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Cold Plasma and Ultrasound Applications in Cleaning of Food Contact Surfaces

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Abstract

Decontamination is vital for food processing. Decontamination techniques can be grouped into known techniques such as heat, steam, chemical solvents or gases, radiation and newly developed techniques. Although these methods may give good results in some cases, their effectiveness varies. The use of some of these methods is limited due to safety issues, sensitivity of the materials to be sterilized, limited efficiency and cost results. This leads to the need to remove unwanted side effects and to develop new technologies that will provide a high level of decontamination for heat sensitive materials. Cold plasma and ultrasound techniques offer a variety of potential applications in the food industry. The main applications of cold plasma can be grouped into food decontamination, improvement of food quality, toxin degradation and surface modification of packaging materials. Cold plasma has been proven to be effective for inactivation of various pathogens and degradation organisms without adverse effect. Removal of dirt and residues from the food contact surface and inactivation of microorganisms appear as a result of ultrasound-induced cavitation. It is responsible for the removal of organic foreign substances on the surfaces and is the basic mechanism of ultrasound. In addition to the cleaning effect, the ultrasound has the ability to inactivate certain microorganisms. This study aims to investigate current research and trends in decontamination of food contact surfaces to emphasize cold plasma and ultrasonic applications in the food industry.

Keywords: cold plasma, decontamination, food safety, food contact surfaces, sanitation, ultrasound

1. Introduction

Despite technological advances in the food industry, maintaining hygienic control of equipment and utensils used during processing is still a problem today. Equipment and utensils contaminate food if it is not sterilized as required. It may also reduce the shelf life of the food and the safety of the product [1].

Cleaning and disinfection in food processing are important operations because of the significant contributions to food hygiene and safety. Residues which remain equipment surfaces cannot totally removed by conventional methods and have caused contamination risk. In addition, these methods cause time and energy loss [2].

In recent years, non-thermal sterilization technology has been developed to meet the needs of consumers (such as high pressure processing, ultraviolet, ultrasound, pulsed electric field, irradiation, electrolized water, cold plasma). Among the mentioned sterilization techniques, cold plasma is one of the new sterilization technologies and has a great potential for the protection of foodstuffs due to its high yield and limited side effects [3]. In addition, ultrasound has been applied as a sanitising practice in food manufacturing based on its strong physical and chemical energy on microorganisms, a result of intracellular cavitation [4]. This review will give a brief overview of the cold plasma and ultrasound applications used in the food industry. Subsequently, recent studies of food contact surfaces, tools and equipment decontamination with cold plasma and ultrasound applications have been investigated.

2. Cold Plasma Technology

In general, conventional sterilization techniques, chemical agents, ionizing radiation, and high thermal-pressure exposures are used to get rid of microbial contamination. However, these techniques can damage food and create problems for biological materials [5]. Furthermore, consumers demand for minimally processed foods, this encourages the development of new decontamination techniques, like cold atmospheric plasma system [6]. Plasma; is formed by increasing the energy of the gas of the material to rearrange the electrical structure of the atoms and molecules [7]. Normally, there is an equal positive and negative charge on each atom in the gas phase. The energy given to the substance when it is in the gas phase increases the relative vacancy between the atoms or molecules that make up the substance. It allows the electrons in the compound to be separated. This is called ionization. Ionization in sufficiently energized gas is repeated many times and free electron and ion clouds start to form. As a result, positively charged particles, that is, atoms that have lost their electrons (ions), negatively charged particles (electrons) and uncharged particles are formed. This resulting mixture is called plasma [8]. At the same time, free radicals and reactive species are formed depending on the gas used in the plasma. Cold atmospheric plasma has the potential to inactivation of microorganisms in food production, thereby increasing food safety [9]. Cold plasma can be produced if most of the energy is transmitted to electrons and only reaches high values. There are various plasma chemical reactions in abundance. In this case, neutral particles and ions have only negligible energy and remain cold. Low macroscopic temperature is the main characteristic of Cold plasma and enables the processing of thermolabile materials. Cold plasma can be produced by electrical discharges in gases under low or atmospheric pressure [10]. Plasma species can interact with bacterial cells, effectively inactivate microorganisms, including spores and viruses [11]. In recent years, nonthermal plasmas have been employed for this purpose, such as dielectric barrier discharge [12], atmospheric pressure plasma jet [13] and needle plasma [14].

There are many studies in the literature focused on investigating the plasma decontamination process conditions for different food products targeting different microorganisms. In this decontamination process; there is considerable interest in understanding the plasma inactivation mechanisms for microorganisms. Recently, it has been proven that plasma can effectively inactivate foodborne pathogenic bacteria such as Escherichia *coli* O157:H7 [15], *Listeria monocytogenes* [16], *Campylobacter* [17], *Salmonella* [18], *Staphylococcus aureus* [19].

There are very few non-thermal technologies for control and degradation of toxic compounds in food products. Cold plasma technology is promising for the disruption of various food toxins that are of interest to food researchers. It is focused on the removal of mycotoxins and pesticides from the food by cold plasma technology. Cold plasma applications have shown that mycotoxins are significantly reduced in various food products [20-22]. Researchers are now focusing on optimizing process parameters to enhance degradation efficiency and investigating degradation mechanisms [23]. In addition, pesticides are toxic to humans. For this reason, all food products should be strictly regulated and controlled under the toxicity limit. It has been reported that cold plasma treatments are effective in the deterioration of many pesticides in various food products. [24, 25].

Since food allergens are mainly proteins, likely to be studied in the next few years, they may increase certain reactions affecting allergenic properties. While the specific mechanical pathway is still uncertain, various mechanisms may be responsible for changes in the food allergen following cold plasma treatment. The first leads to the loss of protein solubility, the formation of insoluble aggregates or the cross-linking of proteins, so that the linear epitopes are replaced by their cleavage as they convert conformational isotopes [26]. Along with many studies related to the use of cold plasma in food decontamination, while for food contact surfaces are limited. These studies are shown in Table 1.

2.1 Plasma System Advantages and Disadvantages

Atmospheric plasma offers a number of advantages over other technologies in terms of food safety. Because it is a dry process, it can be easily adapted to a food production. It requires very little energy and requires low operating costs. Reactive gas species return to their original state within a few hours after treatment and require short treatment times. It provides very fast sterilization for only a few minutes. The surface treatment process does not affect most food and vitamins. Process works at ambient temperatures (ideal for thermo-labile products) Depending on the plasma type, it is possible to inactivate the pathogen on a very large scale. It is environmentally friendly because natural gas es used [9].

The possibility of causing chemical changes in the treatment of fatty foods and other sensitive food products should be questioned with further study of the suitability of the cold plasma. Cold plasma application can cause short chain fatty acids, aldehydes, hydroxyl acids, keto acids, flavorings and odors.

In addition, other food components such as antioxidants may affect the decontamination efficiency of the cold plasma; for this reason, optimization studies for plasma treatment should be applied specifically for each product [26]. The research community focuses on process parameters such as plasma sources and process gases in order to maximize microbial inactivation and minimize the effect on product quality. Because a minimum impact on product quality is an important factor for the implementation and acceptance of the application. Other limitations of the plazma may include reduced firmness of fruits and vegetables, discoloration and elevated acidity. Furthermore, the effectiveness of the plasma process was greatly influenced by the surface topography of the samples.

It is also important to provide comprehensive cost analysis for large-scale applications. However, this is mainly determined by the choice of feed gas and electricity. Until now, no commercial process has been applied for decontamination of products because there is not enough system that can be scaled according to industrial conditions and cost-effective. The high costs of the first installation, the need for safety precautions, special equipment and trained personnel are the disadvantages of these operations. It is also not clear how consumers will react to products processed with cold atmospheric pressure plasma technology [27].

3. Ultrasound Applications

Ultrasound is given as high frequency sound waves as the human ear cannot hear [40]. It covers frequent applications, typically up to 10 MHz, with the definition of sound waves at the 20 kHz or higher level. To provide cavitation causing microbial inactivation in food processes, sound waves between 20 and 100 kHz are used [41]. There are two different types of ultrasound technique: low intensity ultrasound and high intensity ultrasound [42-44]. Low intensity ultrasound is used to obtain information about the physicochemical properties of food. The application of high intensity ultrasound is used to modify the physical properties of a substance [45].

Low-frequency ultrasound, also known as power ultrasound, has a broad process potential with the ability to cause desired physical and chemical changes in products for food industry applications. It has been reported that extractions help in emulsification, sterilization, degassing, defoaming, freezing, filtration, microorganism inactivation, homogenization, activation / inactivation of enzymes, surface cleaning, depolymerization, crystallization, screening, biocomponent separation, cleaning, atomization and drying [46-48]. In the cleaning and surface decontamination processes, it is used in commercial cleaning systems for cleaning poultry slaughterhouse equipments and especially in internal cleaning of pipes which cannot be easily cleaned with existing methods [49].

In recent years, the physical and chemical effects of ultrasound in liquid and solid media have been used at large scale in food processing applications. However, various studies suggest that ultrasonication of food and its products is a potential and feasible technology that can be used in many areas of the food industry in the near future [50]. It is an innovative technology that has applications in the analysis and modification of foodstuffs [48].

On the other hand, despite the technological advances in the food industry, maintaining hygienic control of equipment and equipment used during processing is still a problem today. Equipment and utensils can contaminate food if they are not sterilized as required, thus reducing shelf life and product safety. The conventional cleaning procedure is manual washing followed by a complete immersion of chlorinated water (concentration of 2-5 mg / l chlorine) in a continuous stream to prevent soil build up, sterilization for at least 20 s at 82.0 °C or 15 s at 82.2 °C. In this case, any decrease in water temperature and immersion time during sanitation can be regarded as extremely dangerous because thermophilic and mesophilic microorganisms can survive and pass through the product in these temperature changes [1]. Conventional heat treatments, such as washing pipes with hot water or sterilization with water vapor, typically require a high energy input and a very long process time, even if the object is surface sterilized or disinfected. In addition, all parts subjected to a treatment, including fittings, valves and seals, must be made from suitable heat-resistant materials. New hygiene and disinfection technologies have become the focus of the food industry due to the increasing demands of consumers for modern food standards and regulations requirements and food quality [2].

The ultrasonic cleaning that is being used today is accepted as a classical technique both for industry and at the same time both scientific and laboratory. Their origins date back to the 1950s and began to be established about 40 years ago. In the food industry on deposits or residues on moulds or cutting tools need to be hygienically removed. Because of the effectiveness of ultrasonic cleaning; it is capable of dislodging and removing surface contamination in the form of inorganic dirt or microbiological material through the shock waves and jet formation that accompany the acoustic cavitation bubble collapse. This type of cleaning can be used for both small and large items and can penetrate deep into crevices and cavities in the surface of an object [51].

Table1. Plasma system applications on food contact surfaces

Microorganism and desired effect	Matrix	Plasma Type	Processing Parameters	Main result	References
E. coli, S. aureus	Glass slides	Parallel-plate dielectric barrier discharge	7-10 s treatment, Air, 60 kHz voltage power	Gram+ microbe more resistant than Gram-	[28]
L. monocytogenes	Disposable plastic trays, aluminum foil, and paper cups	Atmospheric pressure plasma	Input power (75, 100, 125,150 W) exposure time (60, 90, 120 s).	Higher inactivation on disposable plastic tray than that on aluminum foil and paper cups	[29]
A. niger, B. subtilis spores	Polyethylene terephthalate blank Foils	Cascaded dielectric barrier discharge	Relative Humidity (RH)	Higher RH, higher inactivation efficiency	[30]
Salmonella Enteritidis	Egg shells	Atmospheric pressure plasma, DBD	Input power 2-3 kV, 1 MHz, 5 min	Reduction factor ranging between 0.22 and 2.27 log CFU/egg	[31]
Increase the surface energy (by cleaning and chemically activating the surface)	AISI 316 stainless steel	Plasma Tact system	V= 150 kW 5-10 min, Argon or Helium gases	Increase in surface free energy consistent with an increase in the polar energy	[32]
lubrication layer cleaning	Steel surfaces	Atmospheric pressure air plasma torch	Frequency 17 kHz, high tension discharge of 20 kV, rotating torch 1900 rpm	Metal samples were cleaned with a solvent-free and rapid application	[33]
Salmonella spp.	304 and 316 stainless steels, Test surfaces of finishes: 2B, Hair line (HL), and Mirror (MR).	Ultraviolet-C radiation and atmospheric pressure plasma jet	Air injection rate 5 L min-1 with input power of 650 W	D values ranged from 2.66 (304 2B) to 3.43 s (316 MR). The temperature of surface showed a sudden increase in temperature up to 180 ° C in 15 s	[34]
Pseudomonas aeruginosa	304 and 316 stainless steels, Test surfaces of finishes: 2B, Hair line (HL), and Mirror (MR).	Atmospheric pressure plasma jet	Air injection rate of 5 l/min, output power of 360W	D-values on the 316 stainless steel type ranged 2.53s (MR) to 3.16 s (2B); 304 type ranged from 1.95 s (HL) to 3.27 s (2B) Temperature rise was observed on all surface.	[35]
Enterobacter sakazakii	316 stainless steels	Radio frequency plasma polymerization	Discharge power of 20–80 W time: 10 min	45 W and 10 min was reduced by 99.74%. Decreasing the biofilm formation	[36]
Norovirus-1 and hepatitis A virus	Stainless steel surfaces	Cold Atmospheric plasma	10-30s exposure times, gas: air	Norovirus and hepatitis A to 0.65-3.89 and 0.77-2.02 log10 PFU/ml	[37]
Escherichia coli	Polyethylene and stainless steel surfaces	Radio frequency plasma	13.6 MHz, discharge power 0-100 W, 0-30 min, gases: nitrogen, oxygen, air, water vapor	Water vapor was most effective (about 7 log10 reduction. Temperature was 44 °C an it was relatively cold	[38]
Escherichia coli and *Staphylococcus epidermidis*	Stainless steel, silicon and polyethylene terephthalate (PET)	Gliding arc discharge microplasma system	High purity air (79% nitrogen and 21% oxygen) or nitrogen plasma for 1-10 minutes	Significant 5 min with nitrogen gas ($p < 0.05$). In every gas type, the temperature of all surfaces did not rise above 35 °C.	[39]

Mason et al. [52] reported a target frequency of 20-100 kHz and a target specific power ranging from about 0.2 to> 2,000 W / cm^2. In ultrasonic cleaning, the adhesives are separated from a surface using an aqueous medium as a sound emitter. Separation can be supported by detergents added to the liquid. The main mechanism responsible for the removal of insoluble impurities is the cavity overlying a threshold ultrasonic power when the alternative compression and expansion are strong enough to break the molecular bonds between the surface and the impurities. One of the disadvantages of ultrasound is the possibility that long-term vibration can cause surface erosion because bubbles create intense stress pulses on the surfaces, and numerous repetitions of such stress bumps can lead to material removal [2].

Ultrasonic cleaning is based on the principle that water is shaken at a certain rate with sound waves. In normal cleaning, the brush cannot always reach all surfaces. The vibration created by the sound waves resembles brushing at high speed. When the water is liquid at 60 °C and atmospheric pressure (0 bar), it will start to evaporate when the pressure drops below 0.8 bar. Ultrasonic waves cause very rapid pressure increases and decreases in the fluid. A sudden decrease in this pressure cause gas bubbles to form in the water and the bubbles burst with a sudden increase in pressure. This movement of gas bubbles in the water is called "cavitation" [53]. The removal of dirt and food residues from the surface and the inactivation of microorganisms appear as a consequence of cavitation. There are indications that this technology can be used alone or in combination with chemical disinfectants in the food industry [54].

High-intensity ultrasonic cavitation is used in cleaning processes. The micro-jets impacting the solid surface also allow the liquid to be injected into the solid. Depending on the system structure, the bubbles sometimes do not collapse and continue to vibrate at the same frequency as the applied ultrasound. These changes in pressure have the effect of constantly squeezing the sponge. This "sponge effect" allows the liquid inside the solid to come out and enter into the liquor of the external liquid [49].

Cavitation is responsible for the removal of organic foreign substances from the surface and is the basic mechanism of ultrasound. In addition to the cleaning effect, the ultrasound has the ability to inactivate certain microorganisms. It is stated that the activity of microbial inactivation depends on the target microorganism, contact time, ultrasound frequency and amplitude, temperature and pH, material composition and volume [1, 55].

Ultrasonic cleaning is used especially for sterilization of hard surfaces. In general, the industrial cooking of food leads to the adherence of the products in the cooking container [48]. The most widespread application of ultrasound is the cutting of fragile foodstuffs. Indeed, it is well adapted to food, which cannot tolerate great deformations under the effect of a blade, or to products that are difficult to slice by the tools traditionally used like rotary blades or knives with teeth. Another characteristic of this technique lies in hygiene improvement since the vibration prevents the adherence of the product on the blade and thus reduces the development of microorganisms on the surface i.e. ultrasonic vibrations provide “auto cleaning” of the blade. The accuracy and repetitively of the cut produces a reduction in losses relative to the cutting and a better standardization of the weight and dimensions of portions.

Two different types of ultrasonic devices are used, ultrasonic cleaning baths and ultrasonic probes. Ultrasonic cleaning baths are widely used for solid dispersion, degassing solutions or cleaning materials. They are cheap and easy to use, but are less used for chemical reactions. This equipment has different capacities. Typical tank sizes range from 10 to 2500 liters. The ultrasonic baths have transducers located on the walls and / or bottoms of the tanks and ultrasonic energy is sent directly to the liquid. Generally, this type of ultrasonic operates at about 40 kHz and produces high densities at fixed levels. The depth of the liquid is important to maintain these densities and the ultrasound in the liquid should not be less than half the wavelength. In the ultrasonic bath process, frequencies are released by a mechanism that creates a more uniform cavitation field and reduces localized wave regions.

Many studies are being used in an ultrasonic bath. This can be explained by the fact that sound waves can be spread more homogeneously in liquid medium and the system does not require special adaptation. However, the disadvantages of these applications are that the only constant frequency operation is possible, less acoustical intensity can be applied than probe applications and poor temperature control. The advantage of direct probe applications is that high energy can be transferred to the center without loss and can be used more effectively than ultrasonic power due to controllable energy transfer. However, the direct probes limit the use of fixed frequency, temperature control is very difficult because of the possibility of radical formation and the presence of metal transition due to corrosion on metallic surfaces [56].

Many ultrasonic systems are designed for use in food processing. For example, an ultrasonic bath can be used as a reactor for chicken pens to avoid cross contamination. Ultrasonic flow systems are used for liquid foods passing through a vibrating tube. The sound energy generated for the transducer is connected to the outside of the pipe is transferred directly to the flowing liquid [54].

Numerous studies have been carried out for microbial inactivation of the ultrasound [57-60]. However, few studies were found for surface sanitation. The ultrasonic application studies used for surface cleaning are shown in table 2.

There are a number of different chemicals (acid, alkali, enzyme and hypochlorite) and physical methods used to clean a dirty membrane. These methods, which often require extensive cleaning using a range of chemical reagents, have cause membrane damaging and secondary pollution, and also they are unreliable, time consuming and expensive. The membranes used in whey or milk ultrafiltration are regularly cleaned to ensure hygienic handling and to preserve membrane performance. The use of non-optimal cleaning conditions causes unnecessary operational costs due to overuse of chemicals. Furthermore, non-optimal conditions considerably reduce the life of the membrane. Ultrasonication has proven to be an effective approach to maintaining constant motion and cleaning in ultrafiltration or microfiltration processes [50].

Table 2. Ultrasonic application studies used in surface cleaning

Working product	Working conditions	Purpose of	Main results	References
Wine industry	High-intensity ultrasonic	Surface cleaning	Elimination of tartrate deposits and deep-seated microbial contamination of oak. Rejuvenation of oak.	[61]
Egg surface	Ozone and ultrasonic (US) (35 kHz, 1200 W, 3 min and 35 kHz, 1200 W, 6 min)	Disinfection of egg surface	US applications have encountered wear and cracks in the resulting egg shell.	[62]
Stainless steel surface	a) Low-concentration neutralized electrolyzed water (LCNEW) b) Ultrason (37 kHz, 80 W) c)LCNEW+ultrason	Disinfectant effect on food contact surface	The combination of LCNEW with ultrasound appeared to be a promising approach to sterilize food equipment.	[4]
The dairy industry membrane	a) Chemical cleaning and ultrasonic (20 kHz and 300 W) b) without ultrasound application	The effectiveness of membrane cleaning	It has been concluded that the use of ultrasonic technology is an effective and promising technique for increasing cleaning efficiency.	[63]
The dairy industry membrane	Two membrane modules (flat sheet and tubular) are used.	The effect of ultrasounds (US) on the membrane cleaning efficiency. The influence of ultrasonic frequency and the US appli- cation modes (submerging the membrane module inside the US bath or applying US to the cleaning solution)	Demonstrated that membrane cleaning with US was effective and this effectiveness increased at lower frequencies. Although no significant differences were observed between the two different US applications modes tested, slightly higher cleaning efficiencies values placing the membrane module at the bottom of the tank were achieved.	[64]
Fish and meat transportation boxes and live-chicken transportation crates	A short treatment (1 to 2s) of combined steam (95°C) and ultrasound	Effect of process	The steam-ultrasound treatment may be an effective replacement for disinfection processes and that it can be used for continuous disinfection at fast process lines	[65]

3.1 Ultrasound Advantages and Disadvantages

Ultrasonication is reported to have advantages such as lower investment cost, reliability and ease of cleaning compared to conventional methods [66,67]. Ultrasonic application has a wide range of potentialities due to its functional properties, low energy requirement, shortened process times and reduced cost of repair [45]. Since it is environmentally friendly, it is also accepted as green technology. One of the disadvantages of ultrasound is the possibility that long-term vibration can cause surface erosion because bubbles create intense stress pulses on the surfaces, and numerous repetitions of such stress bumps can lead to material removal [2]. Although widely used in laboratory studies, it has not yet been fully integrated into the industry (Mediterranean). There are many issues that need to be clarified in terms of the advantages and disadvantages of ultrasonics [67]. In this regard, it is thought that the studies for the industrial use of ultrasonic applications will be important.

4. Conclusions

Quality, healthy and safe food production; to ensure that the raw material is supplied in sufficient hygienic conditions, to pay attention to personnel hygiene, to clean the tools and equipments in the food production places as required, to suit the operation and cold storage temperatures. Plasma and ultrasonic techniques, which are new technologies proposed for cleaning, are promising for the food industry and provide a competitive application potential. The use of these techniques is being enhanced by new consumer demands, technological developments and economic advantages. Developing nonthermal plasma systems and ultrasound applications can be used for decontamination of food contact surfaces when used alone or in combination, and are seen as a replacement for traditional food preservation methods in the future.

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