IJAS

International Journal of Agriculture Sciences
ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 7, Issue 12, 2015, pp.-801-808.
Available online at http://www.bioinfopublication.org/jouarchive.php?opt=&jouid=BPJ0000217

RECENT ADVANCES IN THE APPLICATIONS OF NON-THERMAL TECHNOLOGIES AS EFFECTIVE FOOD PROCESSING TECHNIQUES

JOLVIS POU K.R.*
Department of Agricultural Engineering, Triguna Sen School of Technology, Assam University, Silchar-788011, India
*Corresponding E-mail: jolvispou@gmail.com

Received: October 17, 2015; Revised: October 30, 2015; Accepted: November 02, 2015

Abstract-Thermal processing effectively reduces the number of microorganisms. However, not only the self-life but also the quality attributes of the food is necessary for the consumers. In response to the public health concerns and the preference of customers, researchers and scientists are under intense research and development to utilize the potential of non thermal technologies as an alternative or complimentary process to traditional methods of food processing. Recent advances in emerging food-processing technologies, such as high pressure, pulse electric field, ultrasound, magnetic field and irradiation amongst others have exhibited the fresh-like, palatable, microbiologically safe, high quality and additive free food products. Extensive investigations in the last decade have revealed the potential of non -thermal technologies as promising food processing techniques. In this paper, the aspects associated with applying non-thermal technologies as food processing methods are reviewed, including its working mechanism and its application in the food processing.

Keywords- Food processing, HPP, irradiation, magnetic field, non-thermal, PEF and ultrasound

Citation: Jolvis Pou K. R. (2015) Recent Advances in the Applications of Non-Thermal Technologies as Effective Food Processing Techniques. International Journal of Agriculture Sciences, ISSN: 0975-3710 & E-ISSN: 0975-9107, Volume 7, Issue 12, pp.-801-808.

Introduction

Food processing can be understood as an activity undertaken in order to change or retain or improve the quality, structure, characteristics and form of the food with the objective of preventing or minimising the negative changes in the food [1]. Food cannot be taken as such, it required one or more post harvest operations like cleaning, physical separation, molecular separation, chemical transformation, preservation, packaging etc., apart being necessary for its preservation. Food processing is as old as human civilization where foods were commonly subjected to smoking, roasting, steaming, boiling, sun drying etc. Conventionally, most foods are thermally processed (e.g. blanching, pasteurization, sterilization, drying) by treating at temperature of 60 to 100 ºC or more for a few seconds to minutes [2]. The large amount of energy transferred to the food may trigger unwanted reactions thereby leading to undesirable changes in the food [3]. Thermal processing effectively reduces the number of microorganisms, but the fact is not only the shelf life but also the quality attributes of the food is necessary for the consumers. A goal of food manufacturers is to develop and employ processing technologies that retain or produce desirable organoleptic properties or reduce undesirable changes in food due to processing [4].

Therefore, the concepts of non-thermal as alternative techniques of food processing are being developed and implemented. In these methods, the foods are subjected to lower temperature as compared to thermal processing and relatively non-thermal processes utilize less energy. The quality degradation expected from high temperatures is minimal in non-thermal processing [4]. Much emphasis have been giving towards the non thermal processing of food, researchers and scientists are under intense research and development to identify the potential of non thermal technologies as an alternative or complimentary process to traditional methods of food processing. Food can be processed non thermally using the techniques like high pressure processing (HPP), magnetic fields (MF), Ultrasound, pulse electric field (PEF), irradiation, pulsed light, ozone, gas, cold plasma, hurdle technology etc. The current review concerned on the first five techniques as listed and discussed its working mechanism and its applications in the food processing.

High Pressure processing

The true potential of high pressure technology for the food industry was recognized only recently in the 1980s, although attempts have been made in the late 19th century [5]. High pressure processing of food works on two general principles. The first is Le Chatelier's Principle, which states that, when a system at equilibrium is disturbed, the system then responds in a way that tends to minimize the disturbance [6]. In other words, high pressure enhances reactions that result in a decrease in volume but opposes reactions that involve an increase in volume. Secondly, the Pascal's law states that, the external pressure exerted on a fluid is distributed evenly (isostatic) and instantaneously throughout a sample under pressure, whether the sample is in direct contact or indirect (flexible package) contact with the pressure medium [7]. Therefore, HPP is independent of time/mass of the food [8]. Some of the most generally used pressures transmitting media are like water, ethanol, silicone oil, sodium benzoate, glycol, castor oil etc. HPP can be operated in batch, semi-continuous or continuous processing systems. Generally, high pressure is generated by; direct compression, indirect compression and heating of the pressure medium. In direct compression, the pressure is generated by pressuring a medium with the small-diameter end of a piston. The large-diameter end of the piston is driven by a low pressure pump as shown in [Fig-1] [9]. In case of indirect compression, a high pressure intensifier is used to pump a pressure medium from a reservoir into a closed high pressure vessel until the desired pressure is obtained as shown in [Fig-2] [9].

Applications of HPP in food

HPP has emerged as a novel technology. HPP has been scientifically and

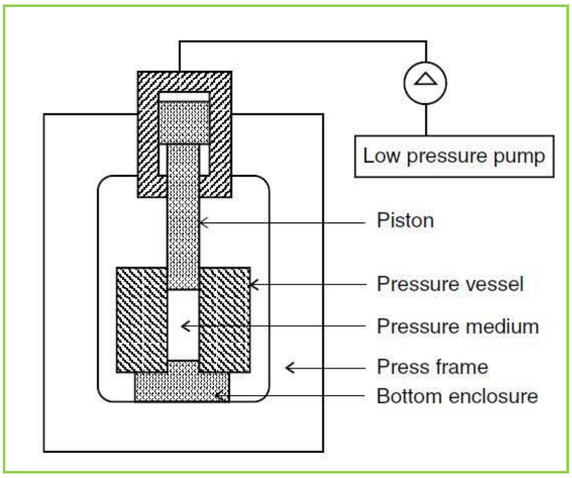

Fig-1 High-pressure generation by direct compression [9]

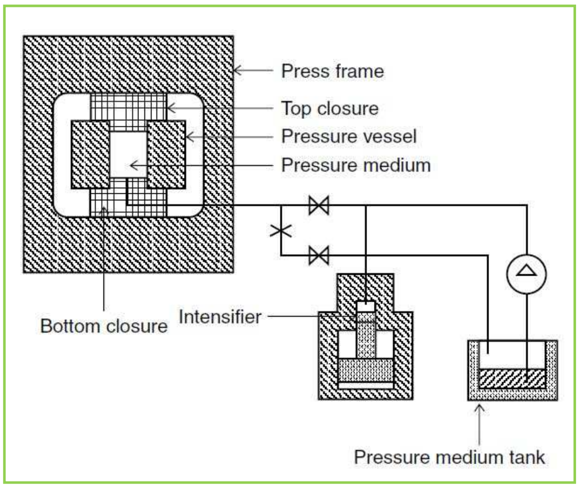

Fig-2 High-pressure generation by indirect compression [9]

commercially proven that it can produce microbial safe and stable products with improved quality characteristics such as enhanced flavor and color. [10]. Treatment of fresh mangoes (Cv. Chousa) at 100-400 MPa with the interval of 100 MPa for 15 and 30 minutes and treatment chamber temperature maintained at 20±1.5 ºC, it was found that, after pressure processing the changes in the values of the three-color parameters (L, a and b) of mango pulp were not significant ($P > 0.05$). The quality parameter (a/b), chroma and hue remained almost constant indicating minimal effect on pigments. The total color change decreased with an increase in pressure intensity and considered to be the best example of an unchanged quality attribute during HPP and treatment time had no effect. The total soluble solids and pH remained unchanged after the HPP [11]. Cheah and Ledward [12], studied on effects of high pressure on the lipid oxidation in minced pork has reported that, there was rapid increased in 2-thiobarbituric number after the treatment of above 300 MPa at room temperature indicating the increased in the rate of lipid oxidation. Similar results were observed by Angsupanich and Ledward [13], pressurised at 400 MPa and above for 20 minutes increased the rate of lipid oxidation on cod (*Gadus morhua)* muscle as measured by thiobarituric acid number. The gel formation of some of the protein rich foods like hen egg white and yolk and a suspension of soy protein were occurred at 588 MPa, 392 MPa and 294 MPa respectively and 196 MPa for the carp actomyosin and the rabbit meat at 25 °C for 30 minutes. It was found that the pressure induced gels have superior qualities in terms of retention of initial colour and flavour and glossiness and softness as compared to heat induced gels [14]. The pressure level of 100 and 200 MPa at 20 °C for 10 minutes and 10 °C for 20 minutes, reduction of microbial populations in vegetables (lettuce and tomatoes) were not significant. For the complete reduction of saccharomyces cerevisiae, the required pressure intensity was 300 MPa at 10 °C for 20 minutes. Similarly, for Gram-negative bacteria and moulds 350 MPa. The Gram-positive bacteria were unable to completely inactivate at 400 MPa. The viable aerobic mesophiles and molds and yeasts were reduced by 1 log unit at 300 MPa and above [15]. Combination of pressure and temperature could better retain the color parameters of lychee in syrup than thermal treatment. It was found that pressurization induced lower color values, including low anthocyanin content. Pressure of 600 MPa at 30 °C or 50 °C was less affective to alleviate polyphenoloxidase, only 49-67% can be inactivated [16]. High pressure of 100-300 MPa for 5-10 minutes at 27±2 °C significantly increased total color difference, browning index, drip loss and total soluble solids, whereas decreased in pH and ascorbic acid content of litchi fruits (Litchi chinensis *cv.* Bombai). Pressurization significantly affected firmness and increased texture properties like springiness, cohesiveness, chewiness and gumminess of litchi fruits. Pressurized at 300 MPa for 10 and 15 minutes, the aerobic mesophiles, yeast and mold and psychrotrophs count were reduced by 3.29, 3.24 and 3.77 $\log_{10}$ cycles, respectively and enhanced shelf-life up to 32 days with minimal changes in physico-chemical attributes and textural parameters during refrigerated storage [17]. High pressure assisted freezing of pork at 200 MPa and -20 °C promotes rapid and uniform nucleation throughout the volume of the sample with small size of the ice crystal thereby minimized the damage to the frozen products [18]. The loss of qualities (ascorbic acid, anthocyanins, total phenols and antioxidant capacity) of high pressure (600 MPa for 4 minutes) treated cloudy and clear strawberry juices showed a fast-to-slow performance during storage [19]. Basmati rice flour dispersions exhibited gelatinization and behaved as viscoelastic fluid on pressure treatment (350-650 MPa for 7.5-15 minutes) with flour-to-water ratios of 1:5, 1:3 and 1:2. Complete gelatinization of protein free isolated rice starch and slurry were found at 550 MPa and 650 MPa for 15 minutes, respectively. Pressure induced gel increased mechanical strength and reduced gelatinization temperature as compared to untreated sample [20]. The combinations of high pressure and pineapple juice were more effective than the same conditions used in isolation on the prevention of browning of Granny Smith and Pink Lady apples when exposed to air. The optimum conditions for best quality retention in both the varieties of apple were reported as 600 Mpa for 5 minutes with 50% apple juice. The combined effect significantly reduced the activity of residual polyphenoloxidase [21]. Color change of mango pulp were found to be significant and retained a maximum of 85, 92 and 90% of its original ascorbic acid, total phenolics and in-vitro antioxidant capacity, respectively after the application of high pressure 100-600 MPa for 1 second to 20 minutes at ambient temperature (30 ± 2 °C). Coliforms were found to be more sensitive to pressure as compared to yeast and molds. High pressure treatment of 600 MPa for 5 minutes was adjudged best for mango pulp which achieved maximum reduction in microflora and moderate changes in quality attributes [22]. The shelf life of high pressure treated (435 MPa for 5 minutes at 25±2 ºC) black tiger shrimp extended for 15 days whereas the untreated shrimp last only for 5 days under chilled storage [23]. Textural properties of all egg components (whole liquid egg, egg white and egg yolk) were significantly changed with pressure level. Egg gels were formed at high-pressure level greater than 600 MPa at temperature well below that required for thermal gel formation with improved physicochemical characteristics and without any cooked flavors [24].

Magnetic Field (MF)

A magnetic field is the area of influence exerted by a magnetic force. Magnetic field at any given point is specified by both a direction and a magnitude (strength). Magnetic fields are created by moving charged particles: in electromagnets, electrons flow through a coil of wire connected to a battery; in permanent magnets, spinning electrons within the atoms generate the field. Magnetic fields may be homogeneous or heterogeneous, and can be in static and oscillating mode. In homogeneous, the magnetic field intensity is uniform in the area enclosed by a magnetic coil. It does not exert an accelerating force. In case of heterogeneous magnetic field, the field intensity is not uniform. The intensities decrease as distance from the centre of the coil increases. Heterogeneous magnetic field exerts an accelerating force. Static magnetic field (SMF) exhibits constant field intensity with time and direction of the field remains the same while in the oscillating magnetic field (OMF), the magnetic waves alternate amplitude. OMF applied in the form of pulses and show intensity gradient over time. Generally magnetic field can be generated by field generation by current in wires, static magnetic field technique, oscillation magnetic field technique and ultra-high magnetic field [25]. The microbial inactivation process using either SMF or OMF as described by Pothakamury et al. [26], the OMF weaken the bonds between ions and proteins used in metabolism and membrane integrity. Magnetic field at the cyclotron frequency loosens the bond between the calcium ion and the calmodulin. Reduction in population of microorganisms might be due to change in the synthesis of deoxyribose nucleic acid (DNA), reorientation of biomolecules and biomembranes to a direction parallel or perpendicular to the applied magnetic field, or a change in the ionic drift across the plasma membrane. Many foods have high electrical resistivity, greater than 10–25 ohms-cm, which is the basic requirement for the application of OMF. The OMF with intensity greater than 2 Tesla has the potential to inactivate microorganisms in food [27].

Applications of magnetic fields in food processing

The growth of *Escherichia E coli B* has been adversely affected by the application of homogeneous magnetic field of 7 Tesla and inhomogeneous magnetic field of 5.2~6.1 Tesla and 3.2~6.7 Tesla. It was found that, the inhomogeneous magnetic field has greater effect as compared to homogeneous magnetic field [28]. The three selected species of microorganisms namely *Ervinia carotovora*, *Streptomyces scabies* and *Alternaria solani*, taken from paralysed potatoes were found to be reduced in surviving colonies under the treatment of oscillating magnetic fields of amplitudes 5-20 Tesla. The resistant of the tested microorganisms were found to be in the order of *Alternaria solani*>*Ervinia carotovora*>*Streptomyces scabies* [29]. The amount of surviving of bacteria and fungi on the oat sprouts (*cv. Akt*) were reduced by half and approximately factor of 10 respectively after being treated with OMF of 5 times repeated pulses of 5 Tesla amplitude and was statistically significant. Treatment with a single pulse of 8 Tesla amplitude was lower in the reduction of microorganism colonies and statistically insignificant but drop in the number of surviving vegetative bacteria forms was observed and statistically significant ($P<0.01$). Polyphenol content and antioxidant activity in oat sprout was found to be increased and statistically significant on treatment with 10 pulses of 3 Tesla amplitude. But on exposure to 1×8 and 3×8 Tesla amplitude did not vary in polyphenol content. However, the antioxidant activity was reduced by about 20% after being exposed to 3×8 Tesla [30]. As observed in [Table-1], the magnetic fields have great influenced on the microorganisms.

Table-1 *Effects of magnetic fields on microorganisms [25,27,31]*

Microorganisms	Nature of magnetic fields	Field strengths (T)	Applications
Burgundy wine yeast cells	Static	0.04	Growth retardation during exposure at 5–150 minutes; no retardation at 10, 15, and 17 minutes
Trichomonas vaginalis	Static	4.60-12	Growth was accelerated
Escherichia coli	Static	5.2-6.1	Magnetic field increased viable cells by 150 times after incubation for 48 hours
Saccharomyces cerevisiae	Static	5-14	Rate of proliferation under the magnetic fields decreased after 16 hours of incubation compared to control sample
Escherichia coli	Oscillation	0.05	Inactivation of cells when concentration was 100 cells mL^{-1}
***Streptococcus thermophilus* in milk**	Oscillation	12.0	Cell population reduced from 25,000 to 970 cells mL^{-1}
***Saccharomyces* in yogurt**	Oscillation	40.0	Cell population reduced from 3500 to 25 cells mL^{-1}
***Saccharomyces* in orange juice**	Oscillation	40.0	Cell population reduced from 25,000 to 6 cells mL^{-1}
Mold spores	Oscillation	7.5	Population reduced from 3000 to 1 spore mL^{-1}
Escherichia coli, Leclercia adecarboxylata,* and *Staphylococcus aureus	Oscillation	0.01	Magnetic field causes the decrease of colony-forming unit (CFU) in all exposed samples. The maximum decrease of CFU was observed for *E. coli*; *S. aureus* strain found to be most resistant to the magnetic field

Pulse electric field

During the 1970s, PEF applications were categorised into two, firstly, reversible electro-permeabilization for DNA transfer into cells and secondly microbial inactivation and food preservation. For the preservation of food, short electric pulses (usually 1-20 µs, but with a range of 50 ns to several milliseconds) with a high field strength (15-80 kV cm^{-1}) were applied to samples placed between two electrodes in a batch or continuous treatment chamber [32]. Generally considered the mechanism of action of PEF on biological cells is associated with local structural changes and the breakdown of the cell membrane, which is a very significant component of the biological cell as it acts as a semi-permeable barrier responsible for transfer of mass and plays a vital role in the synthesis of RNA and DNA, protein and cell wall components as well as many other complex metabolic activities. The cell membrane is considered as a capacitor filled with dielectric material of low electrical conductance and a dielectric constant in the range of 2 [33]. The inactivation of microorganisms occurred when certain threshold electric field intensity is exceeded. Based on the dielectric rapture theory, the external electric field induced an electric potential difference across the cell membrane known as the trans-membrane potential. When the trans-membrane potential reached a critical or threshold value, electroporation or pore formation in the cell membrane occurred. The cell membrane rupture is caused by an induced trans-membrane potential approximately 1V larger than the natural potential of the cell membrane. This lead to increase in permeability of cell membrane for the purpose of gene manipulation or introducing foreign molecules into the cell which results in swelling and the eventual rupture of the cell membrane as represented in [Fig-3] [34,35]. In general PEF consists of; treatment chamber, power source, capacitor bank, switch, voltage source, current and temperature probes. Treatment chamber is one of the most complicated and important components and it can be of different types; static chamber, continuous chamber, continuous coaxial chamber and converged electric field type treatment chamber. Different voltage waveforms can be generated in the form of exponential pulses, square wave pulses, bipolar pulses or oscillatory pulses [34].

Applications of PEF in food processing

Treatment of *Listeria innocua* in milk with PEF of 30 and 40 kV cm^{-1}, 50 µs at 10 ºC inactivated by 1.1 and 3.3 log cycles, respectively. It was reported that the combination of PEF strength of 40 kV cm^{-1} and thermosonication (80 seconds) led to 6.8 log_{10} colony-forming unit (CFU) mL^{-1} inactivation [36]. The PEF technology is much more effective when used with other preservation methods, like high hydrostatic pressure [37, 38]. PEF could be a useful method in liquid food preservation in particular to good sensory and functional properties of final products [37]. Inactivation of *Listeria monocytogenes* increased with the raise of field strength, treatment time and specific energy. The treatment time and total specific energy depended on the electric field strength and decreased at higher electric field strengths. After a treatment of 28 kV cm^{-1}, 2000 µs and 3490 kJ kg^{-1}, the reduction of *Listeria monocytogenes* was found to be 4.77 log_{10} cycles [39]. Putri et al. [40] have simulated and designed a high voltage pulse generator for PEF pasteurization of liquid food. The optimum processing time was reported as 10 seconds with 20 kV against 20 and 40 seconds and there was 88.23% reduction of microbes and specific energy consumption was 29.19 KJ l^{-1} for the pasteurization of apple juice. *Lactobacillus plantarum* treated with PEF intensity in the range of 20-28 kV for 30 to 240 µs showed that cells in the exponential growth stage were more sensitive to PEF treatment than those in the stationary stage [41]. The initial amount of vitamin A, thiamine (B1), riboflavin (B2), cholecalciferol (D), tocopherol and ascorbic acid content did not decrease after been treated with PEF strength from 18.3 to 27.1 kV cm^{-1} up to 400 µs [42]. Under the influence of electric field of 13-87 kV cm^{-1} and pulse period of 2 seconds, exhibited a reduction of 70-85% in lipase, glucose oxidase and heat-stable α-amylase. In case of peroxidise and polyphenol oxidase found 30-40% reduction, whereas in alkaline phosphatase only 5% reduction was reported [43]. Alternating current of high electric field (470 kV m^{-1} for 7 hours) dried of Japanese radish (*Raphanus sativus L.*) slices were found to be superior over oven-drying at 60 ºC for 7 hours in terms of less shrinkage, high absorption of water, better rehydration, less solids loss and better color. At the given conditions the amount water evaporated using high electric field, oven and ambient (25 ºC for 7 hours) were reported as 87.5%, 86.9% and 26.5% respectively [44]. PEF intensity of 1 kV cm^{-1} exhibited as a successful technique of permeabilization for the extraction of red beetroots pigment, with a low energy consumption of about 7 kJ kg^{-1} [45]. Application of high voltage electrostatic field (4-10 kV) on thawing of frozen pork increased the rate of thawing with the applied voltage. The thawed product retained the quality of meat with reduction in the total microbial counts. Additionally, it inhibited microbial growth during post-thawing storage [46].

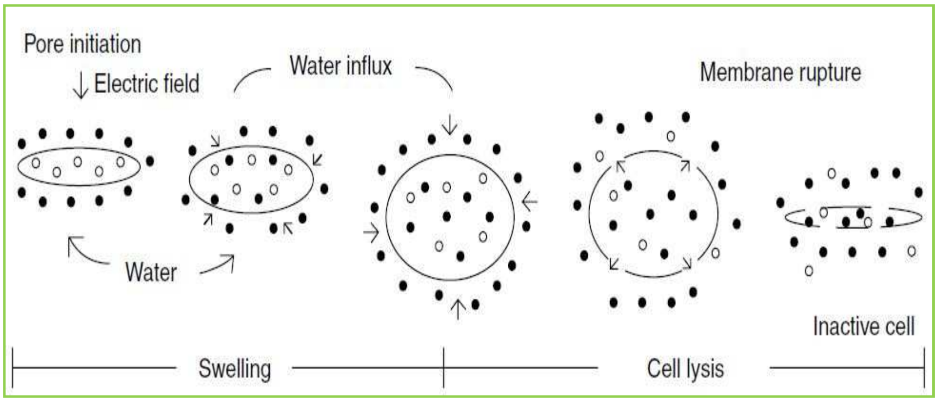

Fig-3 Mechanism of PEF cell inactivation [35]

Irradiation

Irradiation is a physical means of food processing that involves exposing foods to the direct action of electronic, electromagnetic rays to assure the obliteration of food-poisoning microorganisms and insects and to prolong the shelf life of food products [47]. Action of ionization irradiation on biological cells is brought about by the ionization of molecules by creating positive and negative ions by transferring energy in the electrons. The effects on living cells are direct and indirect. In direct action, the chemical events occur as a result of energy deposition by the radiation on the target molecule, and the indirect effects occur due to the formation of reactive diffusible free radicals from the radiolysis of water. These radicals can cause several changes in the molecular structure of organic matter [48]. The specialty of processing food by ionizing radiation is that the very high energy density per atomic transition can cleave molecules and induce ionization, which is not achieved by mere heating. When subjected to irradiation, cells experience DNA damage that cannot be repaired. These cells undergo apoptosis due to which the potential genetic damage from the larger tissue is eliminated, or they undergo nonlethal DNA mutations that are passed on to subsequent cell divisions [49]. Ionization irradiation sources are of two classes; electromagnetic and particulate. Gamma rays and x-rays are electromagnetic in nature and electrons in particulate form. Commercially most gamma irradiations are obtained from radionuclides cobalt 60 (^{60}Co), cesium 137 (^{137}Cs) is an alternative source. X-rays and electron beams are generated from machine sources operated at or below 5 MeV and10 MeV respectively [48]. Food exposes to electron beams, x-rays, or γ-rays produces an effect similar to pasteurization, cooking, or other forms of heat treatment, with less detrimental effect on appearance and texture [49].The degree of chemical and physical change produced during irradiation is determined by the energy absorbed called as the absorbed dose or simply dose, measured in kilogray (kGy). Important terms used to describe the applications of irradiation in food processing are; radicidation (about 0.1-8 kGy), radurization (about 0.4-10 kGy) and radappertization (about 10-50 kGy) [50].

Application of irradiation in food processing

The impact of irradiation (0.75 kGy and10 kGy) on the immunochemical detections of milk and egg allergens in foods was reported to be no significant decreases in antigenicity and no significant differences were obtained between the different irradiation doses [51]. The effect of gamma irradiation (2-50 kGy) on molecular structure and physicochemical properties of corn starch studied by Chung and Liu [52] reported that the carboxyl content, amylose leaching, the proportion of short amylopectin branch chain and retrogradation temperature increased with increasing of irradiation dose but decreased in swelling factor, apparent amylose content, the proportion of longer amylopectin branch chain, relative crystallinity, pasting viscosity, gelatinization enthalpy and temperature and retrogradation enthalpy. The resistant starch content slightly decreased at 2 kGy and then increased up to 50 kGy but the slowly digestible starch content showed the opposite trend. The gamma radiation doses of 2.0 kGy were suitable to ensure the microbiological safety, firmness and sensory quality of minimally processed bitter gourd (*Momordica charantia)* stored at 5 °C for 7 days [53]. Electron beam irradiation doses up to 1.0 kGy retained the textural and physical characteristics and microstructural quality attributes of mango fruits and enhanced their shelf life when stored at 12 °C for 21 days [54]. The exposure of Tommy Atkins mangoes to electron beam irradiation doses up to 1.5 kGy maintained the overall quality of the fruits without detriment to their sensory characteristics. The exposure of mangoes to ionizing irradiation increased the concentrations of phenolics compounds, antioxidant activity and reducing sugars content of mangoes [55]. Low-dose electron beam irradiation (0.5 and 1.0 kGy) of fresh-cut cantaloupe with modified-atmosphere packaging exhibits as an effective method of extending shelf life. Irradiated samples shown a lower and more stable rate of respiration. Sensory evaluation of cantaloupe rated the 1.0 kGy sample highest in sweetness and flavor intensity and lowest in off-flavor after about 2 to 3 weeks. Color and texture remained stable for the duration of each study and no clear trends have been observed [56]. Treatment of pre-packed whole-wheat flour (atta) with low dose gamma irradiation of 0.25-1.00 kGy could extend the shelf-life up to 6 months without any adverse effects on total proteins, fat, carbohydrates, vitamin B1 and B2 content, color index, sedimentation value, dough properties, total bacterial and mould count [57]. The X-ray treatment (0.5 kGy) on chicken breast meat and shell egg samples significantly reduced the *Salmonella* population by 1.9 and 3.0 log reduction, respectively, greater than a 6 log CFU reduction was observed with 2.0 and 1.0 kGy X-ray for chicken and shell eggs, respectively. The X-ray has a great antimicrobial potential and shown as a promising technology for the poultry and egg industries [58]. More than a 5 log CFU reduction was achieved for all the tested pathogens after treatment with 2.0 kGy X-ray and no significant effect on color or firmness of cantaloupe was detected [59]. A dose of 6 kGy (X-ray, gamma ray, and electron beam) reduced the total aerobic microbes population effectively without affecting the major quality indicators of red pepper powder. Electron beam irradiation showed a higher inhibitory activity as compared to X-ray and gamma irradiations on the sterilization of total aerobic microbes in red pepper powder [60]. [Table-2] represents the susceptibility of various microorganisms to irradiation. D is the radiation dose required to eliminate 90% (one log cycle reduction) of a bacterial population.

Table -2 *Irradiation D values for food-borne microorganisms [50,61,62]*

Microorganism	D (kGy)
Pathogenic bacteria	
Aeromonas hydrophila	0.04-3.40
Bacillus cereus (vegetative cells)	0.02-0.58
Bacillus cereus (spores)	1.25-4.00
Campylobacter jejuni	0.08-0.32
Clostridium botulinum (spores)	0.41-3.20
Clostridium perfringens (vegetative cells)	0.29-0.85
Escherichia coli	0.23-0.45
Escherichia coli O157:H7	0.24-0.47
Listeria monocytogenes	0.25-0.77
Salmonella	0.37-0.80
Staphylococcus aureus	0.26-0.45
Yersinia enterocolitica	0.04-0.39
Vibrio	0.08-0.44
Spoilage bacteria	
Clostridium sporogenes	2.30-10.90
Micrococcus radiodurans	12.70-14.10
Moraxella phenylpyruvica	0.63-0.88
Pseudomonas putida	0.08-0.11
Sporolactobacillus insulinus (spores)	2.10-2.58
Sporolactobacillus insulinus (vegetatives cells)	0.35-0.53
Streptococcus faecalis	0.65-0.70
Viruses	2.02-8.10

Ultrasound

Ultrasonic waves are similar to sound waves which propagate through solids, liquids, or gases, but their frequencies are far too high for perception by the human ear. Typically, the range of frequencies perceived by humans is 20 Hz to 20 kHz, while ultrasound is from about 20-1.2×10^{10} kHz. Ultrasound has the properties such as reflection, interference, adsorption and scattering and can be propagated through solids, liquids, and gases. Sound waves can be of longitudinal and transverse waves. In the former, the direction of particle motion is the same as the wave motion and capable of propagating through solids, liquids, or gases, thus widely used in ultrasonic applications. In the latter case, the direction of particle motion is perpendicular to the wave motion and these waves can only travel in solids [63]. Two properties of sound to appreciate the possibilities. The first is the use of sound as a diagnostic tool, e.g. in non-destructive evaluation. The second is the use of sound as a source of energy e.g. in sonochemistry. Generally ultrasound applications are divided into two broad categories: high-and low-intensity applications. Low-intensity applications tend to use frequencies above 100 kHz with energies below 1 W cm^{-2} whereas in high-intensity or power ultrasound applications (< 100 kHz, energies >10 W cm^{-2}). In the food industry, low-intensity ultrasound is used as an analytical technique either to control a process or to obtain information about different physicochemical properties of foods. High intensity or power ultrasound applications have significant effect on the material being tested generally by generation of intense cavitation [64]. Ultrasound is propagated via a series of compression and rarefaction waves induced in the molecules of the medium through which it passes. At sufficiently high power the rarefaction cycle may exceed the attractive forces of the molecules of the liquid and lead to the formation of cavitation bubbles [65]. Acoustic cavitation can be broadly grouped into two, transient and stable. In transient, bubbles grow by a process known as rectified diffusion, i.e. small amounts of vapour or gas from the medium enters the bubble during its expansion phase and is not fully expelled during compression. Each bubble will slightly affect the localized field experienced by neighbouring bubbles as the acoustic field that influences an individual bubble among the many thousands generated in a cavitating fluid is not uniform. Under such circumstances the irregular field will cause the cavitation bubble to become unstable and implode as shown in [Fig-4] [64, 65, 66]. This produces high local temperatures and pressures that would disintegrate biological cells and/or denature any enzymes present. The imploding bubble also results in the formation of high shear forces and liquid jets in the solvent that may also have sufficient energy to physically damage the cell wall/membrane. Stable cavitations; on the other hand, refers to bubbles that oscillate in a regular fashion for many acoustic cycles. The bubbles induce micro streaming in the surrounding liquid, which can also induce stress in any microbiological species present. The micro-streaming effect therefore provides a large force, without the bubbles having to burst [66].

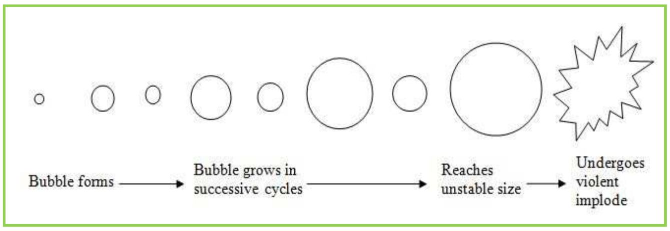

Fig-4 The acoustic generation of a cavitation bubble [66]

Applications of ultrasound in food processing

The emulsion quality and stability and the best system of cheese aroma encapsulation were obtained using ultrasound with maltodextrin as support which is known for poor emulsification properties [67]. Ultrasound processing of food at low power levels enhanced enzymatic reactions e.g. α-amylase, invertase and amyloglucosidase for starch, sucrose and glycogen hydrolysis respectively and inactivation of spoilage enzymes e.g. pectinmethylesterase, polyphenoloxidase at higher power levels [68]. Droplets size determination of corn-oil-in -water emulsions using ultrasonic and light scattering methods showed the same general trends of decreased size with increased degree ofhomogenisation. Ultrasonic sensors may be more appropriate for optically opaque, concentrated emulsions commonly found in foods [69]. Ultrasonic osmotic dehydration of apples (var. Golden) used lower solution temperatures to obtain higher water loss and solute gain rates, while retaining the color, flavour and thermally unstable nutritive components [70]. Inactivation of peroxidase, lipoxygenase, and polyphenol oxidase by the combined process of heat and untrasonic greatly increased with ultrasonic wave amplitude [71]. Ultrasonic treatment could be used as a novel method for tenderizing meat after a shorter aging period. The capability of ultrasound to bind the meat pieces in restructured meat products suggests an alternative to salt [72]. Ultrasound exhibited various possible applications in food processing as shown in [Table-3].

Table-3 *Some applications of ultrasound in food processing [63]*

Application	Description
Anti-microbial effects	Microbial destruction, microbial removal from the surfaces
Heat transfer	Increase the rate of freezing, thawing, and cooking
Mass transfer	Increase the rate of mass transfer in drying (solid, liquid, and osmotic drying), brining, membrane separation, dewatering, and bed filtration
Meat processing	Meat tenderisation
Homogenization, emulsification, encapsulation	Homogenise and emulsify milk, mayonnaise
Fermentation and aging	Increase rate of fermentation and aging (e.g.,wine)
Crystallization	Control of nucleation and crystal growth
Cutting	Cut fresh and frozen food products, including composite or multilayer foods
Defoaming, defrothing, and degassing	Defoam carbonated drinks, beer and other liquids during canning; defoam microbial fermenters; remove dissolved gasses from liquids
Cell disruption and extraction	Enhance extraction of compounds (e.g., enzymes, proteins, fruit juices, essential oils)
Enzyme activity and protein denaturation	Enzyme inactivation; protein denaturation; enhance enzyme activity
Polymerisation and depolymerisation	Polymerisation and depolymerisation of polymers

Some drawbacks of non-thermal technologies

The limited commercialization of high pressure processing is due to difficulty in the fabrication of pressure vessels that will tolerate very high pressures [9]. One of the main drawbacks of non-thermal applications at the present time is the cost of this technology [73]. Therefore, food manufacturers prefer conventional methods of food processing over non-thermal methods [73]. Electric field treatment is not suitable for foods susceptible to dielectric breakdown and therefore limited primarily to liquid foods. Solid foods containing air bubbles which brings dielectric breakdown are not suitable for electric field treatment [34]. It is reported the difficulty in designing treatment chambers with a uniform electric field distribution for the processing of solid foods and liquid foods with particulates [74]. A metal package is not suitable to be subjected under magnetic field [75]. One of the major disadvantages of ultrasound is that the sample containing gas bubbles inhibit the propagation of ultrasonic wave through the food due to the attenuation of ultrasound [76].

Conclusions

The retention of nutritive components, colour, aroma and other organoleptic qualities while at the same time prolong the shelf life by inactivating food spoilage microorganisms and enzymes and enhanced food safety and quality are the enormous choice and benefits to both the food processors and consumers. Food technologists and researchers have revealed the greater aspects of non-thermal methods over conventional methods of food processing. Studies have shown the combined treatment, based on the hurdle technology concept, has better possibilities in food processing, with the effect sometimes being synergistic.

Acknowledgements

The author gratefully acknowledge honorable Vice Chancellor, Assam University, Dean, Triguna Sen School of Technology, Assam University and Head of the Department, Agricultural Engineering, Assam University for providing all the necessary facilities and opportunity to carry out this study. The author pays homage to all the researchers in the field of non-thermal food processing technologies.

References

[1] Sahay K.M. and Singh K.K. (2013) Unit operations of agricultural processing, second revised and enlarged edition. Vikas Publishing House Pvt. Ltd., Noida.
[2] Jay J.M. (1992) Modern food microbiology, fourth edition. Van Nostrand Reinhold, New York.
[3] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) Emerging technologies in food preservarion, in: Palou E. (eds.), Nonthermal preservation of foods. Marcel Dekker, Inc., New York, pp.1-8.
[4] Hogan E, Kelly A.L. and Da-Wen Sun. (2005). High Pressure processing of food: an overview, in: Da-Wen Sun (eds.). Emerging technologies for food processing. Elsevier Academic Press, UK, pp. 3-32.
[5] Sequeira-Munoz A., Chevalier D., Le Bail A., Ramaswamy H.S. and Simpson B.K. (2006) *Innovative Food Science and Emerging Technologies,* 7, 13–18.
[6] Pauling L. (1964) College Chemistry: An introductory textbook of general chemistry. Freeman and Company, San Francisco.
[7] Olsson S. (1995) Production equipment for commercial use, in: Ledward D.A., Johnston D.E., Earnshaw R.G. and Hastings A.P.M. (eds.). High pressure processing of foods. Nottingham University Press, Nottingham, pp. 167–180.
[8] Zimmeran F. and Bergman C. (1993) *Food Technology,* 47, 162-163.
[9] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) High hydrostatic pressure food processing, in: Palou E. (eds.). Nonthermal preservation of foods. Marcel Dekker, Inc., New York, pp. 8-52.
[10] Barba F.J., Terefe N.S., Buckow R., Knorr D. and Orlien V. (2015) *Food Research International,* doi:10.1016/j.foodres.2015.05.015
[11] Ahmed J., Ramaswamy H.S. and Hiremath N. (2005) *International Journal of Food Science and Technology,* 40, 885–895.
[12] Cheah P.B. and Ledward D.A. (2006) *Meat Science,* 43, 123-134.
[13] Angsupanich K. and Ledward D.A. (1998) *Food Chemistry,* 63, 39-50.
[14] Okamoto M., Kawamura Y. and Hayashi R. (1990) *Agricultural and Biological Chemistry,* 54, 183-189.
[15] Arroyo G., Sanz P.D. and Prestamo G. (1997) *Journal of Applied Microbiology,* 82, 735-742.
[16] Dajanta K., Apichartsrangkoon A. and Somsang S. (2012) *High Pressure Research: An International Journal,* 32, 114-118.
[17] Kaushik N., Kaur B.P. and Rao P.S. (2013) *Food Science and Technology International,* doi:10.1177/1082013213496093
[18] Martino M.N., Otero L., Sanzb P.D. and Zaritzkya N.E. (1998) *Meat Science,* 50, 303-313.
[19] Cao X., Bi X., Huang W., Wu J., Hu X. and Liao X. (2012) *Innovative Food Science and Emerging Technologies,* 16, 181–190.
[20] Ahmed J., Ramaswamy H.S., Ayad A., Alli I. and Alvarez P. (2007) *Journal*

of Cereal Science, 46, 148–156.
[21] Perera N., Gamage T.V., Wakeling L., Gamlath G.G.S. and Versteeg C. (2010) *Innovative Food Science and Emerging Technologies,* 11, 39–46
[22] Kaushik N., Kaur B.P., Rao P.S. and Mishra H.N. (2014) *Innovative Food Science and Emerging Technologies,* 22, 40-50.
[23] Kaur B.P., Kaushik N., Rao P.S. and Chauhan O.P (2013) *Food Bioprocess Technology,* 6, 1390–1400.
[24] Singh A. and Ramaswamy H. (2013) *Journal of Food Research,* 2, 11-24.
[25] Ahmed J. and Ramaswamy H.S. (2007) Applications of magnetic field in food preservation, in: Rahman M.S. (eds.). Handbook of food preservation, second edition, CRC Press, New York, pp. 855-866.
[26] Pothakamury U.R., Barbosa-Cánovas G.V. and Swanson B.G. (1993) *Food Technology,* 47, 85–93.
[27] Hofmann G.A. (1985) Deactivation of microorganisms by an oscillating magnetic field. US Patent 4,524,079, June 18.
[28] Tsuchiya K., Nakamura K., Okuno K., Ano T. and Shoda M. (1996) *Journal of Fermentation and Bioengineering,* 8, 343-346.
[29] Lipiec J., Janas P. and Barabasz W. (2004) *International Agrophysics,* 18, 325-328.
[30] Lipiec J., Janas P., Barabasz W., Pysz M. and Pisulewski P. (2005) *Acta Agrophysica,* 5, 357-365.
[31] Moore R.L. (1979) *Canadian Journal of Microbiology,* 25, 1145–1151.
[32] Picart L. and Cheftel J.C. (2003) Pulsed electric fields, in: Zeuthen P. and Bogh-Sorensen L. (eds.). Food preservation techniques. Woodhead Publishing Ltd., England, pp.360-427.
[33] Toepfl S., Heinz V. and Knorr D. (2005) Over view of pulsed electric field processing for food, in: Da-Wen Sun (eds.). Emerging technologies for food processing. Elsevier Academic Press, UK, pp. 69-97.
[34] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) High intensity pulsed electric fields: processing equipment and design, in: Palou E. (eds.). Nonthermal preservation of foods. Marcel Dekker, Inc., New York, pp. 53-72.
[35] Vega-Mercado H., Gongora-Nieto M.M., Barbosa-Canovas G.V. and Swanson B.G. (2007) Pulsed electric fields in food preservation, in: Rahman M.S. (eds.). Handbook of food preservation, second edition, CRC Press, New York, pp. 783-813.
[36] Noci F., Walkling-Ribeiro M., Cronin D.A., Morgan D.J. and Lyng J.G. (2009) *International Dairy Journal,* 19, 30–35.
[37] Sanchez-Moreno C., Plaza L., Elez-Martinez P., De Ancos B., Martin-Belloso O. and Cano M.P. (2005) *Journal of Agricultural and Food Chemistry,* 53, 4403-4409.
[38] Oziembłowski M. and Kopec W. (2005) *Journal of Food and Nutrition Science,* 14, 31-35.
[39] Alvarez I., Pagan R., Condon S. and Raso J. (2003) *International Journal of Food Microbiology,* 87, 87–95.
[40] Putri R.I., Syamsiana I.N., Hawa L.C. (2010) *International Journal of Computer and Electrical Engineering,* 2, 916-923.
[41] Rodrigo D., Ruiz P., Barbosa-Canovas G.V., Martinez A. and Rodrigo M. (2003) *International Journal of Food Microbiology,* 81, 223–229.
[42] Evrendilek G.A. (2014) *Nutrition and Food Sciences,* doi:10.4172/2155-9600.1000e122.
[43] Ho S.Y., Mittal G.S. and Cross J.D. (1997) *Journal of Food Engineering,* 3, 69-84.
[44] Bajgai T.R. and Hashinaga F. (2001) *Drying Technology: An International Journal,* 19, 2291-2302.
[45] Fincan M., De Vito F. and Dejmek P. (2004) *Journal of Food Engineering,* 64, 381–388.
[46] He X., Liu R., Nirasawa S., Zheng D. and Liu H. (2013) *Journal of Food Engineering,* 115, 245–250.
[47] Lacroix M. (2005) Irradiation of foods, in: Da-Wen Sun (eds.). Emerging technologies for food processing. Elsevier Academic Press, UK, pp. 353-386.
[48] Rahman M.S. (2007) Irradiation preservation of foods, in: Rahman M.S. (eds.). Handbook of food preservation, second edition, CRC Press, New York, pp. 761-782.
[49] Bhattacharjee P. and Singhal R.S. (2010) Effect of irradiation on food texture and rheology, in: Ahmed J., Ramaswamy H.S., Kasapis S. and Boye J.I. (eds.). Novel food processing, effects on rheological and functional properties. CRC Press, New York, pp.103-125.
[50] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) Food irradiation, in: Palou E. (eds.). Nonthermal preservation of foods, Marcel Dekker, Inc., New York, pp. 161-213.
[51] Gomaa A. and Boye J. (2015) *Food Research International,* 74, 275–283.
[52] Chung H.J. and Liu Q. (2009) *Journal of Food Science,* doi: 10.1111/j.1750-3841.2009.01159.x
[53] Khattak M.K., Bibi N., Khattak A.B. and Chaudry M.A. (2005) *Journal of Food Science,* 70, 255-259.
[54] Moreno M., Castell-Perez M.E., Gomes C., Da Silva P.F. and Moreira R.G. (2006) *Journal of Food Science,* 71, 80-86.
[55] Moreno M.A., Castell-Perez M.E., Gomes C., Da Silva P.F., Kim J., Moreira R.G. (2007) *Journal of Food Process Engineering,* 30, 436–457.
[56] Boynton B.B., Welt B.A., Sims C.A., Balaban M.O., Brecht J.K. and Marshall M.R. (2006) *Journal of Food Science,* 71, 149-155.
[57] Marathe S.A., Machaiah J.P., Rao B.Y.K., Pednekar M.D. and Rao V.S. (2002) *International Journal of Food Science and Technology,* 37, 163-168
[58] Mahmoud B.S.M., Yuwei Wu S.C., Nannapaneni R., Sharma C.S. and Coker R. (2015) *Food Control,* 57, 110-114.
[59] Mahmoud B.S.M. (2012) *International Journal of Food Microbiology,* 156, 296-300.
[60] Jung K., Song B.S., Kim M.J., Moon B.G., Go S.M., Kim J.K., Lee Y.J. and Park J.H. (2015) *LWT- Food Science and Technology,* 63, 846-85.
[61] Radomyski T., Murano E.A., Olson D.G. and Murano P.S. (1994) *Journal of Food Protection,* 57, 73-86.
[62] Monk J.D., Beauchat L.R. and Doyle M.P. (1995) *Journal of Food Protection,* 58, 197-208.
[63] Torley P.J. and Bhandari B.R. (2007) Ultrasound in food processing and preservation, in: Rahman M.S. (eds.). Handbook of food preservation, second edition, CRC Press, New York, pp. 713-739.
[64] Salazar J., Chávez J.A., Turó A. and García-Hernández M.J. (2010) Effect of ultrasound on food processing, in: Ahmed J., Ramaswamy H.S., Kasapis S. and Boye J.I. (eds.). Novel food processing, effects on rheological and functional properties.CRC Press, New York, pp.65-84.
[65] Mason T.J., Riera E., Vercet A. and Lopez-Buesa P. (2005) Application of ultrasound, in: Da-Wen Sun (eds.). Emerging technologies for food processing, Elsevier Academic Press, UK, pp. 323-351.
[66] Mason T.J., Paniwny L. and Chemat F. (2003) Ultrasound as a preservation technology, in: Zeuthen P. and Bogh-Sorensen L. (eds.). Food preservation techniques, Woodhead Publishing Ltd., England, pp.303-337.
[67] Mongenot N., Charrier S. and Chalier P. (2000) *Journal of Agricultural Food Chemistry,* 48, 861-867.
[68] Donnella C.P.O., Tiwarib B.K., Bourkec P. and Cullen P.J. (2010) *Trends in Food Science & Technology,* 21, 358-367.
[69] Coupland J.N. and McClements D.J. (2001) *Journal of Food Engineering,* 50, 117-120.
[70] Simal S., Beneditoh J., Sanchez E.S. and Rossello C. (1998) *Journal of Food Engineering,* 36, 323-336.
[71] Lopez P., Sala F.J., de la Fuente J.L., Condon S., Raso J. and Burgos J. (1994) *Journal of Agricultural Food Chemistry,* 42, 252-256.
[72] Jayasooriya S.D., Bhandari B.R., Torley P. and D'Arcy B.R. (2004) *International Journal of Food Properties,* 7, 301-319.
[73] Stoica M., Mihalcea L, Borda D and Alexe P. (2013) *Journal of Agroalimentary Processes and Technologies,* 19, 212-217.
[74] [74] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) Biological effects and applications of pulsed electric fields for the preservation of foods, in: Palou E. (eds.). Nonthermal preservation of

foods. Marcel Dekker, Inc., New York, pp. 73-112.
[75] Barbosa-Canovas G.V., Pothakamurry U.R., Palou E. and Swanson B.G. (1998) Oscillating magnetic fields for food processing, in: Palou E. (eds.). Nonthermal preservation of foods. Marcel Dekker, Inc., New York, pp. 113-138.
[76] McClements D.J. (1995) *Trends in Food Science and Technology,* 6, 293-299.