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SPECIAL

Enhancement of Food Drying and Preservation through Pulsed Electric Fields : A Review

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CTION

one of the most important and possibly the most widely unit operation applied for the long-term preservation of wide variety of drying techniques are available for this depending on their suitability and the properties of the though thermal drying techniques such as convective air dized bed drying (Cohen and Yang, 1995; Lewici, 1998) drying are used in large scale operations, they result in on in product quality, flavour, colour and texture due to essing temperatures or slow drying rates. The drying ot only decreases the water content of the agricultural but can also affect other physical and chemical tics such as destruction of nutrients and enzymatic and atic reactions, among others (Karmas *et al.*, 1992). In onomics (investment and operation) is an important factor. freeze-drying, osmotic drying and vacuum drying, the water from agricultural products is achieved in most cases a dry air flow that eliminates water from the surface of to the air stream. Consequently, fast, gentle, non-thermal techniques, which could overcome these obstacles, are chnological solutions. High electric field drying (HEFD), l method, though exists for a long time gaining lots of orldwide and has great potential for industrial application. required for removal of water depends on temperature re (in the range of 2.5-2.7 MJ/kg) and, depending on the iciency of the drying system. The total energy input conventional drying ranges from 4-6 MU per kg of water epending on the type of dryer, heat and mass transfer roduct and losses on the heating side, as well as to the s, during drying, causes drying efficiency in the range of ulacki, 2002). Membrane semi-permeability is often a or during drying. After removal of free surface water, the s mainly determined by water diffusivity from the sample urface. Agriculture product quality depends notably on our and flavour, these deteriorate during thermal drying. amaging cell membranes can also be advantageous for of mass transfer. Thus, electropermeabilisation can be hance diffusion coefficients within fruit or vegetables ctric field treatment can be operated continuously in a f seconds, with electrical maximum energy requirements of 1-3 kWh/t of product (Lai and Sharma, 2005). This es on the drying of horticultural products by high pulsed s using published information on the application of electric

CTRIC FIELD DRYING (HEFD)/PULSED ELECTRIC NG (PEFD)

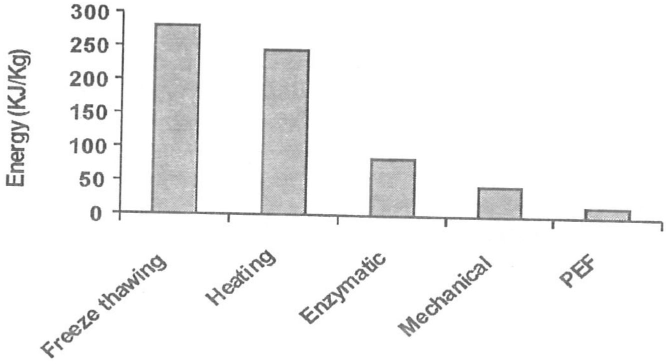

Fig. 1 ***Energy required for cell integration of potato tissue with different techniques***

ions or space charges (air ions) generated by an inhomogeneous electric field. Air ions N2+ , O+2m N2 , O+ and O- are produced by static corona discharges from the sharp point when an external electric field is applied to a point-to-plate electrode system. The air ions which originate from a small region around the needle-point are accelerated by the applied electric force; part of the energy is used for overcoming the frictional resistance due to collisions with neutral molecules. This causes air movements as a whole, which constitutes the electric wind. The electric wind induced by EHDD is considered to be the principal driving force, which accelerates the drying rate through turbulent and vortex motions.

A comparison of energy requirements for different tissue disintegration techniques is shown in Fig 1. Taking into account the low energy input required for a PEF treatment of plant tissues (2-20 kJ/kg), it is evident that there is a potential to reduce the total energy input for product drying (Karmas *et al.*, 1992). PEF processing involves application of a short burst of high voltage to a food item that is placed between two electrodes. Electric current flows only for microseconds through the food. When electrical energy is applied in the form of short pulses, cell membranes are destroyed by mechanical effects with no significant heating of the food (Darabi *et al.*, 2001). The major components of the PEF processing system include a voltage power supply, an energy storage capacitor, a treatment chamber, and discharge and charging resistance switches (Fig.2). Energy from the high voltage power supply is stored in the capacitor. It is observed that, energy stored in the capacitor can be discharged almost instantaneously (in a millionth of second) at very high levels of power. The treatment chamber is used to transfer high intensity pulses to foods. The pulses can be monitored online with an

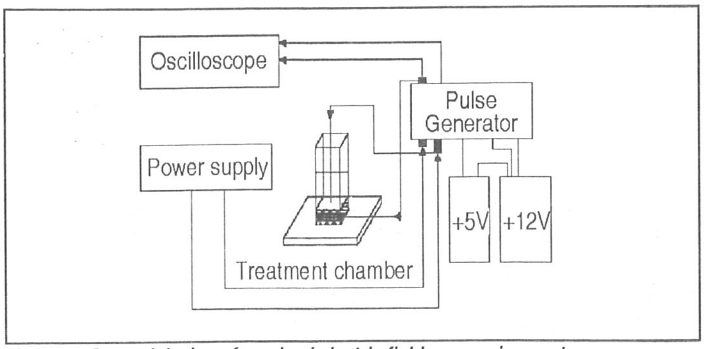

Fig. 2. *General design of a pulsed electric field processing system. (Savoval et al., 2005).*

Basic of Electric Field Processing

A high electric field is expected to orient the dipole water molecules in the drying material towards the direction of the field. This creates order and reduces the entropy of the drying material. Release of heat lowers the entropy, which comes from the material itself and thus lowers its temperature (Cao *et al.,* 2001). The temperature of the drying material will not only reduce due to the evaporative cooling but also due to the mechanism of exothermic release of heat resulting from decreased entropy. Therefore, EHDD is considered a non-thermal physical process (Fig. 3). Rapid drying rate without quality loss endows the EHDD an attractive candidate for applications in the drying of agricultural products, especially in heat sensitive materials like fruits and vegetables. (Jamai and Vorobiev, 2002; Bajgai and Hashinaga, 2001).

Critical Process Factors of Pulsed Electric Fields

Some process factors that affect the PEF technology are electric field intensity (Barbosa-Canovas *et al.,* 2005), pulse width (Cao *et al.,* 2004), treatment time (Kulacki, 2002, Jamai and Vorobiev, 2002), temperature (Taiwo *et al.,* 2002; Ade-Omowaye *et al.,* 2003), and pulse wave shapes (Baigai and Hashinaga, 2001).

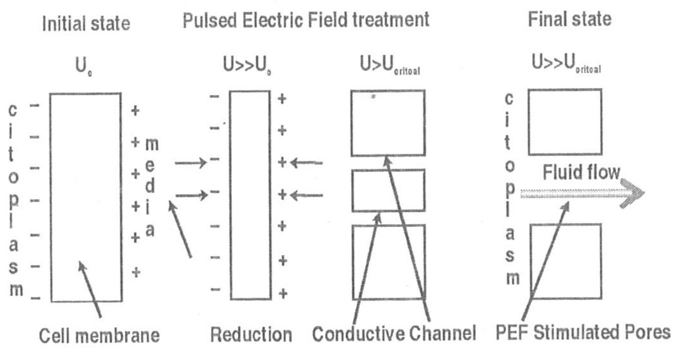

Fig. 3. *Mechanism of Dielectrical breakdown of cell membrane (Savova et al., 2005)*

APPLICATION OF DIFFERENT KIND OF ELECTRIC FIELDS IN DEHYDRATION OF PRODUCTS

The applications of EHD drying in the food and agricultural industry have shown a sustained progression in the past two decades. Numerous applications of the electrical treatment have addressed like cell disruption, metabolite release, fruit storage, food dehydration and preservation (Ho *et al.,* 1995; Lai and Sharma, 2005). The drying experiments for potato disks were done in the interval for drying temperatures 30-70°C. The temperature dependencies of moisture effective diffusion coefficient for instact. PEF-treated and freeze-thawed potato tissues are compared (Lai and Sharma, 2005). It is shown that drying efficiency is a function of the conductivity disintegration index. The influences of corona electrical discharge, electric field between parallel aluminium plate and the direction of electric field on apples (*Malus domestica* Borkh, cv. Fuji and Golden delicious) have been investigated by Atungulu *et al.,* (2005). From the study, effects on the physicochemical properties depended on field type (corona electrical discharge or electric field between parallel plates). Physiologically, apples stored between parallel plate electric field had a suppressed respiration and climacteric peak. Pulsed electric field intensities from 0.75 to 1.5 kV/cm with pulse duration within 100 and 200μ second were studied on apple and potato. The number of pulses applied was up to 120. The drying process was carried out in a convective air oven at 70°C. Results showed that potential advantage for PEF enhanced juice extraction from the tissues even at moderate PEF treatment. PEF treatment increased porosity and particle density but decreased bulk density. Treating the apple samples with PEF resulted in generation of more pores of sizes in the order of cell wall thickness. PEF treatment enhanced drying rates of potato samples. Diffusion coefficients of PEF pretreated potato samples increased by up to 40%. (Raghavan *et al.,* 2004).

An alternating current high electric field (HEF) of 430 kV/m generated by multiple point-to-plate-electrodes was used to dry spinach *(Spinacia oleracea L)* and Japanese radish (*Raphanus sativus L.).* Point electrodes distributed above a layer of fresh spinach were effective in removing moisture. Drying done continuously for 7 h, removed 80.1% of the total moisture compared with 79.8% and 19.3% when dried in an oven (60°C) and in ambient air (25°C), respectively. The ascorbic acid content after six weeks of storage of the dried material was almost three times higher in HEF-dried samples than those oven-dried. HPLC determination of organic acids and sugars indicated no formation of by-products in post-HEF-dried spinach (Bajgai and Hashinaga, 2001). From a quality analysis perspective, treatments with electric field suppressed soluble sugar concentration change. The influence on the physicochemical properties of the apples depended on the magnitude and the direction of the applied electric field was studied (Jamai and Vorobiev, 2002). The 'reversed' (apples on cathode plate) electric field treatment gave a higher weight loss than the corresponding 'non reversed' (apples on anode plate) electric field treatment. Drying enhancement by a HVEF at lower drying temperature was more marked than that at higher temperature. The drying rate increased when the voltage increased and the discharge gap decreased. EHD included an investigation of the drying characteristics of radish and shiitake mushroom under corona discharge where the energy saving and the quality of dried products were evaluated by Xue *et al.,* (1997). The shrinkage of the dried shiitake mushroom was reduced using corona discharge treatment, which showed a possibility of the EHDD for improving the quality of products. Carlon and Latham (1992) optimized on accelerated drying of water-wetted spinach in electric fields and the electric current with functions of several parameters: viz., the strength of the electric field in which the discs were placed; the temperature; the percent relative humidity.

Impact of Electrical Field on Cell Permeability and Porosity

It was shown that liquid-solid separation during extraction or pressing of fruits for juice can be enhanced by electric fields. To induce dielectric breakdown and pore formation in fruit or vegetable tissue, external electrical field strength of approximately 1 kV/cm is required and the cellular tissue is subjected to repetitive pulses with a width in the range of microseconds. Depending on the properties of the tissue and porosity required, the specific energy input required ranges from 2-15 kJ/kg (Atungulu *et al.,* 2005). A temperature increase of a few degrees centigrade will result as the electrical energy is dissipated into the product. The treatment can be applied on whole fruits such as apples or potato tubers, pieces or slices in direct electrode contact or when suspended in water, or directly to fruit mash. The effects of pulsed electric field (PEF) – induced electroplasmolysis on mechanical and structural properties of apple tissue were investigated (Bazhal *et al.,* 2003). PEF treatment decreased bulk density, decreased volume shrinkage, and increased porosity of air-dried apple tissue. The overall average mean size of the PEF-induced pores was 5.86 mm, lower than 7.81 mm obtained for the untreated samples. Taiwo *et al.,* (2003) developed a method for determining cell permeability after different processing techniques. This method measures the conductivity-frequency spectra of the tissue to characterize the proportion of cells with highly permeable membranes. Sample conductivity in a low frequency range of 1-5 kHz and a high frequency range of 3-50 Mhz were compared to calculate the cell disintegration index. This index ranges from 0 (in intact tissue) to 1 (in totally disintegrated tissue after-freeze thawing). A disintegration index of 0.84 was reported for a treatment at 1.6 kV/cm, with 5 pulses. It was shown that the cell disintegration index increases after PEF treatment by a magnitude that depends on treatment intensity. PEF treatment resulted in an increase in the permeability of plant cells which can be exploited to increase drying rates during air dehydration. Taiwo *et al.*, (2003) showed that permeability of potato tissue increased with PEF treatment, which helped to achieve enhanced mass transfer during subsequent fluidized bed drying. It has been demonstrated that PEF treatment could reduce the drying time of potato cubes by approximately one-third. The effect of PEF and other pretreatment on dehydration characteristics of paprika have also been reported (Carlon and Latham, 1992).

Electric Field for Enhancing Osmotic Dehydration

Osmotic dehydration is a technique whereby solid food, whole or in pieces, is placed in a sugar or salt solution of a desired osmotic pressure. Recently, researchers have reported on various combination processes that can improve the mass transfer rate either in sequence or simultaneously with osmotic dehydration. These include application of high pressure processing or PEF treatment of food material prior to osmotic dehydration. PEF treatment has been reported to increase the permeability of plant cells. The increase in permeability of potato and carrot (Rastogi *et al.*, 1999) tissues by PEF treatment resulted in improved mass transfer during fluidized bed drying and osmotic dehydration. 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. 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. High intensity electric field pulses using varying field strengths (0.5, 1.0 and 2.0 kV/cm corresponding to 12, 48 and 192 J/kg, per 400ms) and pulse numbers (2 to 50) were applied to applied slices as a pretreatment to study their influence on mass transfer during osmotic dehydration (OD). Cell membrane permeabilzation increased with increasing field strength and higher pulse number. Higher water loss and solids gain were obtained at 1.0 kV/cm (Taiwo *et al.*, 2003). PEF treatment increased water loss, which was attributed to increased cell membrane permeability in apple. The effect of PEF treatment on solid gain was found to be minimal.

Jamai and Vorobiev, (2002) studies the influence of PEF pretreatment on the mass transfer kinetics of apple slices during osmotic dehydration. Cell membrane premeabilization was found to increase with increasing field strength and pulse number, thus facilitating water loss during osmotic dehydration. Higher water loss and solids gain were obtained at 1.0 kV/cm. Lai and Sharma, (2005) reported that PEF pretreatment resulted in higher moisture loss and solid gain in mangoes during subsequent osmotic dehydration. Ade-Omowaye *et al.*, (2003) studied the influence of changing the pulse number on the mass transfer characteristics of fresh red bell peppers (Capsicum annum L.) during subsequent osmotic dehydration. A significant difference was found in the water loss of the dehydrated samples subjected to 1 and 5 pulses. The increase in water diffusion at elevated temperature was primarily due to swelling and plasticizing of cell membrances, and reduction in the viscosity of the osmotic solution. On the other hand, diffusion during PEF was due to pore formation and breakage of cell membrances

Quality of Osmotic Processed Foods

Taiwo *et al.*, (2003) examined the quality of PEF-treated osmotically-dehydrated apples. It was shown that the pretreated apples turned brown but sample brightness improved with osmotic dehydration time. Maximum deformative force and amount of strain experienced by dried samples were influenced by both the field strength and osmotic dehydration time. Vitamin C content of dried samples was reduced at higher field strengths and at longer osmotic dehydration immersion times. The PEF treatment results in increase in the grape juice yield from 49-54% to 76-78% at 45 min of pressing. The PEF pre-treatment before pressing was found to be more efficient than intermediate PEF treatment during the pressing. It was evident that PEF enhanced expression is promising for production of higher quality juices in wine industry. Ade-Omowaye *et al.*, (2003) compared the quality characteristics of PEF-pretreated and osmotically-treated red paprika with osmotic treatment at higher temperature. The retention of ascorbic acid and carotenoids were higher for PEF pretreated and osmotically-treated paprika. Taiwo et al. (2003) studies the influence of high intensity electric field pulses (HELP) and osmotic dehydration on the rehydration characteristics of apple slices at different temperatures. Rehydration rate increased with temperature but higher rehydration capacity (RC) values were obtained at low temperatures (24°C and 45°C). RC of HELP treated plus osmotic dehydration samples were 10-30% higher than the RC of the untreated plus osmotic dehydration samples.

Limitations of Pulsed Electric Field Technology

Some of the most important current technical drawbacks or limitations of the PEF technology are: Availability of commercial units is the main problem associated with PEF drying. The systems (including treatment chambers and power supply equipment) need to be scaled up to commercial systems. The presence of bubbles, which may lead to non-uniform treatment as well as operational and safety problems is the main technical issue to be solved with PEF drying (Lai and Sharma, 2005). When the applied electric field exceeds the dielectric strength of the gas bubbles, partial discharges take place inside the bubbles that can volatise the liquid and therefore increase the volume of the bubbles. Therefore, the PEF method is not suitable for most of the solid food products containing air bubbles when placed in the treatment chamber. PEF is restricted to products is closely related to its physical structure and chemical composition. Homogeneous liquids with low electrical conductivity provide ideal condition for continuous treatment with the PEF method. Products with high electrical conductivity reduce the resistance of the chamber and consequently require more energy to achieve a specific electrical field. The lack of methods to accurately measure treatment delivery is another drawback. The number and diversity in equipment, limits the validity of conclusions that can be drawn about the effectiveness of particular process conditions (Taiwo *et al.*, 2003; Raghavan *et al.*, 2004). A method to measure treatment delivery would prevent inconsistent results due to variations in PEF systems.

CONCLUSIONS

Electric Field processing is an exciting emerging technology that offers not only enhanced potential for preservation of food but which can also be used to enhance the rate of unit operations such as osmotic dehydration and conventional dehydration. The potential for continuous application and the short processing time makes EF treatment an attractive, alternative candidate as a novel non-thermal unit operation. Since the bulk of past research focused on food pasteurization, current PEF configurations are primarily optimized for fluid foods. Further research may be needed to evaluate various PEF chamber configurations that can provide optimal handling of solid products for subsequent osmotic dehydration operations. Attention must be paid to potential safety problems due to the presence of air entrapped in the food matrix that can cause dielectric breakdown during treatment. EF may be used to modify existing processes or to develop new, energy efficient, environment friendly options for the food and drink industry, as well as for pharmaceutical or biotechnological applications. With respect to directions for future research, the following aspects need to be addressed: i) Agricultural products vary a lot in their characteristics and therefore optimisation

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TABLE 5. *Examples of some Industry-based Applications for Electronic Noses.*

Industry sector	Application area	Specific use types and examples
Agriculture	Crop protection harvest timing & storage meat, seafood, & fish products plant production pre- & post-harvest diseases	Homeland security, safe food supply crop ripeness, preservation treatments freshness, contamination, spoilage cultivar selection, variety characteristics plant disease diagnoses, pest identification detect non-indigenous pests of food crops
Airline transportation Cosmetics	Public safety & welfare passenger & personnel security personal application products fragrance additives	Explosive & flammable materials detection perfume & cologne development product enhancement, consumer appeal
Environmental	Air & water quality monitoring indoor air quality control pollution abatement regulations	Pollution detection, effluents, toxic spills malodor emissions, toxic/hazardous gases control of point-source pollution releases
Food & beverage	Consumer fraud prevention quality control assessments ripeness, food contamination taste, smell characteristics	Ingredient confirmation, content standards brand recognition, product consistency marketable condition, spoilage, shelf life off-flavors, product variety assessments
Manufacturing	Processing controls product uniformity safety, security, work conditions	Product characteristics & consistency aroma and flavor characteristics fire alarms, toxic gas leak detection
Medical & clinical	Pathogen identification pathogen or disease detection physiological conditions	Patient treatment selection, prognoses disease diagnoses, metabolic disorders nutritional status, organ failures
Military	Personnel & population security civilian & military safety	Biological & chemical weapons explosive materials detection
Pharmaceutical	Contamination, product purity variations in product mixtures	Quality control of drug purity formulation consistency & uniformity
Regulatory	Consumer protection environmental protection	Product safety, hazardous characteristics air, water, and soil contamination tests
Scientific research	Botany, ecological studies engineering, material properties microbiology, pathology	Chemotaxonomy, ecosystem functions machine design, chemical processes microbe and metabolite identifications

variety of possible analytes have a number of advantages over traditional analytical instruments. Electronic nose sensors do not require chemical reagents, have good sensitivity and specificity, provide rapid results, and allow non-destructive sampling of odorants or analytes. Furthermore, e-noses generally are far less expensive than analytical systems, easier and cheaper to operate, and have greater potential for portability and field use compared with complex analytical laboratory instruments. Thus, electronic noses have far greater potential to be used eventually by unskilled consumers for innumerable practical applications in residential and public settings. Some disadvantages of e-nose sensing include problems with reproducibility, recovery, negative effects of humidity and temperature on the sensor responses, and inability to identify individual chemical species with sample gases. Thus, electronic noses will never completely replace complex analytical equipment or odor panels for all applications, but offer quick real-time detection and discrimination solutions for applications requiring accurate, rapid and repeated determinations. Such applications are becoming increasingly common and required for highly-mechanized industrial manufacturing processes.

The potential for future developments of innovative e-nose applications is enormous as researchers in many fields of scientific investigation and industrial development become more aware of the capabilities of the electronic nose. The current trend is toward the development of electronic noses for specific purposes or a fairly narrow range of applications. This strategy increases e-nose efficiency by minimizing the number of sensors needed for discriminations, reducing instrument costs, and allowing for greater portability through miniaturization. The new discoveries will lead to the recognition of new ways to exploit the electronic nose to solve many new problems for the benefit of mankind. Similar capabilities for identifying components of solid and liquid mixtures may be possible with devices called electronic tongues.

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of various parameters such as field strength, electrode configuration, air humidity, air temperature and product variety are important for best results. ii) It would be a great benefit to undertake a techno-economic study on the energy saving aspect of electric field drying so as to promote acceptance on an industrial scale.

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