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Novel food processing technologies: An overview

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Abstract
Novel food processing technologies arose as a result of consumer's desire for safe, tasty, fresh and mild processed food products with long shelf life and maintained quality. Recent trend of lifestyle changes, as consumers demand products with a significant nutritional contribution, bioactive compounds, and good sensory properties, posed a great challenge toward food processing sector for the evolution of novel and innovative food processing techniques. The novel food processing technologies, viz. HPP, PEF, Irradiation, ultrasonication and cold plasma which influence on consumer's health have been the major innovations in the field of processing technology. These novel techniques act by prolonging the shelf life, enhancing or maintaining the quality, and to regulate freshness of food product. The main objectives of this review article are to provide basic knowledge of different new and innovative food processing techniques about their way of preservative action, effectiveness and suitability in various types of foods.

Keywords: innovative, shelf life, processing, quality, bioactive

Introduction
Novelty and recent trends in food processing techniques are the result of consumer demand for health promoting foods with high nutritional and nutraceutical values (Bagchi, 2008) [4]. Since ancient times, the approach of the food industry was to provide safe food product with long shelf-life; however, presently it is not enough to simply produce safer food as consumers demand products with a significant nutritional contribution, bioactive compounds, and good sensory properties. The important food quality attributes, such as taste, texture, appearance, and nutritional value, are strongly dependent on the way food is processed (Knoerzer *et al*., 2016) [27]. Microorganisms are the main target organisms for food spoilage and poisoning so are targeted by different food preservation procedures. Food processing methods used by industry rely either on microbial inactivation or inhibition of microbial growth. Conventional heat-dependent pathogen-reduction methods such as thermization, pasteurization and in-container sterilization can adversely affect taste, nutritional value and appearance. Alternative techniques for traditional thermal processing of food have received much interest, due to increased consumer demand to deliver higher quality and better consumer-targeted food products, many innovative food processing techniques called "novel" or "emerging" techniques have been developed. Several novel processing techniques recently introduced; in particular, were high pressure processing (HPP), pulsed electric field (PEF), ultrasonic, irradiation, cold plasma, hydrodynamic cavitation *etc* (Knorr *et al.,* 2011) [28]. Additionally, food products processed through these innovative techniques contribute to global food security by extending shelf life (Knoerzer, *et al*., 2015) [26]. This review aims to describe the basic principles, mechanism of action and applications of some of these emerging technologies.

Novel food processing technologies
Thermal processing is commonly used to extend the shelf-life and to ensure the microbiological safety of food products because of its ability to inactivate microorganisms and spoilage enzymes (Rawson *et al*., 2011) [50]. However, thermal processing can cause detrimental effects on the quality and nutritional values of the fruit-based commercial products. The constituents responsible for color, flavor and taste are typically heat-sensitive, so thermal processing can easily change the quality of the commercial fruit products and affect product acceptability (Gao *et al*., 2016) [18]. Thus, the search for alternative methods for thermal food processing which would generate a safer product with higher quality, nutrient content and sensorial properties incited food scientists to explore other inactivation techniques. Two broad fields of food processing technologies are currently under research, non-thermal

technologies, in which the inactivation factor is by physical hurdles such as pressure, electromagnetic fields, and sound waves, among others; and novel thermal processing technologies, which mainly use energy generated by microwave and radio frequency. However, using such novel technologies to inactivate microorganisms and enzymes in food is not enough. A safer product should also be free of poisonous substances and contact of food with certain materials during processing should be avoided (Lelieveld & Keener, 2007) [31]. Thus, evaluation of the overall quality of food products processed by innovative technologies is an essential requirement before a product can be commercialized.

Novel food processing technologies around the world
Non thermal technologies

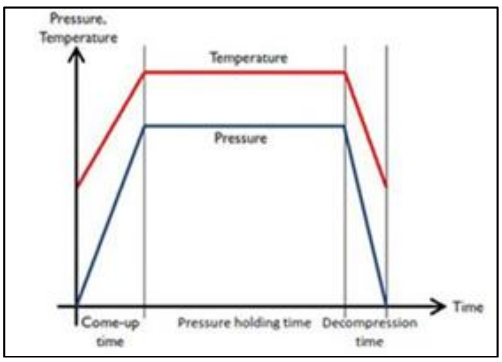
Non thermal technologies	Thermal technologies
High hydrostatic pressure	microwave
Pulsed electric fields	Radio frequency
Irradiation	Ohmic heating
Ultrasound	Inductive heating
Cold plasma	
Ozone	
Supercritical water	

It is worth mentioning that most novel technologies were first studied as prospective microbial inactivation technologies to improve the safety of food. However, important results in the final characteristics of many food items were also observed: such as intact nutrient content in most of the novel food products; unique sensorial properties like color, texture, and appearance; and formation of new aroma compounds. Thus, the search for microbial inactivation technologies not only yielded the possibility of a safer product, but also improved overall product quality, and provided new ingredients for the development of other novel food products.

High pressure processing
High pressure processing (HPP) is one of the promising non-thermal preservation techniques and has proven to be an effective alternative to conventional food preservation technologies to enhance safety and shelf life of perishable foods (Balasubramaniam and Farkas, 2008) [5] with minimal influence on the sensory, physical, and nutritional properties of foods. High pressure processing (HPP) also referred to as ultra high pressure UHP) or high hydrostatic pressure (HHP) is the application of elevated hydrostatic pressures of 150 to 700 MPa for 30 s to inactivate spoilage and pathogenic microorganisms, with the aim of obtaining microbiologically safe food products while avoiding undesirable changes in the sensory, physicochemical and nutritional properties of food (Munoz *et al*, 2007) [40]. Pressure generation is mechanical usually through a fluid (water) which is consequently transmitted to the product. While transmission of pressure is typically thought to be isostatic and near-instantaneous, the inactivation of pathogens requires a prolonged hold at high pressure. This introduces special challenges to manufacturers, because of the substantially high equipment and maintenance costs and possible damage to product quality (Balasubramaniam and Farkas, 2008) [5].
HPP induces less impact on the low molecular weight nutrients such as vitamins and polyphenols, and compounds related to sensory properties such as pigments and flavoring agents compared with conventional thermal processing (Landl *et al*., 2017) [30]. Hence, HPP allows better retention of nutritional values and sensory properties than the traditional pasteurization technologies. HPP has been successfully employed to preserve blueberry juice (Barba *et al*., 2012) [7], strawberry and its puree (Gao *et al*., 2016; Marszałek *et al*., 2017) [18, 33], pawpaw pulp (Zhang *et al*, 2017) [56], apple juices (Nayak *et al*, 2017) [42], cantaloupe puree (Mukhopadhyay *et al*., 2017) [39], grape juice (Chang *et al*, 2017) [10], and so on, extending their shelf-life in 10–60 days range.

Principle
Pascalisation is based actually on activation volume that uses a transferring medium and is applied only in batch processing units. HPP is based on the Le Chatelier's principle indicating that an application of pressure shifts the systems equilibrium to the state that occupies the lowest volume. Therefore any chemical or physical changes (phase transitions, chemical reactions and changes in molecular configuration) accompanied by decrease in volume are enhanced by the application of pressure. Consequently non-covalent bonds are affected while key food quality parameters remain mostly unchanged. However, enzyme reactions can occur (e.g. during pressure build up phase before inactivation), adiabatic heating takes place (approx. 1-2 °C per 100 MPa) and temperature and pressure distribution is not entirely homogenous in processing units.

Mechanism of microbial inactivation
Significant research has been conducted to show the inactivation of microorganisms by the application of high hydrostatic pressure in foods (Donaghy *et al*., 2007) [12]. The efficiency of HPP to inactivate microorganisms is dependent on the target pressure, process temperature, and HT. The relationship between pressure and temperature in a typical HHP was described by (Muntean *et al*., 2016) [41]. Different microorganisms react with different degrees of resistance to HPP treatment and most of the vegetative microorganisms, yeasts, and viruses can be inactivated at or near room temperatures. On the other hand, bacterial spores are extensively resistant to high hydrostatic pressures and for the mold sterilization, a combination of pressure (400-600 MPa) and heat (90-120 °C) is often required. Furthermore the pressure sensitivity of the bacterial cells also depends on the growth phase. Bacterial cells in the stationary growth phase are generally more resistant to pressure than those in the exponential growth phase (Hayman *et al.*, 2007) [21]. For the inactivation of vegetative pathogenic and spoilage microorganisms, HPP pasteurization demands a logarithmic reduction of 5 or 6 in pathogens at chilled or process temperatures less than 45 °C and at pressures above 200 MPa.



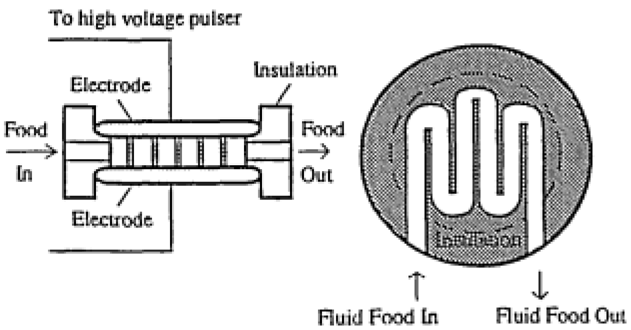
Pressure, Temperature, and Time during a HPP process (Ferstl, 2013).

The response of the microorganisms largely depends on the substrate and food composition during the pressure treatment. On applying pressure following detrimental changes take place that results in the microbial cell destruction:

- Irreversible structural changes of the membrane proteins and other macromolecules, leading to disruption of cell membrane (Muntean *et al*., 2016) [41].
- Destruction of homogeneity of the intermediate layer between the cell wall and the cytoplasmic membrane.
- Inactivation of membrane ATPase (Hoover *et al*., 1989) [23].
- Nucleic acid and ribosomal disruption involved in protein synthesis.

Pulsed electric field

In recent years, pulsed electric field as an emerging technology has got wide interest for pasteurization of heat-sensitive liquid food (Mathys *et al*., 2013) [34], and for refining heat and mass transfer operations in the food industry (Puértolas *et al*., 2016) [49]. PEF provokes the formation of pores (electroporation phenomenon) by exposing the tissues to an electric field for short high voltage pulses in the range of 10-80 KV/cm, resulting in cell membrane permeabilization. Electroporation may be either reversible or irreversible based on the optimization of electric field strength and treatment intensity (Zimmermann, 1986) [57]. In case of reversible electroporation, transient pores formed enables entrapment of materials of interest inside the cell membranes while Irreversible electroporation destroys the cells by permanent membrane damage and is usually used in the processes of microbial inactivation and to increase extraction yield (Dukić-Vuković *et al*., 2017) [14]. This novel technology can ensure good product quality due to its non-thermal nature and low energy consumption. PEF is instant targeted, flexible, energy efficient and because heat is minimized products have longer shelf life whilst maintain better nutritional value than the conventional thermal processing. However PEF technology does have some limitations. For example, any bacterial spores or mould ascospores in food products are usually resistant to PEF treatment, even at high intensity. This property could lead to a failure of the pasteurization process, resulting in a potential food safety hazard (Arroyo *et al*., 2012) [1]. In addition to the spores or ascospores, enzymes are resistant to PEF treatment. PEF processing is restricted to foods with no air bubbles and with low electrical conductivity. If bubbles are present in the PEF treatment chamber, dielectric breakdown will occur.



Schematic drawing of a flow through treatment chamber

Stages of microbial inactivation process

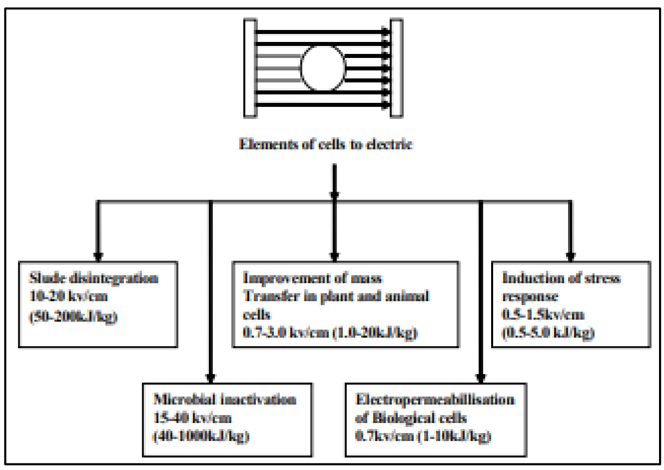
The process of microorganism inactivation can be divided into the following main stages

(i) Initial stage (with the duration from nanoseconds to milliseconds): creation of pores when an electric pulse is applied (electroporation)
(ii) Stage of evolution of the pore population (with the duration from nanoseconds to milliseconds): change in the number of pores and their sizes during an electric treatment.
(iii) Post-treatment stage (with the duration from miliseconds to hours): cell death (complete inactivation) or returning of the cell to its initial viable state due to pore resealing. In the latter case, the damage to the cell induced by the pulsed electric field is sub-lethal.

The final result of the PEF treatment depends on the processes going on during all these stages. During the action of an electric field, more and more cells become electroporated (initial stage of pore formation) and the number of pores and/or their size increase. After an electric pulse, two competing processes proceed: (i) cells return to their former viable state due to pore resealing or (ii) cells die due to the loss of cell membrane integrity and intracellular compounds.

Applications of PEF in food processing

Pulsed electric fields technology has been successfully used for the pasteurization of liquid and semisolid foods such as juices, milk, yogurt, soups, and liquid eggs. Application of PEF processing is limited to food products with no air bubbles and with low electrical conductivity. The maximum particle size in the liquid must be smaller than the gap of the treatment region in the PEF chamber in order to ensure proper treatment. The effect of PEF at low electric fields applied individually or in combination with heating has been investigated in order to improve the extraction yield of intracellular compounds present in fruits and vegetables (Donsì *et al*., 2010) [13]. PEF treatments at 0.1-10 kV/cm increased the extraction of hydrophilic compounds, such as sugar from sugar beet (Eshtiaghi & Knorr, 2002) [15], betaine from red beetroot (López *et al*., 2009) [32] and anthocyanins from grapes, red cabbage (Gachovska *et al*., 2010) [17] or purple fleshed potatoes (Puértolas *et al*, 2013) [48]. PEF has been recently introduced as an alternative pre-maceration treatment to increase and speed-up polyphenolic extraction without altering the sensory properties, highlighting effectiveness in improving wine stability and color quality (Morata *et al*., 2017) [38].



Electropermeabilisation of cells after expose to electric field and application in food and waste water processing with typical electric field strength and energy input requirements.

Cold plasma

Amongst all innovative non-thermal technologies, cold plasma (CP) is a relatively novel technology emerged as an alternative source for surface sterilization and disinfection, for ensuring the quality and safety of minimally processed food and the novelty lies with its non-thermal, economical, versatile and environmentally friendly nature. The term ‘plasma’ refers to a quasi-neutral ionized gas, primarily composed of electrons, ions and reactive neutral species in their fundamental or excited states (Pankaj *et al.*, 2014) [43]. Based on the thermal equilibrium, there are two plasma classes—denominated non-thermal plasma (NTP) or cold plasma and thermal plasma. Cold plasma is generated at 30-60 °C under atmospheric or reduced pressure (vacuum), requires less power, exhibits electron temperatures much higher than the corresponding gas (macroscopic temperature), and does not present a local thermodynamic equilibrium. The cold plasma technique was originally applied to enhance the antimicrobial activity in surface engineering, bio-medical field and polymer industries (Sarangapani *et al.*, 2015) [51]. Due to its excellent antimicrobial ability, cold plasma has attracted much attention for non-thermal preservation of agricultural products, which has been studied for several fresh vegetables and fruits in recent years (Misra *et al.*, 2014) [37]. It is suitable for treatment of heat-sensitive food products because the ions and uncharged molecules gain only a little energy and remain at a low temperature (Pankaj *et al*., 2018) [45].

Effect of Plasma on Microbial Cells

The effect of plasma on microbial cells is cause of plasma ions and cell interactions. The reactive species in plasma is widely accompanied with the direct oxidative effects on the outer surface of microbial cells. The plasma effect depends highly on the presence of water, moist the organism highest the effect and vice versa (Dobrynin *et al*., 2009) [11] Microbial inactivation of plasma is actually based on the fact that plasma reactive species damage the deoxyribonucleic acid (DNA) in the chromosomes. The ROS of interest in plasma processing are hydroxyl radicals, hydrogen peroxide, and the superoxide anion (Wiseman and Halliwell, 1996) [55]. The application of plasma for microbial inactivation results in formation of malondialdehyde (MDA) in microbial cells, which in turn participates in the formation of DNA adducts resulting in cell damage (Dobrynin *et al*., 2009) [11]. In particular, reactive species interacts with water, leading to the formation of OH* ions (Zou *et al*., 2003) [58] which are most reactive and harmful to the cells. It is worth mentioning that the OH* radicals formed in the hydration layer around the DNA molecule are responsible for 90 % of DNA damage. Hydroxyl radicals can then react with nearby organics leading to chain oxidation and thus leads to destruction of DNA molecules as well as cellular membranes and other cell components (Dobrynin *et al*., 2009) [11]. Although it is well documented that reactive oxygen species such as oxygen radicals can produce profound effects on cells by reacting with various macromolecules. The microorganisms are more sensitive to singlet state oxygen leading to destruction of cells (Aziz *et al*., 2014) [2]. On the other hand lipid bi-layer of microbial cell is more susceptible to atomic oxygen as the reactivity of atomic oxygen is much higher than the molecular oxygen leading to the degradation of lipids, proteins and DNA of cells. The damage of the double bonds in lipid bi-layer cause impaired movement of molecules in and out of cell. The bombardment of reactive oxygen species (ROS) on the surface of bacterial cell also disrupts the membrane lipids. (Surowsky *et al.* 2013) [53] found that the active species in plasma react with the amino-acid in proteins which further causes irreversible structural changes in proteins leading to the destruction of the microbial spores.

L + OH• L• + H2O → (1)
L• + O2 L-OO• → (2)
L-OO• + L L• + L-OOH → (3)
L-OOH L-O• → (4)

During application of plasma, microorganisms are exposed to an intense radicals bombardment most likely provoking surface lesions that the living cell cannot repair quickly, this process is termed “etching”. The phenomenon of etching is based on the interaction of relative energetic ions and activated species with the molecules of the substrate. The accumulation of charges imparts an electrostatic force at the outer surface of cell membranes which can cause cell wall rupture called as electropermeabilization as the same principle occurring in pulsed electric fields. During application of plasma treatment where plasma initiates, catalyzes, or helps sustain a complex biological response, compromised membrane structure (e.g. peroxidation) or change in membrane bound proteins and/or enzymes leads to complex cell responses and may affect many cells as the affected cell signal others.

Applications of cold plasma (CP)

In the past cold plasma was used for sterilization of thermo labile materials in the biomedical technology sector and now it is extended to food industries as a novel non-thermal technology. In food industry particularly, current cold plasma research are focused on its applications for food decontamination, enzyme inactivation, toxin degradation, waste water treatment and packaging modifications. Specifically for food processing, cold plasma has proven to be effective for inactivation of food-borne pathogens and spoilage microorganisms. Recently, (Han, *et al.* 2016) reported different inactivation mechanisms for Gram positive and Gram negative bacteria by cold plasma. They observed that cold plasma inactivation of Gram positive bacteria (*Staphylococcus aureus*) was mainly due to intracellular damage and little envelope damage whereas Gram negative bacteria (*Escherichia coli*) was inactivated mainly by cell leakage and low-level DNA damage. Apart from microbial inactivation, effects of cold plasma on the food quality has been another important aspect gaining attention of food researchers. The changes in the enzymatic activity of trypsin after the application of cold plasma was studied by (Dobrynin *et al*., 2009) [11]. It was reported that the plasma was able to change the 3D structure of proteins in trypsin enzymes due to cleavage of peptides bonds. In past few years cold plasma has shown significant potential for degradation of various food toxins especially mycotoxins (Bosch *et al*., 2017) [8] drawing increased interest from food researchers. In case of the packaging materials plasma treatment is used for surface decontamination (Pankaj *et al*., 2016) [44], surface sterilization (Vesel and Mozetic, 2012) [54] and surface treatments such as cleaning, coating, printing, painting, and adhesive bonding. The immobilization of bioactive functional compounds like lysozyme, nisin, vanillin, sodium benzoate, glucose oxidase, bovine lactoferrin, lactoferricin, chitosan, nanosilver, trichlosan, or antimicrobial peptides into the packaging material by plasma treatment has been extensively studied within the emerging field of antimicrobial and active packaging (Pankaj *et al*., 2014) [43]. Phsicochemical effects of plasma generates the formation of oxidizing species: radicals (H*, O*, OH*) may diffuse into the liquids and molecules (H_2O_2, O_3, etc.), shockwave, ultraviolet light and electrohydraulic cavitation may degrade the pollutant in waste water or decomposes the pollutant into other compound (Jiang *et al*., 2013) [25].

Hydrodynamic cavitation

Hydrodynamic cavitation is another non-thermal underexplored technology in food processing (Gogate, 2011) [19]. It is considered more physically effective and energy efficient than the ultrasound treatment. Hydrodynamic cavitation can simply be produced either by mechanical rotation of an object through a liquid or by the passage of fluid through a constriction such as a venturi, an orifice plate or a convergent divergent nozzle resulting in increase in velocity at the expense of local pressure (Huang *et al*., 2013). Because of constriction enormous gas bubbles are created and subsequently collapse violently downstream due to the recovery of pressure, forming strong mechanical waves and high-speed micro jets (Kuldeep *et al*., 2016). Collapsing cavities generate highly reactive hydroxyl radicals which can then be harnessed for a variety of applications. Cavitation number (Cv), a dimensionless parameter, relates the flow conditions with the cavitation intensity. Ideally, cavitation is generated when Cv is between 0.1-1, obtained by adjusting the flow condition and reactor geometry (Bagal and Gogate, 2014) [3]. This novel technology offers several advantages such as no additional chemicals (clean tech), compact and in-line reactors and low costs making it a promising technology platform.

Principle

Novel hydrodynamic cavitation basically describes the process of vaporization, bubble generation and bubble implosion. Cavitation occurs when local pressure drops below saturated vapour pressure and recovers above vapour pressure, as a result of sudden decrease and increase in local pressure. Flashing is said to have occurred if the recovery pressure is not above the vapour pressure. Increase in kinetic energy or an increase in the pipe elevation is responsible for the generation of cavities in the pipe systems.

Cavitation is damaging when uncontrolled. Cavitation power can be harnessed and non destructive by controlling the flow of the cavitation. Controlled cavitation generates free radicals due to disassociation of vapors trapped in the cavitating bubbles. It can be used to enhance chemical reactions or propagate certain unexpected reactions which can lead to degradation or even mineralisation of water constituents without addition of any chemicals. Extent of cavitation taking place in any system is explained in terms of the cavitation number and is simply derived from Bernoulli's theorem expressed by the following equation:

$$Cv = \frac{P2-Pv}{0.5\rho\ V2}$$

Where,

P_2 is downstream pressure

P_v is the vapor pressure of the liquid and;

V is the velocity at constriction where cavitation takes place.

Novel hydrodynamic cavitation application in food industry

Hydrodynamic cavitation phenomenon is of great significance in food extraction and processing. Various high-acid (pH ≥ 4.6) fluid foods have been processed in a hydrodynamic cavitation reactor for commercial sterility. The mechanisms responsible for cellular inactivation are the physical stresses owing to hydrodynamic cavitation, and hence hydrodynamic cavitation reactors can be readily applied for food sterilization. (Milly *et al*. 2007) have investigated the application of hydrodynamic cavitation reactor for sterilization of fluid foods such as tomato juice, apple juice and skim milk. It was reported that hydrodynamic cavitation induced adequate destructive forces to inactivate vegetative cells of bacteria, yeast, yeast ascospores and heat-resistant bacterial spores. The main advantage of using a hydrodynamic cavitation reactor can be lower operating temperatures for sterilization, and hence foods such as acidic fruit juices, salad dressings and milk can be safely processed at reduced processing temperatures, resulting into superior product quality. Recently, (Milly *et al*., 2008) also investigated the application of shock wave reactor for inactivation of *Saccharomyces cerevisiae* in apple juice.

With these few examples with actual fluid foods, it indeed appears that utilizing hydrodynamic cavitation as a processing technology allows processors to minimally heat treat fluid foods while extending shelf life of perishable products such as apple juice. Reducing thermal treatments and thus retaining heat labile nutrients and flavor components by processing with hydrodynamic cavitation creates superior products in today's market where "fresh picked" flavours and healthy/nutritious products drive consumption trends. Apart from food industry, hydrodynamic cavitation has found wide applications in the field of microbial cell disruption (Balasundaram and Pandit, 2001), water disinfection (Chand *et al*., 2007), wastewater treatment (Pradhan and Gogate., 2010) [47] and sludge decomposition (Hirooka *et al*., 2009) [22].

Concluding remarks

Trends in the emergence of novel non-thermal processing technology with improved quality and safety resulted in innovations in processing techniques. Research and development in response to consumer preferences gave rise to HPP, PEF, cold plasma (CP) and hydrodynamic cavitation (HC) food processing techniques that are purely innovative. These innovative processsing technologies contributed toward the enhancement of food quality, safety, feasibility and bioactivity of functional components. Applicability of novel and innovative processing techniques is growing widely because of their health impact and thus resulted in reduced consumer complaints. In the near future traditional thermal processing will be completely replaced by innovative food processing techniques as these techniques are rapidly making their way into the global market.

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