwave drying of banana slices. The product quality in terms of taste, aroma, and rehydration was found to be excellent. Tein et al. (1998) compared dried carrot slices using vacuum/microwave drying with air and freeze drying. Microwave vacuum dried carrot slices had higher rehydration potential, higher β-carotene and vitamin C content, lower density and softer texture than those prepared by air drying. Similar results were reported by Regier et al. (2005), where microwave vacuum dried carrots had the highest carotenoid retention compared with freeze drying and convection drying.

Combined process consisting of an initial air drying step followed by a microwave-vacuum process for producing dried fruits and vegetables of high value. Pre drying to a moisture content of 25–40% wet weight basis (wwb) is carried out in a microwave-vacuum dryer. Dehydration to a final moisture content of 4–6% (wwb) can be executed in continuous air-band dryer or in a moving tray dryer to boost the capacity of microwave-vacuum dryer (Beaudry et al. 2003). Pulsed-microwave-vacuum drying is suitable for temperature sensitive produces (Gunasekaran 1998).

A comparative study was conducted by Cui et al. (2003) for garlic drying. Best quality dried garlic was obtained with freeze drying and microwave vacuum drying as a close second while there was a great loss in garlic pungency with the hot air dried samples. Sharma and Prasad (2006) came to similar conclusion while comparing hot air drying with microwave convective drying of garlic. They obtained a drying time reduction of 80% with superior quality dried garlic by combining microwaves at 0.4 W/g to hot air at 60–70°C.

Microwave osmotic dehydration

There are some food products for which the skin impedes water transport to the surface. In these cases, a pre-treatment is required before osmosis as was described for the pre-treatment of cranberries (Sunjka and Raghavan 2004). Beaudry et al. (2004) studied the effect of microwave convective (0.7W/g and 62°C), hot air (62°C), freeze and vacuum drying (94.6 kPa) methods on the quality of osmotically dehydrated cranberries. With all drying methods, they reported that the constant drying rate period is no longer present following osmotic dehydration. This effect was also reported by Piotrowski et al. (2004) with strawberries. The fastest drying method was microwave convective, and the longest was for hot air drying at 62°C. Venkatachalapathy and Raghavan (1999) reported that combined osmotic microwave dried strawberry was close to that of freeze-dried product in terms of rehydration characteristics and overall sensory evaluation.

Quality attributes and classification

There are several changes taking place in quality parameters during drying and storage. The extent of changes depends on the care taken in preparing the material before dehydration and on the process used. Major quality parameters associated with dried food products include colour, visual appeal, shape of product, flavour, microbial load, retention of nutrients, porosity-bulk density, texture, rehydration properties, water activity, freedom from pests, insects and other contaminants, preservatives, and freedom from taints and off-odours (Ratti 2005). The state of the product, such as glassy, crystalline or rubbery, is also important. These quality parameters can be classified into 4 major groups: i) physical, ii) chemical, iii) microbial and iv) nutritional. Greater stability and quality can be achieved by maintaining the fresh or optimum conditions of the raw materials (Perera 2005).

Physical quality

Physical changes, such as structure, case hardening, collapse, pore formation, cracking, rehydration, caking and stickiness can influence the quality of final dried products. Hot air drying usually destroys the cell structure and thereby takes more time for dehydration while due to solid state of water during freeze drying protects primary structure and shape of products keeping the cells almost intact, with a high porosity end products (Saguy et al. 2004). Pretreatments given to foods before drying or optimal drying conditions are used to create a more porous structure so as to facilitate better mass transfer rates. Maintaining moisture gradient levels in the solid, which is a function of drying rate, can reduce the extent of crust formation; the faster the drying rate, the thinner the crust (Achanta and Okos 1996). Depending on the end use, hard crust and pore formation may be desirable or undesirable. Rahman (2001) has outlined the current knowledge on the mechanism of pore formation in foods during drying and related processes. The glass transition theory is one of the concepts proposed to explain the process of shrinkage and collapse during drying and other related processes. According to this concept, there is negligible collapse (more pores) in a material when it is processed below the glass transition. The higher the process temperature above the glass transition temperature (Tg), the higher the structural collapse. The methods of freeze and hot air drying can be compared based on this theory. In freeze-drying, since the temperature is below Tg' (maximally freeze concentrated Tg), the material is in the glassy state. Hence shrinkage is negligible. As a result the final product is very porous. In hot air drying, on the other hand, since the temperature of drying is above Tg' or Tg, the material is in the rubbery state and substantial shrinkage occurs. Hence the food produced from hot air drying is dense and shrivelled (Peleg 1996, Sablani and Rahman 2002).

Recent experimental results show that the concept of glass transition may not be valid for freeze-drying of all types of biological materials, indicating the need for incorporation of other concepts such as surface tension, structure, surrounding pressure and mechanisms of moisture transport (Sablani and Rahman 2002, Meda and Ratti 2005). Rahman (2001) hypothesised that since capillary force is the main factor responsible for collapse, then counter balancing this force will cause formation of pores and lower shrinkage. This counterbalancing is due to generation of internal pressure, variation in moisture transport mechanism and surrounding pressure. Another factor could be the strength of the solid matrix (ie, ice formation, case hardening and matrix reinforcement). Quality parameters such as volume, shrinkage, apparent density, colour and rehydration behaviour of carrots dried in SS under vacuum were superior to air vacuum dried carrots. Starch gelatinization in potato slices occurred more rapidly in SS drying than in hot air drying, leading to glossy appearance on the surface. Basil leaves dried in SS under vacuum, rendered a product with a higher retention of the original volatile compounds than conventional air drying (Lovedeep et al. 2002).

Rehydration is the process of moistening a dry material. In most cases, dried foods are soaked in water before cooking or consumption, thus rehydration is one of the important quality criteria. In practice, most of the changes during drying are irreversible and rehydration cannot be considered simply as a process reversible to dehydration (Lewicki 1998). In general, absorption of water is rapid at the beginning. A rapid moisture uptake is due to surface and capillary suction. Rahman and Perera (1999) and Lewicki (1998) reviewed the factors affecting the rehydration process. These factors are porosity, capillaries and cavities near the surface, temperature, trapped air bubbles, amorphous-crystalline state, soluble solids, dryness, anions and pH of the soaking water. Porosity, capillaries and cavities near the surface enhance the rehydration process, whereas the presence of trapped air bubbles give a major obstacle to the invasion of fluid. When the cavities are filled with air, water penetrates to the material through its solid phase. In general, temperature strongly increases water rehydration in the early stages. There is a resistance of crystalline structures to salvation that causes development of swelling stresses in the material, whereas amorphous regions hydrate fast. The presence of anions in water affects the volume increase during water absorption (Sablani 2006b).

Texture of dried products are influenced by their moisture content, composition, pH, and product maturity. The chemical changes associated with textural changes in fruits and vegetables include crystallisation of cellulose, degradation of pectin, and starch gelatinisation. In meat products the changes such as aggregation and denaturation of proteins and a loss of water-holding capacity leads to toughening of muscle tissue. The method of drying and process conditions also influence the texture of dried products. Krokida et al. (2001) studied the quality of apple, banana, potato and carrot with different drying methods such as convective, vacuum, microwave, freeze and osmotic drying. It was found that air, vacuum and microwave dried materials caused extensive browning in fruits and vegetables whereas freeze drying seemed to preserve colour changes, resulting a produce with improved colour characteristics.

Chemical quality

Browning, lipid oxidation, colour loss and change of flavour in foods can occur during drying and storage. Browning reactions can be categorised as enzymatic and non-enzymatic (Salunkhe et al. 1991). Enzymatic browning of foods is undesirable because it develops undesirable colour and produces off flavour. The application of heat, sulphur dioxide or sulphites and acids can help control this problem. The major disadvantage of using these treatments for food products is their adverse destructive effect on vitamin B or thiamine. Acids such as citric, malic, phosphoric and ascorbic are also employed to lower pH thus reducing the rate of enzymatic browning. Dipping in osmotic solution can inhibit enzymatic browning in fruits. This treatment can also reduce the moisture content with osmotic pre-concentration. There are three major types of non enzymatic reaction: (i) Maillard reaction, (ii) caramelisation and (iii) ascorbic acid oxidation (Salunkhe et al. 1991). Factors that can influence non-enzymatic browning are water activity, temperature, pH and the chemical composition of foods. Browning tends to occur primarily at the mid-point of drying period. This may be due to migration of soluble constituents towards the centre. Browning is also more severe near the end of the drying period when the moisture level of the sample is low and less evaporative cooling is taking place.

Rapid drying through 15–20% moisture range can minimise the time for Maillard browning. In carbohydrate foods, browning can be controlled by removing or avoiding amines and conversely, in protein foods, by eliminating the reducing sugars. Sulphur treatment can prevent the initial condensation reaction by forming nonreactive hydroxy-sulphonate sugar derivatives. In caramelisation, heating of sugars produces hydroxy methyl furfural, which polymerises easily. This reaction may be slowed by sulphite, which reacts with sugars to decrease the concentration of the aldehydic form. Discolouration of ascorbic acid containing vegetables can occur due to formation of dehydroascorbic acid and diketogluconic acids from ascorbic acid during the final stages of drying. Sulphur treatment can prevent this browning due to reactivity of bisulphite towards carbonyl groups present in the breakdown products (Kadam et al. 2008).

Fatty foods are prone to develop rancidity at very low moisture content (less than monolayer moisture). Lipid oxidation is responsible for rancidity, development of off-flavours, and the loss of fat-soluble vitamins and pigments in many foods, especially in dehydrated foods. Factors that influence the oxidation rate include moisture content, type of substrate (fatty acid), extent of reaction, oxygen content, temperature, presence of metals or natural antioxidants, enzyme activity, UV light, protein content and free amino acid content. Moisture content plays a big part in the rate of oxidation. Air-dried foods are less susceptible to lipid oxidation than freeze-dried products due to lower porosity (Sablani 2006a).

Microbial quality

Dried food products are considered safe with respect to microbial hazard. There is a critical water activity (a_w) below which no micro organisms can grow. Pathogenic bacteria cannot grow below a_w of 0.85–0.86, whereas yeast and moulds are more tolerant to a reduced water activity of

0.80. Usually no growth occurs below a_w of about 0.62 (Sablani 2006a). Reducing the water activity inhibits microbial growth but does not result in a sterile product. The heat of the drying process does reduce total microbial count, but the survival of food spoilage organisms may give rise to problems in the rehydrated product. The type of microflora present in dried products depends on the characteristics of the products, such as pH, composition, pre-treatments, types of endogenous and contaminated microflora and method of drying. Brining (addition of salts) in combination with drying decreases the microbial load. The dried products should be stored under appropriate conditions to protect them from infection by dust, insects and rodents (Rahman et al. 2000).

Nutritional quality

Fruits, vegetables and their products in the dried form are good sources of energy, minerals and vitamins. However, during the process of dehydration, there are changes in nutritional quality (Sablani 2006a). A more number of vitamins such as A, C and thiamine are heat sensitive and sensitive to oxidative degradation. Sulphuring can destroy thiamine and riboflavin while pre-treatments such as blanching and dipping in sulphite solutions reduce the loss of vitamins during drying. As much as 80% decrease in the carotene content of some vegetables may occur if they are dried without enzyme inactivation. However, if the product is adequately blanched then carotene loss can be reduced to 5% Steam blanching retains higher amounts of vitamin C in spinach compared with hot-water blanching (Ramesh et al. 2001). Blanching in sulphite solution can retain more ascorbic acid in okra (Inyang and Ike 1998). Na-metabisulphite treatment was able to reduce oxidation of carotenoid in carrots and L-cysteine-HCl help in retaining highest amount of ascorbic acid (Mohamad and Hussein 1994). SS fluidized bed processing was used for both drying and inactivation of antinutritional factors trypsin inhibitor and urease in soybean (Piotrowski et al. 2004).

The retention of vitamin C in freeze-dried products is significantly higher than that of oven and sun-dried products. Microwave and vacuum drying methods can also reduce the loss of ascorbic acid due to low levels of oxygen. Microwave, Refractance Window, low pressure superheated steam and vacuum drying can also reduce the loss of vitamins due to a low level of oxygen. Shade drying, in the absence of light, can also be effective for the retention of nutrients (Sablani 2006a).

Sensory properties of dried foods are also important in determining quality. These include colour, aroma, flavour, texture and taste. Aroma and flavour can change due to loss of volatile organic compounds, the most common quality deterioration for dried products. Low temperature drying is used for foods that have high economic value such as flavouring agents, herbs and spices (Salunkhe 1991, Singh et al. 2006). Low temperature drying is important for heat sensitive products. Singh et al. (2006) found that low temperature dryer caused minimal damages to leafy vegetables during drying and thereby retained more nutrients than other dryers. Processing in the absence of oxygen can preserve many components which are sensitive to oxidation (Feng et al. 1999). Microwave drying can reduce the drying time and improve the quality (Beaudry et al. 2003). A study by Zhong and Lima (2003) showed that Ohmic heating accelerated the vacuum drying rates of sweet potato.

Influence on storage on quality

A significant loss of nutrients occurs in dried fruits and vegetables during storage. This loss depends on storage temperature, pH, exposure to oxygen, porosity, light and presence of organic acids. The extent of losses depends on the type of vitamins and storage conditions such as the exposure to oxygen and light (Sablani 2006a). During storage of spaghetti, for example, no loss of thiamine and niacin was observed but riboflavin was susceptible to temperature, storage period and light (Watanabe and Ciacco 1990).

In some situations the method of dehydration can also influence the loss of nutrients. For instance, Kaminski et al. (1986) observed a rapid degradation of carotenoids in freeze-dried carrots. They observed that air-drying was more efficient for carotene preservation when stored at ambient temperature. Freeze-dried products are generally more porous. This facilitates oxygen transfer and promotes rapid oxidation of carotene. Cinar (2004) reported that the highest pigment loss was in carrot stored at 40°C (98.1%) while the lowest loss was in sweet potato kept at 4°C (11.3%) during 45 days of storage.

Energy efficiency in drying

Drying is commonly employed to prevent the post harvest deterioration of many fruits and vegetables (Beker 2005). In most cases, some form of through-flow or cross-flow convective dryer is used for this purpose. A common feature of these dryers is their high use of energy. There is considerable concern world wide over global warming which is attributed to green house gases produced by the combustion of fossil fuels. As a result there is increasing pressure to reduce energy consumption, particularly in those countries that are signatories to Kyoto protocol. Raghavan et al. (2005) indicated that about 34% of the world produce requires artificial drying at least for part of the crop.

Ways to reduce energy consumption

Routine care in operation should always form an integral part of crop-dryer operation. Combination drying, another best way to reduce the energy consumption, increases the through-put and improves quality (Raghavan et al. 2005). Optimization of energy through mathematical modelling is another important way to reduce energy consumption (Achariyaviriya et al. 2002). Intermittent drying (Chua et al. 2003) and electro drying technologies (Raghavan et al. 2005) are also used to reduce energy consumption. The application of microwave was found to have a major impact on both the drying time and the energy consumption. The specific energy consumption for the drying of grapes reduced from 81.15 MJ/kg in case of convective drying to 7.11–24.32 MJ/kg by combined microwave – convective drying (Tulasidas et al. 1995a). Wang et al. (2002) described mathematical model of the drying of 4 mm carrot particles in a batch fluidized bed dryer with microwave heating. Infrared-convective dryers reduce the energy consumption of osmotically pre-treated samples of potato and pineapple (Tan et al. 2001). Heat pump dryers and high electric field dryers have the great potential for industrial application, particularly for high value crops because of superior quality of its products, simplicity of design and low energy use (Regaldo et al. 2004).

Conclusion and future trends

Many new dimensions came up in drying technology to reduce the energy utilization and operational cost. Among the technologies, osmotic dehydration, vacuum drying, freeze drying, SS drying, HPD drying microwave drying and spray drying are offering great scope for the production of best quality dried products and powders. Due to their selective and volumetric heating effects, microwaves bring new characteristics such as increased rate of drying, enhanced final product quality and improved energy consumption. The quality of microwave dried commodities is often between air-dried and freeze-dried products. The rapidity of the process yields better colour and aroma retention. Quality is further improved when vacuum is used since the thermal and oxidative stress is reduced. Due to high cost, using single unit operation to dry the produce is not cost effective. Therefore, cost effective alternate systems like combination/hybrid drying should be promoted to reap the advantage of sophisticated drying systems with minimum cost and simple technologies. Combination drying with an initial conventional drying process followed by a microwave finish or microwave vacuum process has proven to reduce drying time while improving product quality and minimising energy requirements. However, several factors should be taken into consideration when developing drying system for the fruits and vegetables. An optimal drying system for the preservation of fruits and vegetables should be cost effective, shorter drying time and with minimum damage to the product. Researchers from different centres are focussing on mathematical modelling and computer simulation as important technology that can provide information on the process parameters that would otherwise be unavailable.

References

Achanta S, Okos MR (1996) Predicting the quality of dehydrated foods and biopolymers–research needs and opportunities. Drying Technol 14:1329–1368

Achariyaviriya A, Tiansuwan J, Soponronnarit S (2002) Energy optimization of whole longan drying. Simulation results. Int J Ambient energy 23:212–220

Ade-Omowaye BIO, Taiwo KA, Eshtiaghi NM, Angersbach A, Knorr D (2003) Comparative evaluation of the effects of pulsed electric field and freezing on cell membrane permeabilisation and mass transfer during dehydration of red bell peppers. Innovative Food Sci Emerging Technol 4:177–188

Alves-Filho O, García-Pascual P, Eikevik TM, Strømmen I (2004) Dehydration of green peas under atmospheric freeze-drying conditions. Proc 14th Int Drying Sym, Vol C, Sao Paulo, Brazil, 22–25 August, p 1521–1528

Azura E, Garcia HS, Beristain C I (1996) Effect of centrifugal force on osmotic dehydration of potatoes and apples. Food Res Int 29:195–199

Beaudry C, Raghvan GSV, Rennie TJ (2003) Micro wave finish drying of osmotically dehydrated cranberries. Drying Technol 21:1797–1810

Beaudry C, Raghavan GSV, Ratti C, Rennie TJ (2004) Effect of four drying methods on the quality of osmotically dehydrated cranberries. Drying Technol 22:521–539

Beker CGJ (2005) Energy efficiency in drying. Stewart Post-harvest Rev 4:8–12

Bezyma LA, Kutovoy VA (2005) Vacuum drying and hybrid technologies. Stewart Post- harvest Rev 4:6–13

Bolin HR, Huxsoll CC, Jackson R (1983) Effect of osmotic agents and concentration on fruit quality. J Food Sci 48:202–205

Brown M (1999) Focusing on freeze drying. Food Manuf 76(9): 34–36

Changrue V, Sunjka PS, Gariepy Y, Raghavan GSV, Wang N (2004) Realtime control of microwave drying process. Proc 14th Int Drying Symp Sao Paulo, Brazil 22–25 August, p 1532–1542

Chou SK, Chua KJ (2001) New hybrid drying technologies for heat sensitive foodstuffs. Tr Food Sci Technol 12:359–369

Chua KJ, Majumdar AS, Chou SK (2003) Intermittent drying of bioproducts. An Overview Bioresour Technol 90:285–295

Chua KJ, Mujumdar AS, Chou SK, Hawlader MNA, Ho JC (2000) Convective drying of banana, guava and potato pieces: effect of cyclical variations of air temperature on drying kinetics and color change. Drying Technol 18:907–936

Cinar I (2004) Carotenoid pigment loss of freeze-dried plant samples under different storage conditions. Food Sci Technol 37:363–367

Conwoy J, Castaigne F, Picard G, Vovau X (1983) Mass transfer considerations in the osmotic dehydration of apples. Can Inst Food Sci Technol 16:25–29

Cui ZW, Xu SY, Sun DW (2003) Dehydration of garlic slices by combined microwave vacuum and air drying. Drying Technol 21:1173–1184

Donsi G, Ferrari G, Nigro R, Maltero PD (1998) Combination of mild dehydration and freeze drying processes to obtain high quality dried vegetables and fruits. Trans, IChemE 76:181–187

Drouzas AE, Schubert H (1996) Microwave application in vacuum drying of fruit. J Food Eng 28:203–209

Erle U (2005) Drying using microwave processing. In: The microwave processing of foods. Schubert H, Regier M (ed), Woodhead Publ, Cambridge, England, p 142–152

Feng H, Tang J, Mattinson DS, Fellman JK (1999) Microwave and spouted bed drying of frozen blue berries. J Food Process Preserv 23:463–479

Filkova I, Majumdar AS (1995) Industrial spray system. In: Hand book of industrial drying, Majumdar AS (ed), Marcel Dekkar Inc, New York, p 263–307

Fito P, Chiralt A, Barat J M, Andres A, Martinez- Monzo J Martinez- Navarrete N (2001) Vacuum impregnation for development of new dehydrated products. J Food Eng 49:297–302

Gabas AL, Bernardi M, Telis-Romero J, Telis VRN (2004) Application of heat pump in drying of apple cylinders. Proc 14th Int Drying Symp, Vol C, São Paulo, Brazil, 22–25 August, p 1922–1929

George SD, Cenkowski S, Muir WE (2004) A review of drying technologies for the preservation of nutritional compounds in waxy skinned fruit. North Central ASAE/CSAE Conf, Winnipeg, Manitoba, Canada, 24–25 September, MB 04–104

Grabowski S, Marcotte M, Ramaswamy HS (2003) Drying of fruits, vegetables, and spices. In: Handbook of Postharvest Technology: Cereals, Fruits, Vegetables, Tea, and Spices., Chakraverty A, Mujumdar AS, Raghavan GSV, Rawaswamy HS (ed), Marcel Dekker, New York, Ch 23, p 653–695

Gunasekaran S (1998) Pulsed microwave-vacuum drying of food materials. Drying Technol 17(3):395–412

Hall CW (1996) Expanding opportunities in drying research and development. Drying Technol 14:1419–1427

Hammami C, Rene F (1997) Determination of freeze drying process variables for strawberries. J Food Eng 32:133–154

Hawkes J, Flink JM (1978) Osmotic concentration of fruit slices prior to dehydration. J Food Process Preserv 2:265–267

Hawlader MNA, Perera CO, Tian M (2006) Properties of modified atmosphere heat pump dried foods. J Food Eng 74:392–401

Hogan MR, Ayers DL, Muller Jr RE, Foster GH, Rall EC, Doering OC (1983) Heat pump for low-temperature grain drying. Trans ASAE 26:1234–1238

Hsuch L, Chen W, Weng YM,Tseng CHY (2003) Chemical composition and antioxidant activity of yam as affected by drying methods. Food Chem 83:85–92

Inyang UE, Ike CI (1998) Effect of blanching, dehydration method, temperature on the ascorbic acid, color, sliminess and other constituents of okra fruit. Int J Food Sci Nutr 49:125–130

Islam M N, Flink J N (1982) Dehydration of potato II. Osmotic concentration and its effects on air drying behaviour. J Food Technol 17:387–403

Jayaraman KS, Gupta DK (1992) Dehydration of fruit and vegetables-recent developments in principles and techniques. Drying Technol 10:1–50

Kadam DM, Samuel DVK, Chandra P, Sikarwar HS (2008) Impact of processing treatment and packaging material on some proteins of stored dehydrated cauliflower. Int J Food Sci Technol 43(1):1–14

Kaminski E, Wasowicz E, Zawirska R, Wower M (1986) The effect of drying and storage of dried carrot on sensory characteristics and volatile constituents. Nahrung 30:819–828

Khin MM, Zhou W, Perera C (2005) Development in combined treatment of coating and osmotic dehydration of food-A review. Int J Food Eng 1:1–19

Khraisheh MAM, McMinn WAM, Magee TRA (2004) Quality and structural changes in starchy foods during microwave and convective drying. Food Res Int 37:497–503

Kohayakawa MN, Silveira-Júnior V, Telis-Romero J (2004) Drying of mango slices using heat pump dryer. Proc 14th Int Drying Symp, Vol B, São Paulo, Brazil, 22–25 August, p 884–891

Krokida MK, Maroulis ZB, Saravacos GD (2001) The effect of method of drying on colour of dehydrated product. Int J Food Sci Technol 36:53–59

Kumar HSD, Radhakrishna K, Nagaraju PK, Rao DV (2001) Effect of combination drying on physico-chemical charcterestics of carrot and pumpkin. J Food Process Preserv 25:447–460

Kumar PS, Sagar VR, Singh U (2006) Effect of tray load on drying kinetics of mango, guava and aonla. J Sci Ind Res 65:659–664

Lai FC, Sharma RK (2005) EHD-enhanced drying with multiple needle electrode. J Electrostatics 63:223–237

Lazarides HN, Katsanidis E, Nickolaidis A (1995) Mass transfer kinetics during osmotic preconcentration aiming at minimal solid uptake. J Food Eng 25:151–156

Leeratamark N, Devahastio S, Chiewchan N (2006) Drying kinetics and quality of potato chips undergoing different drying techniques. J Food Eng 77:635–638

Le Maguer M (1998) Osmotic dehydration: review and future directions. Proc Int Symp Progress in Food Preservation Processes, CERIA, Bruxelles, Belgium, 12–14 April, p 283– 309

Lenart A (1996) Osmo convective drying of fruits and vegetables: Technology and Application. Drying Technol 14:391–413

Lenart A, Flink JM (1984) Osmotic concentration of potato-I: Criteria for the end of point of the osmosis process. J Food Sci Technol 19:45–48

Lerici CL, Pinnavaia G, Dalla Rosa M, Bartolucci L (1985) Osmotic dehydration of fruit: Influence of osmotic agents on drying behaviour and product quality. J Food Sci 50: 1217–1219

Lewicki PP (1998) Effect of pre-drying treatment, drying and rehydration on plant tissue properties: a review. Int J Food Prop 1:1–22

Lovedeep K, Narpinder S, Navdeep SS (2002) Some properties of potatoes and their starches II. Marphological, reheological properties of starches. Food Chem 79:183–192

Master K (2004) Current market driven spray drying activities. Drying Technol 22:1351–1370

Masters K (1991) Spray drying. Hand book, 5th edn, Longman group Ltd, New York

Mayor L, Sereno AM (2004) Modelling shrinkage during convective drying of food materials. J Food Eng 61:373–386

Meda L, Ratti C (2005) Rehydration of freeze dried strawberries at varying temperature. J Food Process Eng 28:233–246

Meda SV, Raghavan GSV (2004) An overview of microwave processing and dielectric properties of agri-food materials. Biosystem Eng 88:1–18

Mohamed S, Hussein R (1994) Effect of low temperature blanching, cysteine-HCl, N-acetyl-L-cysteine, Na metabisulphite and drying temperatures on the firmness and nutrient content of dried carrots. J Food Process Preserv 18:343–348

Nijhuis HH, Torringa HM, Muresan S, Yukel D, Leguijt C, Kloek W (1998) Approaches to improving the quality of dried fruits and vegetables. Tr Food Sci Technol 9:13–20

Nindo CI, Sun T, Wang SW, Tang J, Powers JR (2003) Evaluation of drying technologies for retention of physical quality and antioxidants in asparagus. Lebens Wissen Technol 36:507–516

Nsonzi F, Ramaswamy HS (1998) Osmotic dehydration kinetics of blueberries. Drying Technol 16:725–741

Okos MR, Narsimhan SRK, Weitnauer AC (1992) Food dehydration. In: Handbook of food engineering, Heldman DR, Lund DB (ed), Marcel Dekker Inc, New York, p 437–562

Orsat V, Changrue V, Raghavan GSV (2006) Microwave drying of fruits and vegetables. Stewart Post-Harvest Rev 6:4–9

Orsat V, Raghavan V, Meda V (2005) Microwave technology for food processing: an overview. In: The microwave processing of foods, Schubert H, Regier M (ed), Woodhead Publ, Cambridge, England, p 105–118

Osepchuk JM (2002) Microwave power applications. IEEE Trans Microwave Theory Technol 50:975–985

Paakkonen K, Mattila M (1991) Processing, packaging and storage effects on quality of freeze dried strawberries. J Food Sci 56:1388–1392

Peleg M (1996) On modelling changes in food and biosolids at and around their Tg temperature range. Crit Rev Food Sci Nutr 36:49–67

Perera CO (2005) Selected quality attributes of dried foods. Drying Technol 23:717–730

Piotrowski D, Lenart A, Wardzynski A (2004) Influence of osmotic dehydration on microwave-convective drying of frozen strawberries. J Food Eng 65(4):519–525

Queiroz R, Gabas AL, Telis VRN (2004) Drying kinetics of tomato by using electric resistance and heat pump dryers. Drying Technol 22:1603–1620

Raghavan GSV, Orsat V (1998) Electro-technology in drying and processing of biological materials. Keynote presentation at 11th Int Drying Symp (IDS 98), Halkididi, Greece 19–22 August, P 456–463

Raghavan GSV, Rennie TJ, Sunjka PS, Orsat V, Phaphuangwittayakul W, Terdtoon P (2005) Overview of new techniques for drying biological materials with emphasis on energy aspects. Braz J Chem Eng Cem 22:195–201

Rahman MS (2001) Toward prediction of porosity in foods during drying: a brief review. Drying Technol 19:1–13

Rahman MS, Labuza TP (1999) Water activity and food preservation. In: Handbook of food preservation, Rahman MS (ed), Marcel Dekker, New York, p 339–382

Rahman MS, Perera CO (1999) Drying and food preservation. In: Handbook of food preservation. Rahman MS (ed). Marcel Dekker: New York, p 173–216

Rahman MS, Guizani N, Al–Ruzeiki MH, Al–Khalasi S (2000) Microflora changes in tunas during convection air drying. Drying Technol 18:2369–2379

Ramesh MN, Wolf Tevini D, Jung G (2001) Influence of processing parameters on the drying of spice paprika. J Food Eng 49: 63–72

Rastogi NK, Eshiaghi MN, Knorr D (1999) Accelerated mass transfer during osmotic dehydration of high intensity electrical fields pulse pretreated carrots. J Food Sci 64:1020–1023

Rastogi NK, Niranjan K (2008) Enhanced mass transfer during osmotic dehydration of high pressure treated pineapple. J Food Sci 63:508–511

Rastogi NK, Raghavarao KSMS (2004) Mass transfer during osmotic dehydration of pineapple: Considering Fickian diffusion in cubical configuration. Lebens Wissen Technol 37:43–47

Ratti C (2005) Freeze drying of plant products: where we are and where we are heading to. Stewart Post-harvest Rev 4:5–12

Regaldo C, Blanca E, Garcia- Alimendarez, Miguel A, Durale-Vazquez. (2004) Biotechnological applications of peroxidises. Phytochem Rev 3:243–256

Regier M, Mayer-Miebach E, Behsnilian D, NeffE, Schuchmann HP (2005) Influences of drying and storage of lycopene-rich carrots on the carotenoid content. Drying Technol 23: 989–998

Sablani SS (2006a) Drying of fruits and vegetables: retention of nutritional/ functional quality. Drying Technol 24:428–432

Sablani SS (2006b) Food quality attributes in drying. Stewart Post-harvest Rev 2:1–5

Sablani SS, Rahman MS (2002) Pore formation in selected foods as a function of shelf temperature during freeze drying. Drying Technol 20:1379–1391

Sagar VR, Kumar PS (2007) Processing of guava in the form of dehydrated slices and leather. Acta Hort 735:579–589

Saguy IS, Marabi A, Wallach R (2004) Water imbibition in dry porous foods. Proc 9th Int Conf on Engineering & Food Montpellier, France, 7–11 April, p 147–152

Salunke DK, Bolin HR, Reddy NR (1991) Dehydration. In: Storage, processing and nutritional quality of fruits and vegetables, 2nd edn, Vol II, Processed fruits and vegetables, CRC Press Inc., Boca Raton, FL, p 49–98

Seco JIF-G, Seco JJF-G, Prieto EH, Garcìa MC (2004) Evaluation at industrial scale of electric-driven heat pump dryers (HPD). Holz Roh Werkst 62:261–267

Sharma GP, Prasad S (2006) Optimization of process parameters for microwave drying of garlic cloves. J Food Eng 75: 441–446

Shi JX, Le Maguer M, Wang SL, Liptay A (1997) Application of osmotic treatment in tomato processing-effect of skin treatments on mass transfer in osmotic dehydration of tomatoes. Food Res Int 30:669–674

Shishegarha F, Mackhlouf J, Ratti C (2002) Freeze drying charcterestics of strawberries. Drying Technol 20:131–145

Singh U, Sagar VR, Behera TK, Kumar PS (2006) Effect of drying conditions on the quality of dehydrated selected vegetables. J Food Sci Technol 43:579–582

Soysal Y, Oztekin S, Eren O (2006) Microwave drying of parsley modeling, kinetics and energy aspects. Biosyst Eng 93: 403–413

Sunjka PS, Raghavan GSV (2004) Assessment of pretreatment methods and osmotic dehydration of cranberries. Can Biosyst Eng 4:.35–40

Taiwo KA, Angersbach A, Knorr D (2002) Influence of high intensity electric field pulses and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. J Food Eng 52:185–192

Taiwo KA, Angersbach A, Knorr D (2003) Effects of pulsed electric field on quality factors and mass transfer during osmotic dehydration of apples. J Food Process Eng 26:31–48

Talens P, Hartong S, Martinez-Navarrete N, Chiralt A, Fito P (2000) Kinetics and equilibrium status in osmotic dehydration of strawberry. Proc 12th Int Drying Symp (IDS) 2000", paper 101, Elsevier Sci Amsterdam, Netherlands

Tan M, Chua KJ, Majumder AS, Chou SK (2001) Effect of osmotic pre treatment and infra red radiation on drying and colour changes during drying of potato and pineapple. Drying Technol 19:2193–2207

Tatemoto Y, Yano S, Mawatart Y, Noda K, Komatsu N (2007) Drying characteristics of porous material immersed in a bed glass beads fluedized by superheated steam under reduced pressure. Chem Eng Sci 62:471–480

Tedjo W, Eshiaghi MN, Knorr D (2002) Impact of non- thermal processing on plant metabolities. J Food Eng 56:131–134

Tein ML, Timothy DD, Christine HS (1998) Characterization of vacuum microwave, air and freeze dried carrot slices. Food Res Int 31:111–117

Tulasidas TN, Raghavan GSV, Mujumdar AS (1995a) Microwave drying of grapes in a single mode cavity at 2450 MHz. I. Drying kinetics. Drying Technol 13:1949–1971

Tulasidas TN, Raghavan GSV, Mujumdar AS (1995b) Microwave drying of grapes in a single mode cavity at 2450 MHz. II: Quality and energy aspects. Drying Technol 13:1973–1992

Uddin MS, Hawlader MNA, Hui X (2004) A comparative study on heat pump, microwave and freeze drying of fresh fruits. Proc 14th Int Drying Symp, São Paulo, Brazil, 22–25 August, Vol C, p 2035–2042

Venkatachalapathy K, Raghavan GSV (1999) Combined osmotic and microwave drying of strawberry. Drying Technol 17:837–853

Wang J, Xi YS (2005) Drying characteristics and drying quality of carrot using a two-stage microwave process. J Food Eng 68: 505–511

Wang W, Thorat BN, Chen G, Majumdar AS (2002) Fluidized bed drying of heat sensitive porous material with microwave heating. Proc 13th Int Drying Symp, Beijing, China, 27– 30 August, Vol B, p 901–908

Watanabe E, Ciacco CF (1990) Influence of processing and cooking on the retention of thiamine, riboflavin and niacin in spaghetti. Food Chem 36:223–231

Xian-Ju S, Minzhang, Arun SM (2007) Effect of vacuum microwave predrying quality of vacuum- fried potat chips. Drying Technol 25:2021–2026

Zhong T, Lima M (2003) The effect of Ohmic heating or vacuum drying rate of sweet potato tissue. Bioresour Technol 87: 215–220