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EMERGING TECHNOLOGIES AND TRENDS IN POSTHARVEST PRODUCTS PRESERVATION AND PROCESSING: A REVIEW

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Abstract – *The development of techniques such as instant controlled pressure drop, nanotechnology, pulsed electric field and ultrasound treatment have spanned over many years and culminate today as an effervescent research topic in the food processing field. Mainly striving to improve the efficiency of our current processes and to steer food processing towards a greener, more sustainable state, most of these innovative methods compile promising results when combined with conventional techniques. In the face of undeniable environmental challenges and growing demand from consumers, sustainability and economic values should come hand in hand to consider a responsible future for the food industry. Thus, applications of the presented technologies each have demonstrated lower energy and water consumption, lower processing times and improved end-product quality.*

Keywords: food preservation, sustainability, emerging technologies, postharvest.

I. INTRODUCTION

Postharvest technology encompasses different strategies of processing, packaging and storing food products as to minimize undesirable changes in quality parameters and extend the shelf-life of perishable goods. Some conventional processing techniques such as heating, drying and freezing, have been commonly used for many millennia and are proving to be fundamental in the postharvest food industry today [1]. However, many of these traditional methods impose undesired physical, chemical or microbial changes to the treated product, and often lead to losses in nutritional values and sensory quality. Moreover, low production efficiency and lengthy time and energy consuming procedures are frequently encountered using these conventional techniques. As the turn of the twenty-first century revealed increasingly alarming cues about the environmental challenges ahead, it has become of paramount importance that our various industries respond by pursuing and developing new innovative and sustainable ways to ensure a responsible continuation of our activities. The development of alternative "green"- environmentally friendly-food technologies currently constitute an emerging applied research area. This whole new concept of green processing is based on the discovery and design of technical processes which will mainly reduce energy and water consumption, while safeguarding end-product quality and allowing for better by-products recycling [2]. Current knowledge and basic principles of important emergent technologies like ultrasound, pulsed electric field, nanotechnology and instant controlled pressure drop are briefly reviewed in the hereby paper.

II. INSTANT CONTROLLED PRESSURE DROP TECHNOLOGY

Instant controlled pressure drop (Détente instantanée contrôlée in French or DIC) is an innovative and energy efficient process developed by French chemical engineers, as an alternative to conventional food drying and decontamination methods [3]. Based on thermomechanical effects triggered by abrupt pressure drop, this technique induces instant

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water evaporation and inactivation of vegetative bacteria and spores in treated samples [4]. In addition, the process results in positive texture modification, volume expansion and higher porosity which also increases the efficiency of subsequent solvent extraction processes [2].

A. Process overview

DIC technology is considered to be a high temperature/high pressure short time (HTST) type treatment followed by a rapid pressure drop towards vacuum [4]. The first step of the process consists of a short heating period (10-60 seconds) of the initially put under vacuum product, through dry saturated steam injection under high pressure (up to 1MPa) [3]. The initial vacuum ensures rapid contact between the steam and the sample, thus maximizing heat transfer efficiency. During this step, the product is effectively heated and its moisture content increases 0.1 g H_2O/g dry basis due to vapor condensation [3]. The product is then subjected to an abrupt pressure drop rate (0.5 MPa.s^{-1}) toward a vacuum (3-5 kPa) over a 10 to 60ms time lapse. This rapid pressure drop induces a significant mechanical stress related to the instantaneous auto-vaporization of water and cooling of the sample, which furthermore leads to a swelling phenomenon (product expansion) causing the rupture of cells and secretion of metabolites through cell walls [5]. The instantaneity of the cooling has the advantage of preventing thermal degradation of the sensitive compounds, compared to the traditional convective airflow drying method. Moreover, the newly expanded and porous texture induced by the pressure drop increases specific surface area and reduces diffusion resistance of the sample [3]. These changes ultimately result in improvements in many functional properties of foods while safeguarding their nutritional and sensory quality [6]. The results so far are promising, but the large-scale implementation of DIC has yet to concretize. The costs are still high and maintenance might be demanding.

The equipment required for DIC processing is composed of four major components: (1) an autoclave with a heated jacket which acts as the processing vessel where the product is to be placed, (2) a pneumatic pressure-drop valve ensuring quick and controlled liberation of steam pressure from the processing vessel to the vacuum tank, (3) a vacuum system composed of a vacuum tank with a cooling jacket and (4) an extract collection trap used to recover condensates [2]. The vacuum tank volume is usually 100-130 times higher than the processing vessel and a water ring pump maintains the tank pressure at about 2.5-5 kPa during treatment [3].

B. Drying application of DIC

As mentioned above, convective airflow drying remains the main drying operation in food processing today. Poor end-product quality associated with this method is principally related to thermal degradation and to the compactness of texture at the end stages of the drying process [7]. Because of shrinkage of foods during drying, the water is entrapped in a dense matrix and its movement toward the external surface becomes difficult [3]. It is possible to overcome shrinkage problems by inserting DIC treatment in the drying process, which increases effective water diffusivity and specific exchange surface [8]. The DIC treatment using saturated steam as a texturing fluid improves dehydration kinetic and allows the spray-dried products, such as apple and onion fine powder food, to be expanded [2]. In one demonstration study, the drying process for apple granule powder was reduced from six hours (untreated apple) to one hour for the treated sample after DIC texturing treatment [9]. DIC coupled with hot air drying furthermore allows to preserve nutritional value and bioactive molecules. Alonzo-Macías et al. [10] effectively showed that, at optimal DIC conditions (0.35 MPa of assaturated steam pressure sustained for 10 seconds), treated strawberries had richer anthocyanins and phenolic compounds values compared to other classical drying methods.

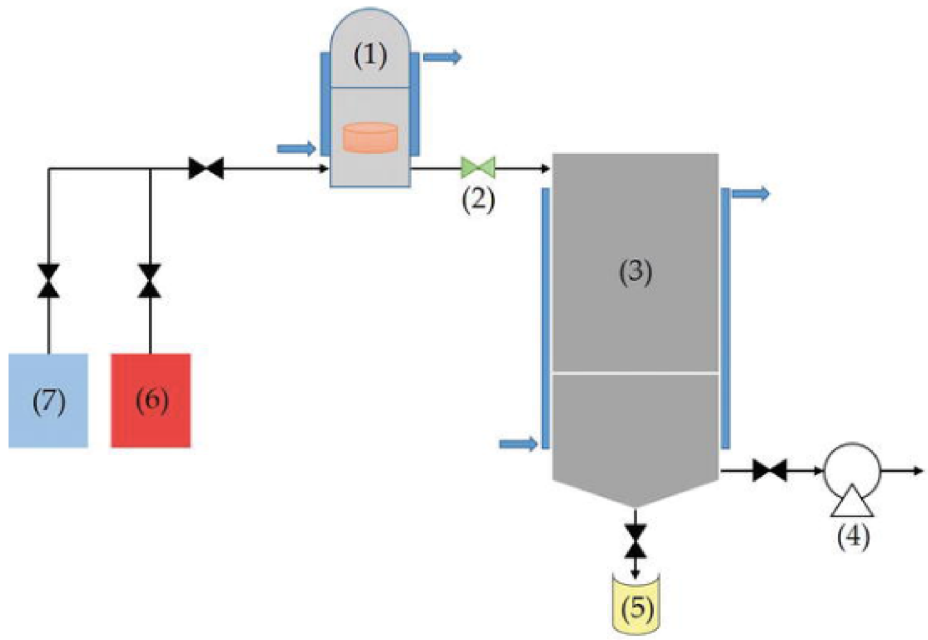

Fig. 1: Representation of a typical DIC equipment setup: (1) treatment vessel, (2) controlled instant pressure drop valve, (3) vacuum tank with cooling jacket, (4) vacuum pump, (5) extract collection trap, (6) steam generator, and (7) air compressor [3]

This technology is also largely used for the postharvest processing of paddy rice, one of the major cereals and raw food source produced throughout the world [11] The DIC treatment combined to classical hot air drying is thus considered to be an intensifying tool for drying processes [2], [3].

C. Decontamination application of DIC

Alongside its application as a drying method, DIC technology can also be used as an effective decontamination process for powders, species, pharmaceutical products, animal feed, fresh-cut fruits and vegetables [3]. Thermal decontamination of solid foods faces several difficulties such as color changes, loss in aromatic compounds and nutritional value, and overall heat damage to the end product [3]. Moreover, high microbial load generally characterizes the dried foods (spices and herbs) and the use of these ingredients in ready-to-eat plates without further heat treatment can be a serious source of hazards [12]. Steam treatment can be used as a simple decontamination method, but its effectiveness reliably depends on the type of product and target microorganisms [13]. Likewise, athermic decontamination processes such as high-pressure treatment are specifically more efficient for thermally sensitive products like food powders. Through the combination of steam heating and high-pressure treatments, DIC technology has shown to be able to eliminate microorganisms in a large array of products [14]. The effective microbial inactivation results from thermomechanical impacts inducing protein denaturation and the explosion of bacterial cells and spores [3].

Concerning allergens removal, DIC treatment also produces a significant reduction in the overall *in vitro* IgE binding for peanuts, lentils, chickpeas and soybeans proteins [15]. The immunoreactivity of soybeans proteins was almost completely abolished with a 3-minute treatment at 0.6 MPa, while a 25 seconds treatment at 0.4 MPa greatly reduced the IgE bindings of whey proteins [15].

III. NANOTECHNOLOGY

The novel field of nanotechnology has had its competence proven in an incredibly diverse range of applications, finding usage in each and every field of science in technology known today [16]. In food science as such, nanotechnology has a lot of potential that can be harnessed for the improvement of the quality and safety of the food. From enhancing shelf life to improving food storage, from tracing contaminants to introducing antibacterial and health supplements in food, advances in applied nanotechnology play a crucial role in food science [17]. This section of the paper is focusing on its applications in the preservation portion of food processing.

A. Nanoencapsulations and Nanoemulsions

Nanoencapsulation is a method that provides several benefits for food processing in general, such as enhanced product stability, protection against oxidation, retention of volatile ingredients, tastemaking and many others [18]. It is carried out via nanocapsules, hollow polymer particles with dimensions in the submicrometer region that can contain large quantities of guest molecules in their empty core domains [19]. These guest molecules can then provide great advantages for food preservation, and even contribute massive health benefits as the nanocapsules are frequently used as active target-specific drug and nutrients carriers [19], [20]. These small-sized capsules can also be involved in the entrapment of odour and unwanted components, resulting in increased shelf life of food [16]. Nanocochleates, nanocoils made from soy based phospholipids, also improve the quality and preservation of processed food by wrapping around micronutrients in order to stabilize them and prevent them from degradation [21]. There are six basic ways of preparing nanocapsules; nanoprecipitation, emulsion-diffusion, double emulsification, emulsion-coacervation, polymer coating and layer-by-layer [22]. Similar to nanoencapsulation, the nanoemulsion technique helps in releasing different flavours, supplements and antimicrobial agents to the food, but do so through stimulations in the form of pH, heat, ultrasonic waves and so forth [16]. Because of their antimicrobial activity, they constitute an efficient way of decontaminating food packaging articles in addition to protecting the functional compounds' flavours from the degrading actions of pH changes, enzymes, temperature and oxidation processes [23]. Nanoemulsions are created either through high energy approaches (high pressure homogenisation, ultrasound method, etc.) or low energy approaches (membrane and spontaneous emulsification, solvent displacement and so forth) [24]. The nanoemulsion and nanoencapsulation methods are commonly considered food processing techniques since they aim at preserving and improving food through internal transformations, such as incorporation of new nutrients and antimicrobial agents [16].

B. Nanoparticles, Nano composites and Nanosensors

Other nanotechnologies operate on the external level, mainly aiming at providing protection from outside factors by acting as a physical barrier or through improving treating and handling techniques [16]. Nanoparticles like nanosilicates, titanium oxide and zinc oxide are used in the form of plastic films to reduce the flow of oxygen inside the packaging container. In doing so, they also decrease the leakage of moisture, keeping the product fresh for a longer period [25]. Silicon dioxide and titanium dioxide are two of the most commonly used nanoparticles in food packaging [16]. The former helps absorbing water molecules in food, acting as a drying agent, while the latter finds its use as a photocatalytic disinfecting agent and as a UV barrier [26], [27]. Nanosized silver particles effectively have antimicrobial properties and protect the food from infestation. It infiltrates the microbial system and disrupts ribosomal activity and the production of enzymes. Being a stable element, having a broader spectrum of activity and being able to penetrate through biofilms are some of the advantages that put silver above the other antimicrobial metallic nanoparticles as a preferable material [26]. Silver nanoparticles are also known to extend shelf life of fruits and vegetables by absorbing and decomposing ethylene [26]. Some other nanoparticles contribute to physical removal of pathogens or unwanted chemicals from food through selective binding [28].

Nanocomposites are usually made up of polymers in combination with nanoparticles, and provide highly versatile chemical functionalities that are used for the development of high barrier properties [29]. Much like some previously mentioned nanoparticles, nanocomposites increase the shelf life of products by acting as a strong gas barrier minimizing the leakage [29]. A common example of such nanocomposites are nanoclays based polymers, which are inexpensive, stable and ecofriendly naturally occurring aluminum silicates [30]. Their biodegradable nature, low density, transparency, good flow, and better surface properties renders them some of the most commercially successful nanocomposites on the market, being especially used for carbonated drinks containers [31].

Nanosensors on the other hand are mainly used to detect changes in the composition of the food, whether in colour, humidity, heat, gas or chemicals [16]. In doing so, they improve food safety by directly alerting the consumers regarding the quality of the product. Other types of sensors are also used to detect food borne pathogens and can be installed right during the packaging steps [32]. This contributes to improving the efficiency and shortening the processing chain, as packaged products don't need to be sent to the lab for sampling before being put on the shelves [16]. The most frequently used sensors in the packaging industry are time-temperature integrator and gas detectors, which are made up of metals (such as palladium, platinum and gold) and conducting polymers [33], [34]. In agriculture, nanosensors are used to assess and monitor soil conditions required for the growth of crops. They also help detecting the presence of pesticides on the surface of fruits and vegetables [16]. Moreover, some sensors have been developed to detect carcinogens [35], and even environmental pollution [36] in food materials. Nanobiosensors are another specific type which proved to be quite efficient at determining the presence of mycotoxins and several other toxic compounds, while making their removal easier [37], [38].

IV. PULSED ELECTRIC FIELD

One of the oldest developed technology presented in this review article, pulsed electric field (PEF) treatment is a non-thermal food processing method where an electric field is applied to a living cell for a very short duration that varies from several nanoseconds to several milliseconds [2]. Non-thermal inactivation of a variety of microorganisms and enzymes through the use of electric fields has been effectively demonstrated as far back as the 1920's [39]. However, it has significantly gained importance in recent years as an emerging technology to replace or complement the traditional thermal techniques, due to the many relevant advantages that this method procures.

A. *Process overview*

Non-thermal processes such as PEF offer the benefits of low energy utilization, low processing temperature and efficient retention of flavours and nutrients while countering spoilage [39]. As shown in figure 2, PEF treatment inactivates microorganisms by induction and alterations in different electric potentials between each side of the membrane, which causes damages to cellular structural integrity and increases membrane permeability [40]. Critical values for inactivation by inducing irreversible electroporation can be easily adjusted for different microorganisms and purposes. Such treatments are mainly intended for food preservation, but can also be applied to improve other processes like extraction of target compounds from food matrices [41].

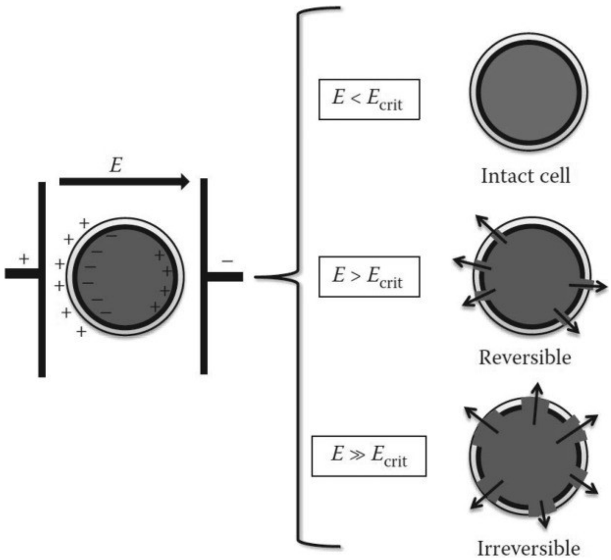

Fig. 2: Schematic mechanism of membrane permeabilization and inactivation, induced by an external electric field. E = external electrical field; E_{crit}= critical external electrical field [40]

The efficiency of PEF depends on the treated food product and on operating parameters such as pulse shape, pulse time/length, intervals between pulses, polarity, strength of electrical field, frequency and target temperature [40]. Despite great promises for the applications of pulsed electric field technology in the food processing domain, some important limitations and challenges still remain to be overcome for industrial implementation. These include high initial equipment cost, scaling-up difficulties, air bubble formation that can induce dielectric breakdowns of treated products, limited inactivation on certain enzymes and resistance of some microbial species, including bacterial spores [42], [40]. In addition, content of diverse chemical components in foods has inconsistent effects on electrical conductivity which makes it hard to implement a "one size fits all" approach. Each food thus need to be separately tested to identify adequate set of PEF parameters [43].

B. Food preservation applications

As aforementioned, PEF treatment can achieve better quality retention in products compared to thermal processing, especially in liquid food [2], [40]. In a particular study, treated beverages with PEF seemed to have higher contents of polyphenols, carotenoids and vitamins compared to those treated via heat pasteurization [44]. PEF treated foods are often packaged after their preservative treatment, although an energy friendly "batch mode" treatment in conductive plastic material could also be achieved with similar inactivation results [45]. Given some reported limitations, it may be advantageous to combine PEF with other types of treatment like pH and temperature, as such combinations may provide the required lethality at lower field strength and with lower energy costs [2]. Freezing, another widespread preservation method which has numerous disadvantages on food texture and flavours, exhibits food deteriorations mainly due to the formation of crystals during treatment operations [2]. Reversible electroporation (and the increased membrane permeability associated with it) achieved through PEF enables the introduction of cryoprotectants molecules into the biological cells [46]. This combination leads to a noticeable acceleration of the freezing/thawing process and the decrease of ice propagation rate [47]. Other treatments involving temperature above 60 ^oC and electric field higher than 30kV/cm were shown to be effective on spore inactivation [2]. Moreover, combination of PEF with an osmotic dehydration treatment resulted in an increase of water loss and migration of solutes into the food matrix [48]. A significant energy consumption reduction could also be accomplished via the combination of PEF treatment with freeze drying and radiant and convective heat drying. Cooling and drying times were accelerated when apples and potatoes were electrically treated prior to freeze drying, while similar observations were reported for radiant and convective air drying [2].

V. ULTRASOUND

Ultrasound characterizes a sound frequency in the range between 18 and 100 kHz, which is above human hearing. These high power, low frequency ultrasounds are increasingly used in the food industry as an antimicrobial technique to improve the preservation of postharvest products [2].

A. *Process overview*

The inactivation effect on microorganisms is caused by acoustic cavitation following the passage of frequencies in the food matrix. Cavitation is the process where micro bubbles are created in a liquid phase when subjecting a mixture to ultrasound. These bubbles will grow and oscillate quickly before eventually collapsing due to pressure changes [49]. The contained variations in pressure and temperature lead to the collapse of cell walls, dilution of cell membranes and DNA damage due to free radical production [50]. These violent implosions will also fragment or disrupt the surfaces of solid matrix, thus enhancing mass transfer and accelerating diffusion [2]. The effectiveness of the process ultimately depends on the acoustic frequency, temperature and pressure applied. Lower frequencies will generate larger bubbles and a more violent collapse while higher frequencies will produce more collapse events per unit of time [49]. The current main system by which ultrasounds are delivered to such food products is the horn system (figure 3), where the sonic probe is directly immersed into the medium. The container (reactor) in which the product is placed to receive the treatment is usually made of a double mantle into which cooling water can circulate, in order to counter fast temperature rises and maintain it constant [2]. As of right now, reactors from 30 to 1000L are being developed for industrial trials but it is clear that the scaling up of this technology remains a very concrete limitation [50]. The fact that solids and air contained inside the products affect the depth of infiltration, and thus the efficiency of ultrasound treatment, is also a problematic issue. Furthermore, the creation of free radicals in the food represents a possible harm for consumers [50].

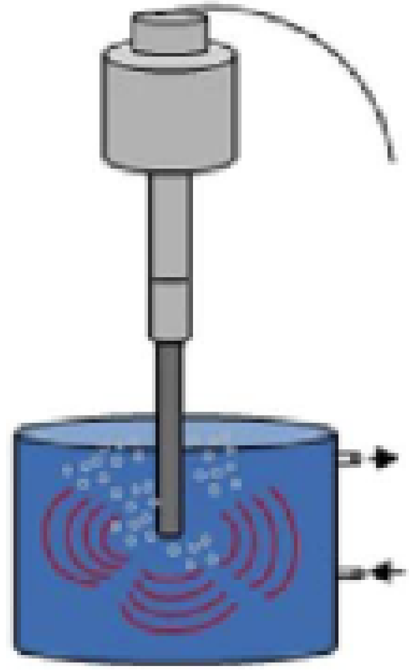

Fig. 3: Schematic depiction of the horn system using a single ultrasonic probe delivering the treatment directly in the medium [2]

B. *Food preservation applications*

Ultrasound alone is known to disrupt biological cells, but combining it with heat treatment can also accelerate the sterilization rate of foods, reducing both the duration and intensity of the thermal treatment and the resulting damages [2]. As with many other preservation methods, ultrasound's antimicrobial efficiency has been studied in length using microorganisms such as *Saccharomyces cerevisiae* and *Escherichia coli* in some culture media and in foods. *S. cerevisiae* has been found to be particularly sensitive to ultrasound treatment compared to other vegetative cells, which is mostly attributed to its larger size [51]. The combination of heat treatment with ultrasound has been observed to produce a synergistic effect, greatly increasing kill rates for *E. coli, P. fluorescens, S. aureus* and *L. monocytogenes* in water and phosphate buffers, as well as in milk [2]. Some food materials require enzyme inactivation in order to be stabilized, which can easily be achieved via heat treatment. However, high heat resistance of some enzymes may be a problem as prolonged heat treatment negatively modify some food properties. Increased interest in alternative methods like ultrasonication thus drove enzyme inactivation research in that field. The effects of ultrasonic waves on proteins are complex in nature. Under oxygenic conditions, polymeric globular proteins are broken down into subunits by the waves in such a manner that the quaternary structure is not recoverable. If the ultrasonic irradiation is long enough, proteins can be hydrolysed and polypeptide chains can be broken [2]. Generally, ultrasonic treatment in combination with other treatments is more effective in food enzyme inactivation. Manothermosonication (MTS), which is the combination of heat, ultrasound and pressure treatments, has an increased effectiveness compared to ultrasonication alone and inactivates several enzymes at lower temperatures and/or in shorter time than thermal treatments at the same temperatures [50].

VI. CONCLUSION

In conclusion, the use and research of innovative and green technologies in all facets of the food industry is becoming increasingly important with the growing environmental challenges ahead of us. Emerging methods such as instant controlled pressure drop, nanotechnologies, pulsed electric field and ultrasound treatment, have all shown their potential in reducing energy and water consumption while also maintaining, or even improving, end-product quality in post-harvest preservation processes. Through their combination with conventional techniques like temperature or convective air drying treatments, these technologies have demonstrated significant reductions in processing time and have enabled the circumvention of traditional deteriorations and limitations. In addition, the use of several of these methods for preservation purposes also generates many more advantages for other processes related to extraction and food transformation. While the current results are very promising, most have been obtained at laboratory scale and many apparent issues still remain to be resolved in order to pursue industrial scale implementation. Nonetheless, the growing consumers awareness and demand for eco-friendly industrial practices should provide a timely incentive for the food industry to further the research and development of such technologies, and to initiate an imperative green transition.

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