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Pulsed electric field and high voltage electrical discharge - innovative food electrotechnologies. A review

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Abstract

Various alternative technologies have been designed in the food processing context due to the increase of consumers' demand for high quality foods. Amongst these, the Pulsed Electric Fields and High Voltage Electrical Discharge electrotechnologies are considered a feasible alternative to conventional food processing technologies due to their properties, such as: microorganism inactivation with retention of the foods' sensory quality, positive effect on enhancing the active compounds extraction, and green extraction. This paper reviews the mechanism of Pulsed Electric Fields and High Voltage Electrical Discharge technologies for microorganism inactivation, while addressing the benefits and drawbacks of these technologies.

Keywords: Pulsed Electric Field, High Voltage Electrical Discharge, Food processing, Antimicrobial effect, Bioactive compounds extraction

1.Introduction

Numerous emerging technologies have been developed in the food processing context due to the increase of consumers' requirements for high sensory and nutritional quality food products [1, 2]. These emerging technologies not only prove efficiency at food processing level, but also have the potential to revolutionize the bioprocessing industry [3, 4]. Amongst these, the Pulsed Electric Fields (PEF) and High Voltage Electrical Discharge (HVED) are the most referred to as alternative food technologies, also known as electro-technologies, based on the application of pulsed electrical field [4]. PEF is used in different domains like the food industry (*e.g.* spoilage microorganism inactivation, food processing – both liquids or solids, extraction of different active compounds), biotechnology (*e.g.* direct gene electrotransfer), and medicine (tissue ablation, *e.g.* liver ablation) [1, 2, 4-11]. PEF involves the intermittent (<300 Hz) high voltage electric short pulses (from a few microseconds to a few milliseconds) or ultrashort pulses (a few nanoseconds), having between 0.1 to 50 kV/cm or even more function of the potential difference between the electrodes, applied to a target biological material (cells from plant tissues, food matrices, microbial cell suspensions), causing a temporary or a permanent electropermeabilization of cell plasma membranes [1, 2, 6-9, 12-16]. For the pulpy plant tissues the crucial electric field (EF) strength is in the range of 0.1-10 kV/cm, for hard vegetable materials (*e.g.* grape or sesame seeds) the EF values are up to 20 kV/cm, whilst for microbial cells EF is in the range of 12-20 kV/cm (5-20 kV/cm for archaea and bacteria, and 1-12 kV/cm in case of the microalgae and yeasts) [6, 8, 14, 15]. PEF efficiency is influenced by several interdependent factors, such as: biological factors (cell arrangement, position, and density; size, cell shape, and type; envelope structure; tissue characteristics), physical and chemical properties of the treated fluids (conductivity, ionic strength, and *p*H), distance between the working electrodes and their geometry, and the electrical parameters (amplitude, shape, duration, number of the electric pulses, and frequency) [1, 2, 4, 8, 10, 13-16]. The efficacy of PEF is conditioned by the sum of all these factors, the maximum electropermeabilization being obtained by applying different combinations of EF strengths and treating times (the number of pulses multiplied by the duration of pulse) [8].

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HVED is used in different domains just like PEF: the food industry (*e.g.* inactivation of enzymes and undesirable microorganisms; non-thermal pasteurization and sterilization of the liquid food products), biotechnology (*e.g.* yeast cell breakdown for subsequent protein release; extraction of active compounds from different biomass plants like grape by-products, flaxseed cake, fennel, olive kernels, rapeseeds, sesame cake, beet pulp, and dried stevia leaves), and medicine [1, 17-20]. HVED technology employs powerful dynamic shock waves created by an electrical arc, which generates the breakdown of the cell membranes and tissues, and accelerates the extraction of intracellular components [1, 18, 21-23]. This technology directly sends energy into a liquid through a plasma channel created by a high-current/high-voltage arc discharge between two electrodes submerged within a treatment chamber [17, 20, 21, 23, 24]. HVED processing impact may be maximized by some factors, such as: biological factors (*e.g.* initial concentration of the cells, type of the microorganism), the physical and chemical characteristics of the liquid (*e.g.* conductivity, *p*H, volume, distribution of the chemical radicals), working electrode material, geometry of electrodes, distance between the electrodes, and several electrical parameters (*e.g.* electric field voltage, amplitude, number of the pulses) [19, 20]. The objective of this review is to highlight some aspects related to the mechanism, benefits and drawbacks of both PEF and HVED. It is expected that the information displayed in this review should open new research vistas aimed at implementing these technologies at large food bioprocessing scale, due to their more innovative features and potential applications in developing innovative food products.

2. PEF

PEF includes the application of short pulsed high electric field to a material placed between two electrodes, and has the irreversible microbial electroporation ability that leads to the killing of microorganisms [2].

2.1. PEF mechanism

The inactivation of the biological cells (eukaryotic and prokaryotic) by an external EF is a dynamic multi-phase process that consists of: (*i*) the increasing of the cell transmembrane potential, (*ii*) the pore beginning phase, (*iii*) the population pore evolution phase, and (*iv*) the post-treatment phase (either pore resealing occurs or the cell plasma membrane is not able to recover the pores) [10, 13, 16]. Pore resealing can be entirely reversible and the cells survive, or irreversible when the small different compounds go out of the cells and the cells die [10, 13, 16]. Membrane stability changes when the cells are exposed to EF, the ions migrate toward the cell plasma membrane, creating the free charges with opposite sign (- and +) that line up the outer and inner membrane sides [2, 10, 25]. These free charges accumulated on both membrane sides are attracted to each other, and induce electrocompression that takes the place of the membrane elastic resistance [10, 13]. The accumulation of free charges on the cell plasma membrane generates an initial transmembrane potential (TP) [13]. EF use induces a potential (IP - induced potential) that is overlapped onto the TP, and it makes the TP reach a critical value (BP-breakdown potential), and the formation of pores or nanopores (in case of nanosecond PEF) takes place (electroporation) [2, 9, 10, 13, 25]. The electroporation action can go from the magnification of existing pores to the start of new pores of temporary or permanent nature, even impacting the intracellular structures [4]. More precisely, the membrane break occurs when and where the sum of the TP and IP equals the BP [13]. The cell plasma membrane may be broken as an effect of Joule overheating of the plasma membrane surface, or of the chemical disequilibrium induced by the increased transmembrane transport throughout the membrane pores [2, 10, 16]. The great transmembrane potential sets a pressure on the plasma membrane that leads to lowering the membrane thickness, losing the membrane integrity, and cell rupture [13]. The biological cells (bacteria, fungi, mammalian) die after PEF either by letting go of the intracellular components outside of the cells, or through apoptosis or necrosis and/or osmotic swelling [10, 13, 16]. These phenomena occur when the transmembrane potential is approximately 1 V (critical value) [4, 10, 13]. The electrical breakdown, as effect of the PEF, can be reversible (pore resealing, with applications in biotechnology, medicine, molecular biology) or irreversible (applications in the food industry to retain the quality of foods, and vegetable processing, mainly cell disintegration and permeabilization within tissues) [2, 10, 13]. Nevertheless, the mechanism of electroporation is not fully elucidated [8].

2.2.PEF benefits

PEF has proved useful in enhancing food quality (*e.g.* minimizing fat uptake; reducing the effect on sensory features like color, flavour; amplifying health-related compounds; improving protein functionality) [2, 8, 10, 14, 15]. PEF treatment decreases the number of microorganisms, enhancing the shelf-life of food products. This technology can also reduce the deterioration of thermolabile compounds (*e.g.* PEF treatment provides superior retention of vitamin C compared to freezing, blanching, and high pressure treatments) [8, 14, 15]. PEF technology also offers extraordinary potential for innovative healthier foods development, being now employed in potato chips manufacturing on industrial scale [8, 14, 15, 26]. PEF punctures the cell walls of the potatoes generating micro holes that permit the asparagine and sugars to be washed out of the potatoes, which decreases acrylamide formation [27]. In the potato industry, future uses of PEF may result in improving the blanching, drying and wastewater treatment [28]. The manufacturing of dried or fried snacks from other vegetables (tubers or roots) can also benefit from PEF [14]. Recently, it has been discovered that PEF improves the solid-liquid extraction of different active compounds like anthocyanins, pectin, polyphenols (from fresh tea leaves, grape seeds, spearmints), pigments (*e.g.* betanine from red beetroot, carotenoids from tomatoes, pumpkin), colorant (from red prickly pear), stevioside, rebaudioside A and chlorophyll b (from stevia leaves), as well as oils extraction from different vegetables (*e.g.* olive, potato, pepper) [3, 4, 8-10, 14, 15, 29-37]. This innovative electrotechnology can be successfully included amongst other modern green extraction technologies (*e.g.* enzyme assisted extraction, high voltage electric discharge, hydrostatic pressure processing, microwave-assisted extraction, pressurized liquid extraction, pressurized hot water extraction, supercritical fluid extraction, and ultrasound-assisted extraction) [17, 38, 39]. PEF has also been suggested for enhancing other processing activities, such as hot air drying, freeze-drying, frying, osmotic dehydration, assisting cutting/slicing (*e.g.* vegetable snacks manufacturing) or peeling (whole fruits and vegetables) [8, 14, 15, 40]. PEF action could also be used in softening interventions to include active biocompounds into vegetable materials, viz. a potential strategy to manufacture functional food products [41]. In addition, PEF technology is environmentally ecofriendly, and notably contributes to the development of a green, sustainable, circular economy [4, 14, 42].

2.3.PEF drawbacks

Although PEF technology has many benefits, some researchers pointed out that this technology has a few drawbacks, like high cost of the pulse generators, absence of well standardized procedures, reliability and duration of the systems and bulk capability, electrochemical reactions, corrosion and the migration of electrode construction materials [3, 4, 10, 15]. There is deficient trading accessibility of PEF technology systems due to its great initial price, which is higher than the other food processing equipment (*e.g.* refrigeration) [1, 10]. Therefore, an important percentage of the food manufacturers have decided to use the traditional food processing treatments (*e.g.* canning and refrigeration) as opposite to using PEF technology [1, 10]. In addition, an efficient color extraction from vegetable resources by PEF strongly affects the industrial process in terms of price and time [10]. Finally, one of the most critical problems of PEF may be the corrosion and the migration of metal electrode materials, which can lead to sensory changes in liquid food products [3, 4, 10, 43]. The contamination of the foods with the corrosion products cannot be allowed in food industry, the corrosion products raising health problems for food consumer [44]. Therefore, the manufacturing of working electrodes from materials resistant to corrosion should be investigated [3, 43].

3. HVED

HVED has microbiocidal activity due to the generation of chemically active substances and UV radiation by the discharge itself, as well as shock and acoustic waves [45].

3.1. HVED mechanism

The mechanism of disintegration of biological cells exposed to HVED treatment is a dynamic multi-phase process which consists of: (*i*) generation and propagation of streamer and arc, (*ii*) development of the vapour cavities, (*iii*) generation of the shock wave, and (*iv*) breakdown of the cells (the components go out of the cell) [17, 19]. The breakdown in water consists of two distinct stages, i.e. streamer (S) (pre-breakdown) and electrical arc (AE) (breakdown stage) [42]. In the pre-breakdown stage a S is generated at the point tip due to the high local electrical field, the S consisting of thin ionized vapour channels, which are transmitted towards the opposite electrode (from the positive to the negative electrode) at approximately 30 km/s (positive high voltage applied to the point electrode) [17, 19, 21, 23, 24, 46]. When the S becomes the grounded plane electrode, an AE occurs within the ionized vapour channels, the arc resistance decreases in a few nanoseconds (a very short time). That is why the current increases and the voltage is released very rapidly, so the gap is almost short circuited, the current being restricted by the external electrical circuit. The electrical energy per pulse refers to the sum of the energy first released when the S propagates, and the energy later dissipated in the AE [17]. In the inter-electrodes space, the gaseous bubbles arise and propagate (maximum diameter of a bubble being approximately 12 mm or about 2 mm for the filament) during the processes of S and AE generation, with a longer lifetime during the AE process (2000 milliseconds) than the S process (400 milliseconds) [17, 42]. The gaseous bubble passes through four stages (appearance, expansion, implosion and collapse); the expansion of the gaseous bubbles leads to a very fast movement of a significant mass of fluid which encloses the ionized vapour plasma channels, and distorts the solid material. When an AE occurs as the S becomes the plane electrode, the energy scattered unexpectedly enhances within the filament and results in further increase of the vapor volume [17]. A shock wave is generated and conveyed in the enclosing liquid, and a great number of small dimension cavitation bubbles with short lifetime (400 milliseconds) are shared out in the liquid volume [17, 42]. AEs are related with the emission of a strong shock wave, which transmits radially into the liquid volume, the shock wave being accompanied by a rarefaction wave that generates cavitations [17]. The collapse of these cavitations generates powerful secondary shocks with very short lifetime (60 nanoseconds) that disintegrate the biological cell structure and consequently the intracellular compounds get out of the cell [1, 17, 23]. The shock wave could be accompanied by an acoustic energy due to the pressure (about 100 bar) in the treatment chamber [17, 47]. The transmission of shock waves and the explosion of cavitation bubbles lead to particle fragmentation at specific energy input per pulse (*e.g.* grape seeds treated by electrical discharges are fragmented when the pressure shock wave is higher than 100 bar) [17, 19, 21]. At a lower specific energy input per pulse, a weaker shock wave (pressures below 100 bar) develops, and the grape seeds are almost intact and look like the untreated seeds. Biological cells that are located in the front of the shock wave are forwarded to a great compression in a very short period (micro- or nanoseconds) [17]. After the successful discharge treatment, the size of the particles treated by electrical discharge is first similar to that obtained after grinding the product; the size decrease after the discharge treatment has a positive impact on the extraction efficacy of the active compounds [17, 19]. The arc discharge leads to the production of hot localized plasma that firmly emits high-intensity UV light (with mutagenic impact on the cells), produces shock waves (mechanical breakdown of the cell membranes) and induces hydroxyl radical formation (oxidative cell damage) during water photodissociation [1, 17, 42].

3.2. HVED benefits

HVED treatment shows better retention of the fresh flavor and nutritional value, and prolongs the shelf life of liquid food products (*e.g.* HVED-treated fresh-squeezed grapefruit juice was found to have fresh flavor and a shelf life of more than 100 days) [20]. Besides, as a non-thermal technique, HVED can extract bioactive compounds in mild temperatures and the temperature elevation after extraction is low, for which the thermal reduction of active compounds could be excluded [19]. Moreover, HVED technology is regarded as a good choice in disinfecting food contact surfaces due to its high efficacy on spoilage and pathogenic bacteria destruction [20]. In addition, HVED technology is considered environmentally ecofriendly [17, 19, 42].

3.3. HVED drawbacks

Although HVED technology has several advantages [1, 17, 19, 20], some of these authors pointed out that this technology has a few drawbacks like the contamination of treated foods by chemical products of electrolysis, and disintegration of food particles by shock waves [20]. With indirect arc discharge, the energy from the EF can be converted to plasma, then to shock waves, producing free radicals and oxidizing species within the food that may oxidize some active compounds (*e.g.* polyphenols), thus reducing their beneficial properties [17, 20, 24, 42].

4. Conclusions

It is evident in the literature that the PEF and HVED are developed in the food bioprocessing context. The clear advantages of these pulsed electrotechnologies are microorganism inactivation, retention of the foods' sensory characteristics, positive impact on bioactive compounds extraction, modern green extraction, having a very promising potential for innovative food products design. Despite many benefits, the drawbacks of PEF (electrochemical reactions, corrosion and the migration of electrode construction materials, high cost) and HVED (contamination of treated foods by chemical products of electrolysis and disintegration of food particles by shock waves, high cost) need further research to implement these technologies at large food bioprocessing scale

Compliance with Ethics Requirements. Authors declare that they respect the journal's ethics requirements. Authors declare that they have no conflict of interest and all procedures involving human or animal subjects (if exist) respect the specific regulation and standards.

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