Discover Food

Review

Emerging techniques for the processing of food to ensure higher food safety with enhanced food quality: a review

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Abstract
In recent years the consumer's preference for highly convenient food possessing superior characteristics, high nutritional value with minimum processing, easy to eat, safe, should have a longer shelf life and mouth-watering taste has increased. All these demands of the consumer are impossible to be fulfilled by the existing thermal treatments, which provide food with reduced nutritional and sensory qualities with lesser shelf life. This diverted the attention of food professionals towards non-thermal technologies which are eco-friendly, energy-efficient, and do not process food at a higher temperature for a longer time. As a result, non-thermal technology delivers food with higher nutritional and sensory values and with longer shelf life. Non-thermal treatments are cost-effective technologies that constitute a newer bunch of tools that are developing steadily and are being explored across the globe. This review discusses in brief non-thermal technologies like ultraviolet, pulse electric field, high-pressure processing, ultrasonication, cold plasma, and supercritical carbon dioxide.

Keywords Food preservation · Processing · Non-thermal technology · Nutritional qualities · Sensory attributes · Shelf life · Food safety

Abbreviations

DPPH	Diphenylpicrylhydrazyl
DNA	Deoxyribonucleic
HHP	High hydrostatic pressure
LED	Light emitting diode
MDA	Malondialdehyde
PEF	Pulsed electric field
SC-CO_2	Supercritical carbon dioxide
TBARS	Thiobarbituric acid reactive substances
UHP	Ultra high pressure
UV	Ultraviolet

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1 Introduction

The continual transformation in demand of consumer for safe, fresh and nutritious food has slowly but steadily energized the emergence of nonthermal treatment in the food processing sector [1]. The thermal processing of food is known to provide adequate inactivation of pathogenic microorganisms present in food but due to the use of high temperature the nutritional volatile constituents are lost, there is an undesirable change in the organoleptic characteristics and since food is exposed to thermal treatment for longer time there is an adverse effect on the texture of food [2]. The non-thermal treatments refer to treatments in which food is exposed to ambient temperature especially for reducing microbial load and extending the shelf life of food including processed food, raw food etc. (Fig. 1) [3–6]. Since food is exposed to ambient temperatures there is no chance of thermal damage to heat-sensitive food ingredients having nutritional importance, the sensory attributes of food remains unaltered and also food is exposed for a short period of time to non-thermal treatment there is minimum or no change in the texture, appearance and flavours present in food, increases bioavailability of bioactive components in food, decrease in activity of enzyme causing deterioration of food [7–10]. Due to numerous advantages of non-thermal treatment to food, it is considered as a boon to food industry and has a potential prowess to utterly abolish the thermal food processing treatments [11–14]. Consequently, non-thermal treatments have been explored on a large scale in last decade [15–17]. The non-thermal treatments include ultrasonication, supercritical fluids, high pressure processing, pulsed electric fields, ultraviolet, irradiation, oscillating magnetic field, microwave irradiation, cold plasma, blue LED, dense phase carbon dioxide, high voltage arc discharge, hurdle technologies. These non-thermal treatments reduces microbial load present in the food by destroying the cell membranes and genetic material thereby causing disorganization of carbolic and anabolic activities in microorganism [18–20]. All these non-thermal treatments can be employed in single or they can be used in a sequential approach or in amalgamation with each other to bring about maximum damage to microorganism and increase shelf life of food by utilizing energy efficiently for a fleeting time and keeping nutritional, textural, organoleptic qualities of food intact [21–23]. The type of food and the purpose of operation decides the kind of non-thermal treatments to be employed. The non-thermal treatments may be specific or non-specific with reference to the kind of food processed. Pulsed electric fields are extensively used for fluid foods like processing of fruit juices, squash, milk etc. with the strength of electric field varying from 20 to 80 kV/cm. The treatment destroys cell membranes of microorganism in treatment time of less than one second [24–27]. Irradiations are usually preferred for the treatment on solid food material. The ionizing radiations used include high speed electrons, high power

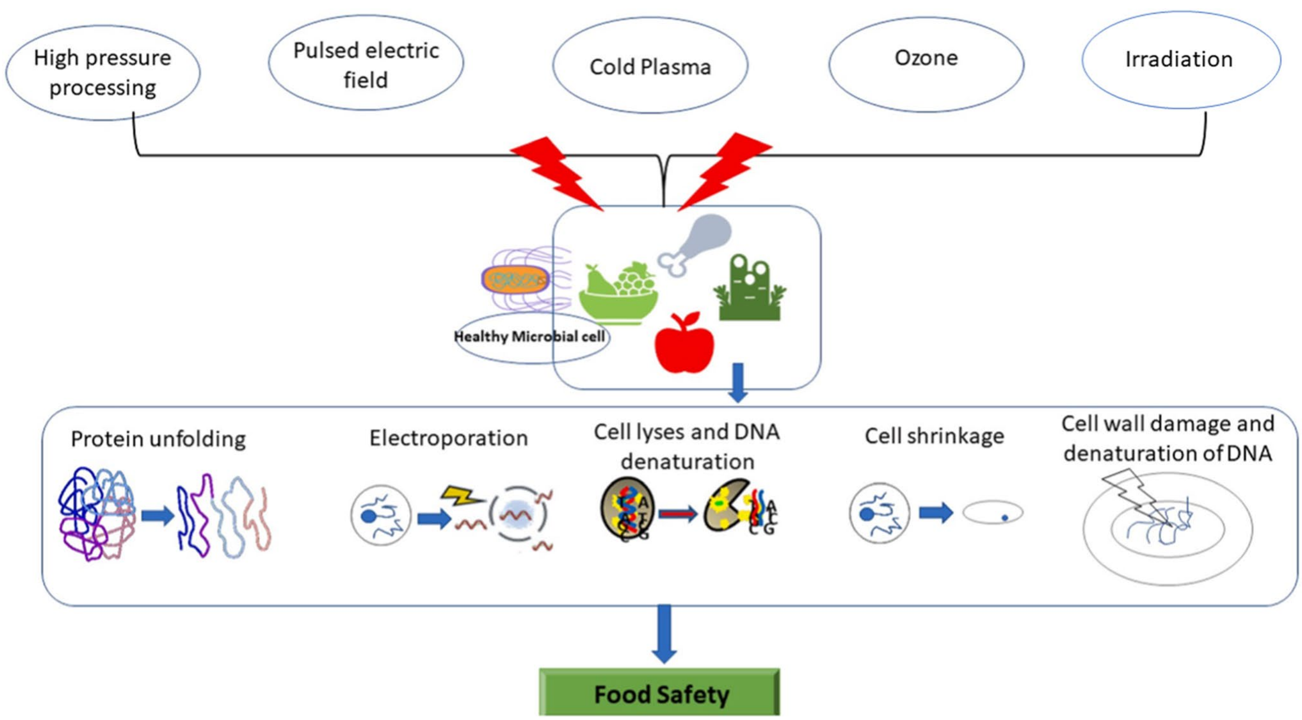

Fig. 1 Non thermal technologies to ensure higher food safety (Adapted with permission from Elsevier [210])

photons, X-rays with a first-hand damage to the membranes of microbial cells and the disruption in genetic makeup of cells [28, 29]. High pressure processing is used for treating a large volume of food before packaging it. The use of high pressure makes membranes of microbial cells permeable and degrades it. The pressure is usually in the range of 150–450 MPa at low temperature of around 40–60 °C [30, 31]. Non thermal techniques like ultraviolet and cold plasma are used for treating of exterior surface of raw fruits, processed food, and packaging material, additionally ultraviolet light is also used for treating food processing equipment before and after food processing operations. They results in sudden changes in the deoxyribonucleic acid and damage to the biological membrane of lipids in the microorganisms [32, 33]. These treatments are also used in combination with each other to maximise the effect and increasing the keeping quality of food for longer duration of time [34]. Non thermal treatments like pulsed electric field, and cold plasma can be employed for the physiological changes in the properties of food ingredients to improve their functionality and application [35]. Supercritical fluids treatment and ultrasonication along with processing are also used for the intensified synthesis and extraction of bioactive from various natural spices, condiments, flowers, plants which have high nutraceutical value [36, 37]. The non-thermal treatments are still not fully developed in food industries and there is scuffle in the mind of food professional with the technical aspects of these techniques. This review focuses on the basic principles of these treatments, their action on microorganism to ensure higher food safety, current application, and future scope of these non-thermal technologies in food processing sector.

2 Non-thermal technologies

2.1 Pulsed electric field

Pulsed electric field (PEF) is a sustainable well organized non-thermal treatment method mainly employed to reduce the microbial load in food and enhance the shelf life. PEF is also used for deactivating enzymes responsible for food spoilage [38]. PEF technology consist of food treatment compartment, energy supply unit, surveillance system [39, 40]. The maximum success of PEF treatment is achieved with a good design of treatment compartment [41]. Treatment compartment comprise of two electrodes usually made up of stainless steel. The food material to be treated is kept in the middle of two electrodes in treatment compartment [42] and a pulse of high electric field is generated from energy supply unit. The food is exposed to the pulse of high intensity usually 10–90 kV/cm for a period of very small duration routinely from microseconds to milliseconds [40]. Since food in exposed to pulse of high intensity just for microseconds there is on undesirable changes in food and its natural state is maintained. In case of liquid foods, the flow pattern of liquid food is very important to achieve maximum disinfection of liquid food. If the flow of liquid food in treatment compartment is stream line there is chances of uneven treatment and in order to achieve maximum effect of treatment in such cases pulse of high intensity and frequency is required [39, 43]. If the flow of liquid is turbulent there is intermixing of liquid layers and formation of eddies, due to this the microbial load are divulged to the high intensity pulse and are destroyed. Turbulence can be generated naturally or forcefully by putting hindrance in the path of liquid flow or by fluctuating flow rates of liquid food [44, 45]. The most critical unit in PEF system is the energy supply unit used for creating pulse. This pulsating system is composite and require high economical cost for development and maintaining of the energy supply unit [46, 47] which is the main hindrance in exploitation of PEF on a large scale. The total energy required for the PEF is calculated as

$$E_{Total} = V_{max} \times I_{max} \times \gamma f, \quad (1)$$

where E_{Total} is the energy provided to the PEF system, V_{max} voltage of pulse supplied to system in Volts, I_{max} is the maximum current into the treatment compartment in Ampere, γ is the width of the pulse generated, f is frequency of generated pulse in Hertz. Surveillance system is the principal segment of PEF system. The PEF system variables like flow rate of liquid food, temperature of treatment compartment, frequency and width of generated pulse, pulse voltage in the compartment are controlled and monitored using surveillance system in pulse electric field [48]. There are different theories proposed till date which explains how the PFE is effective as a non-thermal technology. The most recent accepted theory is "free radical theory". According to this theory there is formation of free radicals and hydrogen peroxide. These free radicals enter in the membranes of the cell. When they enter in the cell membranes, they initiate oxidation process and the cell components like lipids, proteins are oxidized and also there is adverse effect on the enzymes which is lethal for the cell and cell cannot survive and this results in decrease in population of microorganism in the treated sample.

The extent of PEF treatment largely depends on the outer membrane of cells, orientation of cell including its dimensions in terms of width, diameter, cell behaviour in presence of electric field [47]. PEF is widely used for treatment of liquid foods namely fruit juices, milk and milk products, egg and meat products. The application of PEF is summarized in Table 1. A recent study reported that the PEF assisted process is excellent for extraction of bioactive from fruits and gave higher yield as compared to the conventional method [49]. Novickij et al. [42] investigated effect of combination of PEF and antimicrobial agent against growth of *Salmonella. typhimurium* and *Listeria innocua*. The PEF with field strength of 30 kV/cm at 40 °C for 2 min was sufficient to retard the growth of microorganisms even in the metabolically active phase. Timmermans et al. [50] studied effectiveness of PEF with milder condition against pathogenic microorganisms such as *Escherichia coli*, *Listeria planatrum*, *Listeria monocytogenes*, *Salmonella* in liquid foods. The low electric field with intensity of 2.7 kV/cm and pulse width of 15–1000 µm were more effective than the higher intensity of 10 kV/cm and pulse width of 2 µs. Higher intensity effect was found to be effective in case of juice with high acidity and low intensity showed excellent results for juices with high and low acidity. Moens et al. [40] has successfully employed PEF with intensity of 1.01 kV/cm, pulse width 145 µm and 2 Hz frequency as a non-thermal pre-treatment to retain the surface appearance of carrot tissues and after treatment the tissues were pliable and reduced deterioration of surface of during the process of processing. Maza et al. [51] investigated use of PEF in wine making. The wine was prepared using PEF with inlet liquid flow in treatment compartment as 2500 kg/h. The PEF assisted wine showed higher content of polyphenols, anthocyanin, tannins as 64.3 AU, 840.3 mg/L, 1458.4 mg/L which was 46.9 AU, 814 mg/L, 1313.3 mg/L respectively after 6 days of fermentation in wine with conventional process. The PEF assisted wine also showed higher concentration of fragrance compounds as compared to conventional wine. The PEF is also used for increasing shelf life of alcoholic beverages like wine by destruction of most vulnerable microorganisms. Different field intensity of 31, 40, 50 kV/cm were applied in PEF treatment compartment of wine which reduced the load of yeast *Brettanomyces bruxellensia* in wine as 1. 2.1, 3 log reduction respectively. The PEF treated wine did not showed any increase in the iron, chromium and nickel ion concentration and were in line with the conventionally produced wine [52]. Martín-García et al. [53] treated by-product of brewing industry with PEF before extraction process. The PEF as a preliminary operation enhance the available and unavailable phenolic components to 101 µg/g d.w. and 539.46 µg/g d.w. respectively which was very low 37.58 µg/g d.w. and 326 µg/g d.w. respectively in untreated sample. PEF is also used for destruction of microorganisms and enhance shelf life of beers without change in its organoleptic characteristics. PEF with field intensity of 45 kV/cm and pulse width of 70 µs resulted in deactivating *Sacchromyces cerevisiae* spore *octad*. Different beers with alcohol % as 0%, 2.5%, 4%, 4.5%. 5%, 7% were tested for decrease in load of *S. cerevisiae* with log reduction as 0.2, 0.8, 1.1, 0.9, 1.7, 2.2 respectively indicating that the PEF showed more effectiveness in beer sample containing high alcohol [54]. Meza-Jiménez et al. [55] studied effect of PEF on possible changes on its residual activity, relative protein concentration, sulfhydryl group content, and structural changes. The effect of PEF on papain was investigated with variation in PEF parameters and flow rate. 20% depletion in sulfhydryl group was observed at 13 kV/cm field intensity and lower volumetric flow of 0.2 Lmin-1. The highest reduction in amount of relative protein was obtained at 10 kV/cm with volumetric flow of 0.4 L min^{-1}. PEF successfully altered the shape of papain enzyme and deactivated it there by arresting its activity. Liu et al. [56] showed in his studies that the PEF treatment to egg protein results in increase in anti-oxidant and anti-inflammatory potential of ovomucid depleted egg white. DPPH analysis showed increased antioxidant potential of hydrolysate at acidic pH after PEF treatment as compared to untreated sample. Same effect was observed for increase in inflammatory activity of hydrolysate in HT-29 cell against IL-8 formation. Wu et al. [57] reported enhanced physiological properties of protein when exposed to PEF with field intensity of 25 kV/cm and pulse width 600 µs and pulse width up to 400 µs has no effect on the protein properties. Rise in the pulse width to 600 µs showed significant changes in protein properties. There was change in the mean particle size from 466.6 to 639.06 nm and heterogeneity of protein changed from 0.31 to 0.29 at 0 µs and 600 µs respectively with no oxidative damage to protein and little ionized effect to sulfhydryl group of protein. Pulse electric field also had an excellent effect on the properties of long fibril protein of meat from broiler. The field intensity less than 18 kV/cm showed enhanced properties of long fibril protein in terms of its solubility, shearing characteristics and enhancement in SH group of proteins. There was adverse effect on these properties with rise in PEF intensity beyond 18 kV/cm [58, 59]. Li et al. [60] investigated effect of PEF on textural and chemical qualities of salmon fish which was freezed at − 18 °C and then defrost at 10 °C. PEF treatment was given with field intensity as 1 kV/cm, 200 µs width of generated pulse at 50 Hz frequency. Texture was analysed using texture analyser TA-XT2i, the PEF treated sample showed 204.22 g^{-1}, 28.24%, 85.94 mm, 143.39 N, 122.98 N values for hardness, resilience, springiness, gumminess, chewiness respectively which was 173.30 g^{-1}, 26.22%, 80.37 mm, 123.16 N, 113.82 N for untreated sample. The values of PEF treated fish was very close to unpreserved fresh fish. PEF treatment enhanced the texture [61] of fish. Lipid oxidation in fish sample was measured using TBARS value. The PEF treated sample showed higher oxidation as compared to untreated

Table 1 Important application and technical aspects of PEF in food sector

Sr: no.	Application	Food	Pulse width (µs)	Frequency (HZ)	Strength of electric field (kV/cm)	Conclusion	References
1	Extraction	Peach Pomace	4	0.1	10	PEF gave higher extraction efficiency as compared to conventional method	[49]
2	Microbial inactivation	Pectin	500		30	Effective against *S. Typhimurium*, *L. Innocua*	[42]
3	Moderation of biochemical traits	Oat flour	20		4.4	Enhanced β-glucan content without change in the chemical composition of flour	[207]
4	Texture improvement	Carrot	145		1.01	Surface turned pliable with reduced damage to surface while processing	[40]
5	Microbial inactivation	Orange juice, watermelon juice, coconut water	1000		2.7	Effective against *E. coli*, *L. monocytogenes*, *Salmonella*, *Lactobacillus plantarum*	[50]
6	Intensification of bioactive	Fruit juice (papaya and mango juice)	230		30	Intensification of bioactive like anthocyanins and carotenoids in fruit juices	[208]
7	Improved colour and flavour	Grape wine	200	200	10	PEF assisted wine making showed higher concentration of anthocyanins, tannins and aroma compounds	[51]
8	Preservation of wine	Wine	1.7	100	50	Reduction in *Brettanomyces bruxellensia* population with no effect on the total metal ion concentration	[52]
9	Extraction of valuables from brewing industry waste	Brewer spent grain	14.5	50	2.5	Intensification in the available and unavailable phenolic components to 101 µg/g d.w. and 539.46 µg/g d.w. respectively which was very low 37.58 µg/g d.w. and 326 µg/g d.w. respectively in untreated sample	[53]
10	Preservation	Beer	70		45	Beer sample with varying alcohol (%) were exposed to PEF. The beer containing more alcohol showed maximum log reduction	[54]
11	Preservation	Enzyme	288 and 144	0.2	13 and 10	13 kV/cm and 288 µs deteriorate sulfhydryl group and 10 kV/cm and 188 µs reduced the amount of residual proteins. This inactivating papain	[55]
12	Enhancing neutraceutical properties	Egg	20	300	1.7	Increase in antioxidant and anti-inflammatory potential of hydrolysate	[56]
13	Steadiness of protein	Egg	600	100	25	Enhanced protein properties beyond 400 µs with no oxidative damage to protein	[57]
14	Enhancing protein properties	Chicken meat		0–1000	0–28	Increase in protein properties up to 18 kV/cm of field intensity	[58, 59]
15	Evaluate effect on quality of fish	Salmon fish	200	50	1	PEF treated fish showed improved texture with no damage to protein but slight oxidation of lipids	[60]
16	Texture improvement	Red meat	20	50	0.8 – 1.1	Enhanced colour and texture with slight oxidation of unsaturated fatty acids	[62]

Table 1 (continued)

Sr: no.	Application	Food	Pulse width (μs)	Frequency (HZ)	Strength of electric field (kV/cm)	Conclusion	References
17	Quality	Abalone	20	50	0.66, 1.38, 2	PEF aided with heat showed little changes in physiochemical traits whereas increase in heat altered texture, colour and initiated lipid oxidation	[63]
18	Structure	Strawberry	40	2	1.07	PEF preliminary treatment enhanced the texture and crunchiness in freeze dried strawberries	[64]

sample, the value was 0.40 mg MDA/kg for PEF treated sample and 0.33 mg MDA/kg in untreated sample. The total volatile base nitrogen value for PEF treated fish was 13.74 mg/g and 26.25 mg/g for untreated sample indicating that nitrogen released due to damage to protein was less in PEF treated sample. Similar study was reported for red meat using different PEF parameters (frequency 50 Hz, pulse width 20 µs, field intensity 0.8–1.1 kV/cm) showed enhanced tenderness and eye appealing texture with slight oxidation of unsaturated fatty acids [62]. Effect of pulse electric field aided with heat and unaided with heat on sea lobsters showed that PEF showed little changes on physicochemical characteristics of abalone. Whereas PEF aided with heat at different temperature of 70 °C, 80 °C, 90 °C showed changes in texture and colour due to heat. TBARS value of PEF with heat at 70 °C was 0.437 mg MDA/kg, 0.436 mg MDA/kg. 0.426 mg MDA/kg which increased to 0.669, 0.684, 0.726 mg MDA/kg for PEF with heat at 90 °C for field strength of 0.66 kV/cm. 1.38 kV/cm, 2 kV/cm respectively. Lipid oxidation initiated with increase in temperature for both PEF treated and untreated samples [63]. Lammerskitten et al. [64] studied effect of PEF as a preliminary treatment before freeze drying on strawberry. PEF treated sample showed uniform drying with excellent size and bulk with eye appealing colour with higher porosity and good brittleness as compared to control sample. The critical study of the literature showed that pulse electric field as a non-thermal treatment showed wide application in food and aided sector. With so many advantages there are certain disadvantages also reported like PEF may induce oxidation of unsaturated fatty acid and increases saturated fatty acid content, there may be migration of metal from electrode material in to the food which may adversely affect the organoleptic characteristics of food [65].

2.2 Bridganization

Bridganization commonly referred to as ultra high-pressure treatment/high hydrostatic pressure treatment. The UHP treatment is one of the oldest non-thermal technologies employed in food and allied sector. It was developed in early 90 s and was first exploited commercially for preparation of fruit preserves in Japan. A typical UHP instrument consists of pressure compartment in which food is kept, pressure generating structure, system to control the entire process. The working pressure range of UHP for food is in between 250 and 650 MPa [66]. Food is kept in the pressure compartment and the compartment lid is closed from the top. Water is the medium for generating pressure. This water sometime contains small amount of soluble oil. The water is introduced in the compartment from bottom and food is pressurized. The desired pressure is developed and maintained throughout the entire operation. The instrumentation for UHP is very simple and hence it is among the highly exploited non-thermal treatment in food processing sector till date [67]. UHP treatment gives high reduction in the microbial load present in food without affecting the natural colour, flavour, appearance and organoleptic properties of food as compared with the conventional processes of preservation using heat. Hence food preserved using UHP treatment have gain much acceptance from consumers [68]. The theory behind the destruction of microorganism due to high pressure explains that the reduction in load of microorganisms present in food may be due to breaking of secondary and quaternary structure of protein thus causing denaturation in protein leading to cell death, change in the pH of the microbial cell with disorganization of the cellular structure leading to cell death [69]. UHP is highly effective against pathogenic bacteria which involves moulds, yeast, gram positive and gram-negative bacteria. But still the potency of the UHP process is governed by the pressure on food, total time of exposure and temperature maintained in the pressure compartment. The inactivation varies with the type of microorganism some are resistant to the treatment with low pressure like prokaryotes, yeast, moulds can resist pressure up to 400 MPa compared with the eukaryotes, and parasites [70, 71]. Due to its simple construction, working and good impact on the product the UHP finds numerous applications in food sector. The application of UHP is listed in Table 2. Rios-Corripio et al. [72] treated fermented beverage using UHP with varying pressure and time combinations of 500 MPa and 10 min (T1), 550 MPa and 10 min (T2), 600 MPa and 5 min (T3). The antioxidant capacity was enhanced in UHP treated sample as 304.61, 315.46, and 325.99 mg Trolox/100 mL day for T1, T2 and T3 respectively which was 304.61 mg Trolox/100 mL day for untreated sample after 42 days of storage. Total flavonoids were 100.96, 104.97. 107.49 mg quercetin/100 mL day for T1, T2, T3 respectively which was 97.57 mg quercetin/100 mL day for untreated sample. Same trend was observed for phenolic but the alcohol content remains in line with the untreated sample even after 42 days of storage. The colour and the organoleptic characteristics were retained after storage of 42 days for UHP beverage. The strong aroma of fruit juice is its identity of being fresh and natural. The carbohydrates have ability to bind the aroma components and arrest its release. The mango juice was subjected to HHP treatment of 600 MPa for 5 min and retention of aroma compound was compared in HHP sample and untreated sample. The instrumental analysis showed higher release of aroma chemicals in HHP treated sample than untreated with loss of some of volatile aroma components in HHP treated sample [73, 74]. Bulut and Karatzas [75] investigated combined effect of freezing and HHP on reduction in load of *E. coli* in orange juice and phosphate buffer

Table 2 Food subjected to high hydrostatic pressure treatment and its effect on food to ensure food safety

Sr: no.	Food	Pressure (MPa)	Time	Conclusion	References
1	Fermented beverage	500, 550 and 600	10, 10, 5 min	Improved physiological properties with enhanced antioxidant capacity, phenolic compound, flavonoids without change in colour and organoleptic characteristics	[72]
2	Fruit Juices	600	5 min	HHP treatment showed slower release of aroma compound as compared to untreated sample. The freshness of treated sample was maintained for more days compared to untreated sample	[73, 74]
3	Orange juice	250	15 min	HHP treatment coupled with freezing showed higher reduction *E. coli* load as compared with HHP alone	[75]
4	Acai juice	300, 400, 600	1 and 3 min	400 MPa for 3 min gave maximum reduction in load of microorganisms in acai juice with pH 4 and 2.9° soluble solids	[77]
5	Acai juice	400–600	5–15 min	Reduced *Alicyclobacillus acidoterrestris* spores with treatment at 600 MPa for 13.5 min. Showed 37% enhanced anthocyanin extraction in juice as compared with the thermal processed sample which showed reduced anthocyanin by 16% as compared with control sample	[78]
6	Glycation of protein	0.1, 100, 200, 300	3 days	HHP treatment enhanced selective glycation of protein when treated at higher pressure of 200 MPa and increased the functional properties of proteins for numerous food application	[79]
7	Fruit berry	200, 350, 500	1, 5.5, 10 min	HPP treated sample showed same content of phenolic constituents compared with other drying methods. The freeze drying showed enhanced anthocyanin and conventional drying in oven showed enhanced ellagitannins which was not observed with HHP treated sample	[80]
8	Carrot pomace	300, 400, 500, 600	1 min	Enhance physical and chemical properties of dietary fibre from carrot pomace for its numerous application	[81]
9	Whole milk	600	5 min	Reduced microbial load and decrease in *E. coli* with loss of volatile aroma compounds	[82]
10	Milk	600	1.5, 2.5, 5	HHP treatment twice for 2.5 min was more effective than single HHP treatment of 5 min	[83]
11	Human milk	593.96	233 s	Reduction in population of bacterial spores	[84]
12	Cheese	600 MPa	5, 10, 15 min	Increased yield and purity of α-lactalbumin and β-lactoglobulin	[85]
13	Whey protein	100–600	15–30 min	HHP treatment showed greater unfolding of protein structure increasing thiol group quantity at 400 MPa for 15 min. Selected enzymes showed higher hydrolysis ability in HHP treated sample as compared with the control sample	[86]
14	Micellar casein	300, 450, 600	5 min	Reconstituted casein micellar showed stable chemical and physical properties when stored for 7 days with little change in colour when treated at 450 and 600 MPa	[87]
15	Prickly pear	100, 350, 600	5 min	Increased antioxidant and anti-inflammatory activity of pulp and peel when treated at 350 MPa for 5 min	[88]
16	Bacteria	100–450	0–40 min	*Lactobacillus bulgaris* survived at the higher pressure conditions whereas *Lactococcus lactis* was less stable at higher pressure. Severe pressure and higher exposure time lead to decrease in the load of bacterial cells	[89]
17	Beef patties	300	5 min	HHP increased cooking losses with decrease in moisture of patties and reduced colour. Combination of HHP and addition of soy protein to patties showed improve colour and formation of 3-d mixed protein network due to interaction of different denatured proteins	[90]
18	Sea food	250	5 min	HHP as a preliminary biocatalyst impregnation technology showed improved texture with higher water holding capacity and increased tenderization in fish meat compared with other preliminary treatment of injection and immersion	[91]
19	Chicken breast	400, 500	1–5 min	Decrease in *Salmonella* spp. with increase in pressure of HHP treatment	[92]
20	Meat muscle	0–600	6 min	Increase in treatment pressure resulted in onset of lipid oxidation even if haemoglobin is removed from the surface of meat	[209]

saline. HHP treatment alone has less effect on population of *E. coli* as compared to combined effect of freezing and HHP treatment. The reduction in *E. coli* load was 1.83 log reduction CFU/mL and 6.83 log reduction CFU/mL for non-frozen HHP and frozen HHP (400 MPa, 9 min) sample respectively, similar result were seen for orange juice, the reduction was 3.84 and 4.88 log reduction CFU/mL in non-frozen HHP and frozen HHP (250 MPa, 15 min) juice respectively. The HHP treatment is extensively employed in fruit juices to reduce the load of pathogenic microorganism and to enhance the keeping qualities of fruit juice without any observable effect on the nutritional and sensory attributes of fruit juices [76]. Gouvea et al. [77] studied effect of HHP treatment on reduction in microbial load of acai juice with different pH and soluble solids. Reduction of 6 log CFU/mL in load of *Salmonella* spp. and *Listeria monocytogenes* was obtained at 400 MPa for 3 min followed by 7 days freezing juice with pH 4 and 2.9° soluble solids. With increase in the pH and soluble solid of juice the microbial inactivation also slowed down to 5 log CFU/mL. The high hydrostatic pressure treatment is also effective in deactivating bacterial spores. HHP treatment of 600 MPa for 13.5 min reduced *Alicyclobacillus acidoterrestris* spores load in acai juice and also deactivated *Lactobacillus fructivorans* by 6.7 log cycle by treating at 600 MPa for 5 min. The mesophilic and yeast count of HHP treated acai juice stored at refrigeration was 2.77 and 1 log CFU/mL at 28 day which was 2.82 and 1 log CFU/mL on first day as compared to untreated sample in which mesophilic and yeast count increased to 6.25 and 7.25 log CFU/mL on 28 day which was 4.98 and 3.15 log CFU/mL on first day. The HHP also enhanced the extraction of anthocyanin by 37% as compared to control sample [78]. Liu et al. [79] reported that the HHP treatment is useful in attachment of polysaccharide to protein and to increase the functional properties of protein. The selected glycation of soybean protein with flaxseed gun occurred which increased the solubility of protein by 86.84% when treated with HHP of 200 MPa for 3 days at 60 °C. Pimenta Inada et al. [80] studied effect of HHP and other drying methods on increase in bioactive mainly phenolic constituents. The HHP treated sample showed same phenolic constituent as compared with the drying in conventional oven and lyophilisation process. The conventional drying showed increased content of ellagitannins and lyophilisation process showed increased content of anthocyanin which was not observed in HHP treated sample. Yu et al. [81] studied HHP as an effective nonthermal treatment for enhancing the physical and chemical property of dietary fibre from carrot. The dried carrot powder was subjected to HHP treatment of 300, 400, 500, 600 MPa for one minute. The treatment at 400 MPa showed enhanced adsorption of glucose as 2.634 mmol/g. 500 MPa enhanced oil retention and water swelling properties as 2.35 g/g and 10.02 mL/g respectively. 600 MPa increased water retention and cation exchange property as 7.14 g/g and 2.29 mmol/g. This HHP can be successfully utilized for modification of physical and chemical properties to increase the application of desired food ingredient in food industry. Milk is an emulsion containing fat dispersed in water and milk is a complete food and a good medium for growth of microorganism to multiply and grow. HHP finds extensive application in milk and milk products to arrest the activity of spoilage bacteria. Liu et al. [82] studied effect of HHP on quality of milk and compared it with the normal heat treatment. HHP treatment of 600 MPa for 15 min showed no load of diseases causing bacteria in milk with population of *E. coli* less than 1 CFU/mL with total count of bacteria as 2.9×10^2 CFU/mL same as high temperature pasteurization. HHP coupled with microfiltration showed less load of total bacteria as 1.9×10^1 CFU/mL. The volatile components responsible for aroma in milk were lost in HHP and high temperature treated milk but the aroma compounds were very much retained in milk processed at low temperature (63 °C). To achieve higher microbial inactivation in milk, milk can be subjected to HHP treatment for more than one time. Raw milk and skim milk were treated with HHP once for 5 min and twice for 2.5 min. The HHP treatment twice for 2.5 min showed higher reduction in microbial load than single HHP treatment for 5 min. Total bacterial count was below detection level in HHP treated raw milk which was 7.1 log CFU/mL. Total bacterial count was 2.93 log CFU/mL and 3.29 log CFU/mL for single HHP and double HHP treatment in skim milk. There was decrease in the short chain fatty acid composition of raw milk in HHP treatment twice at 2.5 min as compared to one HHP for 5 min. There was reduction in the amount of volatile constituents of both raw and skim milk [83]. The HHP is also effective against bacterial spores in human milk [84]. Marciniak et al. [85] studied effect of single HHP and multiple HHP on the soluble and precipitate protein fraction of acidified cheese whey protein. Single HHP at 600 MPa resulted in 95% yield of α-lactalbumin with 75% purity and 88% β-lactoglobulin with 98% purity. Carullo et al. [86] studied effect of variation in HHP pressure and time on the shape and functional properties of whey protein isolate. Low HHP pressure were unable to change the structure. Pressure of 200–400 MPa had good effect on structure with exposing of thiol group. Maximum quantity of thiol group 12.43 ± 0.21 μmol SH/g_{prot} was obtained at 400 MPa for 15 min. HHP treated sample showed good foaming properties. Hydrolysis ability of selected biocatalyst was enhanced in HHP treated sample. HHP also shows excellent effect on the other fraction of milk protein i.e., casein. HHP treatment using higher pressure beyond 450 MPa showed excellent effect on chemical properties of reconstituted casein micellar protein. The structure of protein was firm even after storage of 7 days at 10 °C [87]. Gómez-Maqueo et al. [88] showed increase in the amount of bioactive components of opuntia pulp subjected to HHP treatment. Antioxidant potential of pulp increased when treated at

350 MPa for 5 min and Enhanced anti-inflammatory activity at 600 MPa for fruit peel and 350 MPa for fruit pulp. Giannoglou et al. [89] studied effect of HHP treatment on acid forming ability of lactic acid bacteria namely *Lactobacillus bulgaris*, *Streptococcus thermophilus* and *Lactococcus lactis*. *Lactobacillus bulgaris* survived at the higher-pressure conditions whereas *Lactococcus lactis* was less stable at higher pressure. Severe pressure and higher exposure time lead to decrease in the load of bacterial cells. Bernasconi et al. [90] showed that the HHP treatment at 300 MPa for 5 min results in enhancing loss during cooking, increase in hardness and reduction in the available moisture. The combined effect of HHP and soy protein isolate showed improved texture with colour similar to control sample and HHP treatment triggered breaking of protein structure which led to interaction of different proteins forming a 3-D matrix of protein. Pizarro-Oteíza et al. [91] studied effect HHP as preliminary impregnation treatment on the enzyme induced texture improvement of Chilean abalone. HHP impregnation pre-treatment at 300 MPa for 5 min showed excellent tenderization effectiveness of 30.8% with improved water holding capacity of fish meat as 87.85 ± 0.25 g per 100 g and enhanced sensory traits and textural properties which was similar to control sample as compared with the other impregnation preliminary treatment of injection and immersion. Cap et al. [92] studied deactivation of microbial load in chicken fillets with HHP treatment from 100 to 600 MPa. It was observed that with increase in the pressure there was decrease in the load of *Salmonella* spp. which was 4.55 log CFU/g and 3.43 log CFU/g in tryptic soy agar and xylose lysine desoxycholate agar respectively at 400 MPa. Increase in pressure beyond 400 MPa showed nil population load of *Salmonella* spp. The HHP treatment had adverse effect on texture and colour of breast fillets. The exposure of meat to HHP treatment at higher pressure can cause oxidation of meat fat. TBARS value increased from 0.1, 0.3, 0.5 µmol/kg on first day and 2.6, 6.4, 10.2 µmol/kg on seventh day when treated with 200, 400, 600 MPa pressure respectively which was 0.2 and 1.2 µmol/kg for untreated sample on first and seventh day respectively. It is seen that the HHP treatment not only reduces microbial load in food but also enhances physical, chemical, textural, sensory and nutritional qualities of food if treated with proper pressure time combination. Higher pressures may lead to undesirable changes in food. In spite of certain disadvantages HHP is extensively used and is also commercialized non-thermal technology because of simple instrumentation and economic operation.

2.3 Ultrasonication

The ultrasonication is commonly referred to as ultrasound or sonication treatment. Ultrasonication is an eco-friendly and green non-thermal technology which is highly exploited in food, organic synthesis, textiles, pharma, paint, petrochemical industries. In ultrasound there is generation, growth and collapse of cavity bubbles which create high energy. In ultrasonication there is passage of ultrasound through the medium. This ultrasound creates cavitation. With the passage of ultrasound through the medium there is formation of expansion cycle, the expansion cycle forms bubbles, this bubble increases in size to its maximum and then collapse in the compression cycle. The collapse of cavity generates shock wave with high energy which brings about required changes in product. Ultrasonication can be direct or indirect sonication. In direct sonication a sonication horn is immersed in the liquid food and in indirect sonication the food is kept in a container and this container is immersed in the ultrasonic bath. The cavitation effect during ultrasound process can be used for intensified extraction of bioactive, enzyme/microbial deactivation, enhanced heat/mass transfer during processing, intensified synthesis of lipids, change in rheological properties, separation of compounds, and formation of stable emulsion etc. [93, 94]. Ultrasonication operates in three different frequency variations i.e. 10–100 kHz (less frequency) which produces cavities of larger size which collapse and high energy is generated, 100–1 MHz (medium frequency) produces cavities of optimum size which are favourable for formation of chemical radicals and 1–10 MHz (more frequency) produces cavities of small size. The medium frequency sonication produces chemical radicals which can cause undesirable changes in food are not used in food sector [95]. Depending on the purpose of treatment the frequencies can be varied. Ultrasonication is most commonly used for extraction, emulsification, filtration, encapsulation, curing of meat etc. Ultrasonication with different duty cycle and frequencies can be employed for various application. Various applications with use of different ultrasonic parameter is summarized in Table 3. Vural et al. [96] used direct ultrasonication for extraction of antioxidants from olive leaves using 0.97% duty cycle for 14.22 min. The use of ultrasound for extraction using solvent shown higher extraction as 7.19 ± 0.44 mg/g dw, 88.3 ± 2.4 mg/g dw, 5.95 ± 0.19 mg/g dw for phenolic constituents, antioxidant activity, oleuropin. Ding et al. [97] used ultrasonic extraction of soluble and insoluble fibres from the algae *Nannochloropsis oceanica.* Ultrasonic assisted extraction at 20% duty cycle showed enhance physical and chemical properties of soluble fraction as 96.8 ± 0.3% solubility in water, 1.31 ± 0.03 g/g capacity of holding water, 1.12 ± 0.01 g/g capacity of holding oil which was 90.8 ± 0.31% solubility in water, 1.17 ± 0.01 g/g capacity of holding water, 1.04 ± 0.01 g/g capacity of holding oil for extraction done using alkali. Ultrasound gave highest yield of 17.5% with more than 90% purity

Table 3 Application of ultrasonication with ultrasound parameter on the food

Application	Duty cycle (%) or power (W)	Irradiation time	Type	Conclusion	References
Extraction of oleuropein from olive leaves	0.97	14.22 min	Direct sonication using probe and solvent	Enhanced extraction of phenolic compounds, oleuropin and antioxidants from olive leaves	[96]
Extraction of dietary fiber from *Nannochloropsis oceanica*	20	20–40 min	Indirect sonication using sonication bath	Ultrasonic assisted extraction gave 17.5% yield with more than 90% purity and enhanced physical and chemical properties	[97]
Extraction of protein from Australian rock lobster head	50	5 min	Indirect	Higher yield (99%) of protein using ultrasonication	[98]
Extraction of phenolic compound from rye bran			Indirect	Extracted large amount of phenolic with higher antioxidant ability as compared with conventional process	[99]
Extraction of anthocyanin			Indirect	5.98 mg/g of anthocyanin were extracted using ultrasonication which was near to theoretical yield of 5.87 mg/g	[100]
Synthesis of novel fat	80	25 min	Direct sonication	Intensified synthesis of medium chain triglyceride having neutraceutical application	[37]
Synthesis of structured lipids	60	9.6 h	Direct sonication	Ultrasonication gave 84.5% of yield in 9.6 h of acidolysis reaction between medium chain fatty acid and edible oil containing long chain triglycerides	[102]
Frying	0, 200, 400, 600, 800 W	12 min	Sonication fryer	Enhanced flavour of fried food due to increase oxidation of lipids which released volatile aroma compounds	[108]
Cooking	0, 400, 600, 800 W		Indirect	Reduced lipid oxidation during cold storage for 28 days	[109]
Functionalization	0.9, 1. 1.3 W/cm^2	30 min	Ultrasonic bath (indirect)	Ultrasound treatment enhanced various functional properties like foam formation, gel formation, emulsion formation properties of flaxseed protein	[110]
Thawing	200, 400, 600 W		Ultrasonic bath (indirect)	Ultrasonic treated sample showed less thawing time with enhanced nutritional components including essential amino acids, vitamins etc.	[111]

Table 3 (continued)

Application	Duty cycle (%) or power (W)	Irradiation time	Type	Conclusion	References
Drying	25 kHz frequency	20 min	Ultrasound bath (indirect)	Increased rate of water removal from treated sample compared with untreated sample. The moisture and solute diffusivity was increased and was 7.300×10^{-10} m^2/s and 3.511×10^{-10} m^2/s respectively	[112]
Bitterness	20 kHz frequency	60 min	Indirect	Reduction in bitterness of green walnut jam due to ultrasonication assisted extraction prior to processing	[113]
Freezing	20 kHz and 28 kHz		Newly developed freezing system containing refrigerator, coolant tank, freezing tank, ultrasonic panel	Use of double frequency ultrasonic freezing showed improved physiochemical properties with reduced freezing time and increased rate of freezing	[114]
Hydrolysis	25 kHz	300 min	Indirect	Lipase pre-treated with ultrasonication shower enhanced rate of hydrolysis of milk fat	[115]
Preservation	20% duty cycle, 20 kHz	10 min	Indirect	Thyme essential oil emulsion produced using ultrasonication showed increased activity of essential oil against *E. coli*	[116]
Physiochemical properties	28, 40, 80 kHz		Indirect	Enhanced physical and chemical properties of gluten which enhanced the cooking and textural behaviour of noodle prepared using these treated glutens	[122]
Meat curing	50% duty cycle and 20 kHz frequency	10 min	Direct using probe	Makes meat tenderer with improved water holding ability of meat and improved texture	[123]
Preservation	20 kHz	5, 10, 15 min	Direct using probe	Enhanced shelf life of cucumber and superior qualities were shown by sample treated for 10 min	[124]
Edible packaging	40 kHz	15 min	Direct using probe	Edible packaging showed enhanced properties after ultrasonic treatment	[125]

of dietary fibre which have many applications in processed food as an important ingredient. Nguyen et al. investigated ultrasonic assisted extraction of protein from the lobster head which is rich source of protein. With use of ultrasonication 99% proteins were extracted which contained 39% essential amino acids in it with improved physicochemical properties. The ultrasonication is also for extraction of bioactive from waste generated from grains. The traditional extraction gave 8.7 µg/g, 6.4 µg/g, 6.8 µg/g, 1.3 µg/g, 9.2 µg/g, and 7.6 µg/g of sinapic acid, ferulic acid, caffeic acid, gallic acid, para coumaric acid, protocatechuic acid respectively which was higher with ultrasonic extraction as 12.6 µg/g, 9.8 µg/g, 10.3 µg/g, 3.9 µg/g, 14.4 µg/g, and 11.9 µg/g respectively. These compounds showed higher antioxidant ability as compared to one extracted from traditional method [99]. Zhang et al. [100] reported higher yield of anthocyanin 5.98 mg/g from remaining of mulberry in wine making using ultrasonication. The obtained yield was close to the theoretical yield of 5.87 mg/g. In ultrasound there is generation of local hot spots with high energy, this energy can be utilized for the synthesis of various compounds. Ultrasonication results in intensified synthesis with reduction in time and increase in yield. There are studies reported in literature showing ultrasonication as a green process for synthesis of certain neutraceutical fat. Jadhav and Annapure [101] reported intensified synthesis of medium chain triglyceride using ultrasonic pre-treatment, i.e. the maximum yield of 92% using 80% duty cycle for 25 min. More et al. [102] investigated synthesis of structured lipids using ultrasonication and reported higher yield of 84.5% using acidolysis reaction between medium chain fatty acid and traditional oil containing long chain triglyceride. Similar work for intensified synthesis is also reported for low-calorie designer lipids [103, 104], triglyceride of medium chain fatty acids [105–107]. Zhang et al. [108] investigated effect of ultrasound assisted frying on the development of flavour in fried pieces of meat. Ultrasound frying produced good flavour in fried meat due to increased level of oxidation in fat which released volatile aroma compounds which contributed to the enhanced flavour of fried food. The free amino acid analysed showed that with increase in power the amount of essential amino acid decreased with increase in the amount of non-essential amino acids. The ultrasound results in increase lipid oxidation during frying but cooking under ultrasound treatment results in reduced rancidity of cooked food during storage. TBARS value for food cooked using low power was low which was highest for food cooked using 800 W. The TBRAS value decrease during cold storage for ultrasound cooked food but TBARS value increased for untreated food giving rancid flavour. Electronic nose showed that there was no flavour change in for cooked at 0, 400, 600 W till 7 day of storage which changed slightly up to 21 days but flavour profile was stable for food cooked at 80 W. The untreated sample showed observable changes since 7 days which increased with storage period [109]. Juodeikiene et al. [110] used ultrasound to enhance the functional properties o flaxseed proteins to be used for microencapsulation or coating purpose. The variation in ultrasonic power showed enhanced functional properties. Treatment at approx. 1 W/cm^2 and acidic pH showed improved emulsification ability of albumin. With increase in ultrasound power to 1.3 W/cm^2 the gel forming ability of protein was enhanced and a more stable gel structure was seen. Globulin showed enhanced foam forming ability with the ultrasound treatment at 0.9 W/cm^2 and neutral pH. Guo et al. [111] investigated effect of ultrasonication thawing on quality of meat of white yak. The thawing time was 1200 s, 2300 s, 3100 s for sample treated at 600, 400, 200 W which was 4000 s for untreated sample of meat. The formation of flavour compound was more in sample treated at 400, 600 W due to lipid oxidation checked by TBARS value which was 0.46, 0.61, 0.79 mg MDA/kg for 200. 400, 600 W respectively and 0.57 mg MDA/kg for untreated sample. Ultrasound treatment also enhanced the mineral, vitamin, essential and non-essential amino acid content in meat sample. Prithani and Dash [112] investigated effect of ultrasonication as a preliminary treatment to kiwi fruit subjected to osmotic drying. Azuara model showed that removal of water from ultrasound treated kiwi was almost 16–20% more than the untreated sample which was also confirmed by Weibull model showing β_w value as 0.616 for treated kiwi and 0.723 for untreated. The moisture and solute diffusivity were increased and was 7.300×10^{-10} m^2/s and 3.511×10^{-10} m^2/s, respectively. The treatment is also given to fruits and vegetables before processing to remove the undesirable traits from fruits before processing. Ultrasound assisted extraction before processing of green walnut jam showed higher extraction of bitterness causing bioactive from walnut compared with conventional process. Jam produced using ultrasonication debitterness process showed higher sensory acceptability compared with conventional process [113]. Tian et al. [114] designed a freezing process based on ultrasonication using one or two frequency. The main component of the freezer was refrigerator, freezing tank, coolant silo, ultrasound panel, thermocouple unit. Ultrasound freezing of potatoes was carried out using single frequency 20 kHz and dual frequency of 20 and 28 kHz. The use of double frequency showed greater reduction in freezing time with enhanced rate of freezing. Hardness of potato sample after freezing were reported as 11.2 N, 11.4 N for double frequency treatment and 10.4 N, 9.6 N for single frequency of 20 kHz and 28 kHz respectively. The hardness of double frequency processed were nearer to hardness of fresh sample i.e., 12.7 N and conventional freezed sample showed hardness of 8.3 N which was very less compared to fresh sample. Thus, use of double frequency ultrasound assisted freezing have advantages over conventional freezing. Soares et al. [115] investigated effect of ultrasonication on enhancing hydrolytic activity of lipase on goat milk fat. Lipase pre-treated before hydrolysis increased the activity of lipase hydrolysis. The activity of lipase increased by 12%, 23%, 28% with decrease in temperature 55, 40, 25 °C respectively. He et al. [116] studied production of stable nanosized thyme essential oil emulsion using ultrasonication. This essential oil proved to be an effective preservative against the population of *E. coli* on surface of cherry tomatoes. There are various studies reported in literature showing excellent effect of ultrasonication against pathogenic microorganism in food and food products [117–121]. Zhang et al. [122] investigated effect of triple frequency sonication on quality of gluten and resulting noodle. The use of triple frequency (28, 40, 80 kHz) showed improved physical and chemical characters of gluten as compared to single (28 kHz) and double (28 and 40 kHz). The noodles prepared using triple frequency treated gluten showed less cooking time of less than 4 min with 0.05–0.06% protein loss. Xiong et al. [123] studied outcome of coupling ultrasonication with salting agent on the quality of chicken breast. The combination of ultrasonication with curing agent like sodium bicarbonate showed enhanced rate of curing in chicken breast, improved tenderness of meat with increase water holding ability of meat. The combined effect of ultrasonication with the curing agent showed excellent effect on chicken breast meat which can also be employed for other red meat for making meat tender with enhance textural properties. Fan et al. [124] studied effect of ultrasonic treatment on fresh cucumber which was packaged using modified atmospheric packaging on quality attributes during storage. The ultrasonic treatment of 5, 10 15 min were given. Ultrasonic treated sample showed increase in malondialdehyde content with progress of storage indicating lipid oxidation. The ascorbic content decreased with progress of storage time. Ascorbic acid was highest for sample treated for 10 min. There was decrease in flavour after 15 days and the treatment of 10 min showed excellent quality attributes of cucumber. Thus, proper time and intensity combination plays important role in preservation of quality off fruits and vegetables. The ultrasonication can also be used for increasing properties of edible films used for packaging of food and processed food products [125]. There are many applications of ultrasonication in food sector but almost all the applications are limited to laboratory scale, there need to be more awareness among the consumer regarding this technology so that they can demand for processed using novel technologies, which may force food industries to use this technology to deliver safe and nutritious food to consumer. Table 3 summarizes the technical details of ultrasonication with application to food.

3 Cold plasma technology

Cold plasma is one of the emerging non-thermal technologies. Cold plasma is basically a surface phenomenon used for inactivation of microorganisms present on surface of food. Plasma refers to fourth state of matter other than solid, liquid and gas. There is change in state of matter with absorption of energy. When energy of gas state is increased there is ionization of gas molecules which results in the formation of plasma [32, 126]. The ionization in gases can be done using various methods like microwave plasma, plasma torch, plasma jet, dielectric discharge. The composition of resulting plasma depends on the type of gas (carrier gas) which is ionized. The carrier gas which are ionized can be air, nitrogen, oxygen, helium etc. [127]. The ionization in gases is generated at an ambient temperature nearer to room temperature and does not depend on higher temperature to achieve reduction in microbial load which do not deteriorate the quality of food treated by cold plasma. The instrumentation assembly of cold plasma is very simple and consists of food treatment compartment, gas and pressure system, discharge device. In food processing sector cold plasma is employed for reduction in microbial load, inactivation of food spoiling enzymes, modification of physical and chemical properties of food constituents, surface moderation of food packaging material, increased germination of seeds etc. Energies which cause rise in the kinetic energy of electrons, which in turn enhances collision in gas phase and produces free radicals, electrons, charged ions, radiation which comprises plasma. These reactive species generated deteriorates the DNA fragment of microbial cell leading to cell death. The singlet oxygen and ozone are commonly generated reactive species. These may combine with the water resulting in formation of OH* free radical which are highly lethal for microbial cell DNA, the action of cold plasma on gram positive and gram negative is different (Fig. 2). This is all achieved at ambient temperature and hence food exposed to cold plasma treatment do not show any deterioration to texture, colour, flavour, nutritional composition which remains intact. Cold plasma is also effective against viruses and spores. Application of cold plasma to food to ensure higher food safety with higher quality in terms of sensory and nutritional attributes is summarized in Table 4. Recent study published [128] showed effectiveness of cold plasma in deactivating spores without loss of volatile heat sensitive nutritionally important components from powdered microalgae (*Spirulina*). Lin et al. [129] reported effectiveness of cold plasma using nitrogen as carrier gas against *Salmonella Typhimurium* on surface of egg. The treatment resulted in damaged to DNA of microbial cells and reduced total count by 3.13 log CFU/cm^2. Cold plasma

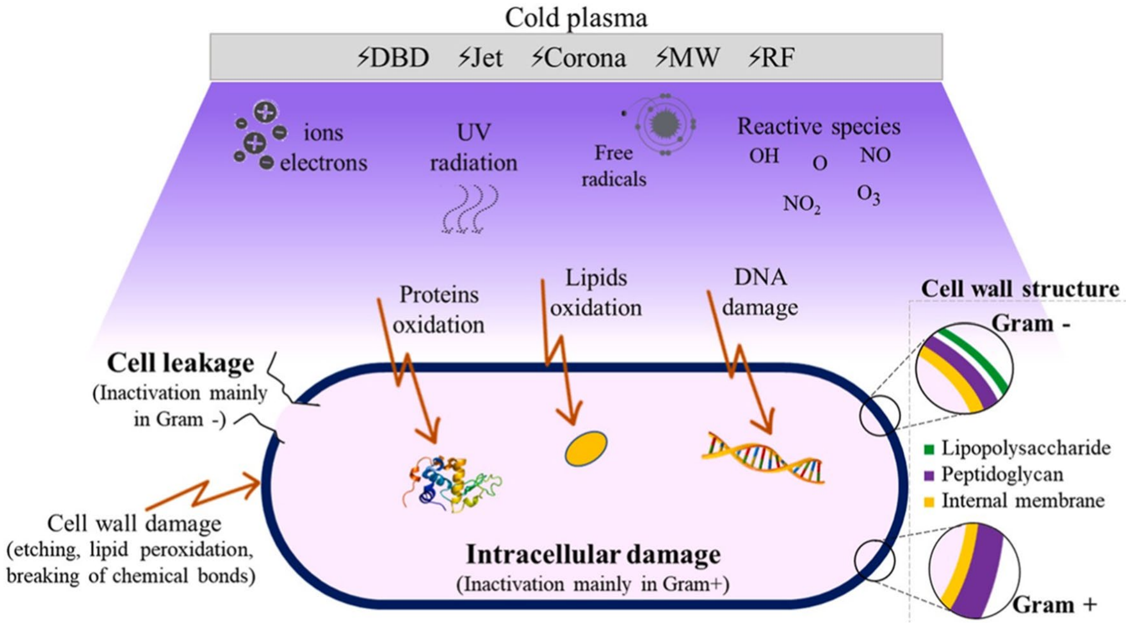

Fig. 2 Effect of cold plasma on the gram positive and gram-negative bacteria (Adapted with permission from Elsevier [211])

also inactivated *Salmonella Typhimurium* by reduction in extracellular DNA, extracellular protein, extracellular carbohydrates from 26.5, 68.5, 32.1 µg/mL to 8.6, 12.3, 8.4 µg/mL respectively. The treatment has zero effect on the quality of egg surface and organoleptic quality of egg. Shirani et al. [130] investigated surface decontamination of almond using argon cold plasma and with more exposure to treatment there was higher reduction in microbial load. The population of *Staphylococcus aureus* was reduced to 2.72 log CFU/g. Treatment was effective against yeast and moulds also with reduction as 1.81, 2.95 log CFU/g for load of yeast and mould respectively when exposed to cold plasma for 20 min. The texture of almond became tough when exposed to cold plasma for 20 min as compared with 5 and 10 min. Giannoglou et al. [131] investigated effect of cold plasma on processing of salad to enhance the keeping quality of rocket leaves. The population of microorganism decreased about 1.02 log CFU/g, higher destruction of *Pseudomonas* spp. was obtained about 7 log CFU/g. The shelf life of cold plasma treated sample increase to 5 days, 3.5 days, and 2 days which was 2.5 days, 2 days, 1.5 days for untreated sample stored at 2 °C, 4 °C, 9 °C respectively. Bang et al. [132] reported effectiveness of treatment on packaged oranges. The oranges were initially treated with antimicrobial agent and then packaged. The cold plasma was applied to packaged oranges. The treatment reduced the population of *Penicillium digitatum* by more than 75% without changes in chemical composition of oranges and without altering the texture of oranges but the shine on the surface was lost. The cold plasma treatment is also effective for enhancing shelf life of packaged fermented fruits and vegetables. Recent study reported that the cold plasma treatment enhanced the quality of packaged fermented food as compared to pasteurized sample [133]. Lin et al. [134] reported positive effect of air cold plasma on the quality of fish pickled in wine. The cold plasma treatment sample at 60 kv, 50 kv, 40 kv showed 6.33 and 6.78 pH, 6.41 and 7.04, 6.36 and 7.73 on first and 12 days of storage respectively which was 8.79 for untreated sample. The total and essential amino acid content increased with increasing intensity of treatment which was 5.34 mg/g (60 kv), 4.98 (50 kv), 4.89 (40 kv), 4.5 (untreated sample) for essential amino acid. No oxidative deterioration was observed during storage. Chen et al. [135] reported increased encapsulation ability by use of cold plasma. Cold plasma treatment resulted in unfolding of protein structure which resulted in enhanced interlinkage between chitosan and zein which formed and stable nanoparticle with size 370 nm. Different voltage treatment of 0, 30, 40, 50, 60 V with exposure for 2 min using air as carrier gas. Among this 40 V with exposure for 2 min gave excellent encapsulation ability and stability during diffusion in solution. Cold plasma with variation in voltage and exposure time and use of proper carrier gas will be useful for creating a stable encapsulation with smaller particle size even a nano sized particle. One such recent study reported by Mahdavian Mehr and Koocheki [136], formation of a nanoparticle from protein of *Lathyrus sativus*. The cold plasma treatment also increases physical and chemical properties of food without any observable change in the quality of food products, so that the treated foods can find numerous applications in food. Romani et al. [137] treated film made from fish protein to enhance its properties as an excellent food package. Cold plasma treatment was given to the protein film along with applying

Table 4 Application of cold plasma to food to ensure higher food safety with higher quality in terms of sensory and nutritional attributes

Application	Carrier gas	Treatment time	Plasma energy	Conclusion	References
Preservation	Air, nitrogen	0–5 min	7–15 Mw/cm^2	Plasma generated from air showed faster inactivation of *Bacilius subtilis* spores as compared to nitrogen plasma. Bit nitrogen plasma showed higher retention of bioactives compared with air plasma	[128]
Preservation	Nitrogen	2 min	600 W	The treatment resulted in damaged to DNA of microbial cells and reduced total count by 3.13 log CFU/cm^2 with inactivation of *Salmonella Typhimurium*	[129]
Surface treatment	Argon	5, 10, 15, 20 min		Effective against yeast, moulds and *staphylococcus aureus* without change in nutritional constituent of almond when treated for 20 min but the surface became hard when exposed for 20 min as compared with 5 and 10 min	[130]
Processing		5, 10, 15, 20 min	45 kHz frequency	Decrease in population of microorganism about 1.02 log CFU/g and increase in shelf life of about 6 days as compared with untreated sample	[131]
In package treatment		1, 2, 3, 4 min	26 and 27 kv voltage	Reduction in *Penicillium digitatum* by more than 75% without altering chemical and texture composition of oranges with reduction in surface shine	[132]
In package treatment		60 s	50 kHz	Quality parameters of cold plasma treated sample were enhanced as compared to pasteurized sample	[133]
Quality	Air	3 min	40, 50, 60 kv	Positive impact on proteins the essential amino acid content increased with no change in pH and no oxidative damage during storage	[134]
Encapsulation	Air	2 min	0, 30, 40, 50, 60 V voltage	Increased encapsulation ability up to 82.7% with enhanced rate of diffusion in solution due to strong bonding between protein and carbohydrates	[135]
Nanoparticle	Air	600 s	20 kHz	Smaller sized nanoparticles were obtained at 18.6 kv and 600 s with enhanced surface active properties	[136]
Food packaging material	Air	1–5 min	60 Hz	The treatment couple with applying wax increase strength by 175% and decrease water permeability by 65%	[137]
Nano fibre for food packaging	Nitrogen	30 s	350 W	The nanofibre showed active against growth of *E. coli* and DPPH activity was enhanced by 90% with enhanced release ability of phlorotannin as 25% at ambient temperature	[138]
Physiochemical properties	Air	15 and 20 min	50 W and 60 W	Enhanced physical and chemical properties of xanthan gum at 60 W treatment and exposure of 20 min	[35]
Quality of fish lipid and protein	Air	5 min	80 kV	Cold plasma triggered oxidation in lipids and proteins during storage at all conditions, which was also seen in untreated sample	[139]
Binding of aroma compound	Air	150 s	0, 50, 60, 70 V	Treatment at 60 and 70 V increased the unfolding of helical structure with increasing in ability of volatile to be absorbed by proteins enhancing flavour of meat	[140]
Quality of protein	Air	0–10 min	50 kHz	Improved, structural, physical and chemical properties of muscle protein of prawns	[141]

wax on the film to make it more hydrophobic and increase strength to hold more mechanical stress. The treatment couple with applying wax increase strength by 175% and decrease water permeability by 65%. Cui et al. [138] reported use of cold plasma to enhance the activity of food packaging. Nano fibre packaging material was made by encapsulation of phlorotannin in *Momordica charantia*. These nanofibre was treated with cold plasma to increase its activity against bacteria and against oxidation. The nanofibre showed active against growth of *E. coli* and DPPH activity was enhanced by 90% with enhanced release ability of phlorotannin as 25% at ambient temperature. Bulbul et al. [35] reported cold plasma to be effective in alteration of properties of carbohydrates to increase its application in food processing. Cold plasma treatment increases the surface area to 38.57 m^2/g and 46.09 m^2/g when treated at 50 W 15 min and 60 W 20 min respectively which was 32.74 m^2/g for untreated sample. Treatment at 60 W for 20 min showed improved physical properties as compared to untreated sample. Pérez-Andrés et al. [139] reported effect of cold plasma on the extend of lipids and protein oxidation in fish. TBARS value showed that there was no oxidative damage to lipid when treated with cold plasma but the TBARS value increased during storage for treated and untreated sample. Cold plasma treatment showed oxidation in proteins by increase in the carbonyl group. Carbonyl content was 1.5 nmol/mg protein and 2.5 nmol/mg protein for untreated and treated sample. Luo et al. [140] showed that cold plasma improves ability of flavour compound to bind protein and improve flavour of cooked meat. Myofibrillar protein extracted from meat was treated at 0, 50, 60, 70 V for 120 s. The increase in treatment increased the unfolding of helical structure of proteins and increase in the amino acid with hydrophobicity which enhanced volatile compound absorbing capacity of myofibrillar protein. Similar results on the quality of prawns proteins were reported by Ekezie et al. [141]. The cold plasma treatment has proved to be the efficient, environment friendly technology to increase the keeping quality and shelf life of food without use of any harmful chemical preservatives and it also enhances the chemical and physical properties of major food constituents, so that it can be used in various food applications. But with so many advantages there comes some limitations also. It is known that the cold plasma generation results in formation of reactive species, these reactive species triggers oxidation of lipids in foods containing high fat like dairy food, meat and meat product [32, 142]. The oxidation of lipids in food can be controlled by treating samples by decreasing the exposure of food to the cold plasma and proper selection of the carrier gas for generation of plasma. Cold plasma is extensively used on lab scale to explore its advantages to different foods and allied products. The commercial use of cold plasma is still not possible due to unscalability of the cold plasma equipment to process food in bulk. Further there is requirement of food to be recognized as GRAS after treatment using cold plasma. There is still need of increasing awareness among consumer regarding these excellent processing technologies, so that industries can use these technologies with increasing demand from consumers.

4 Supercritical technology

Supercritical technology employs supercritical fluid for achieving the desired applications. When normal fluid is heated above critical temperature and pressurized above its critical pressure it acquires the characteristics of supercritical fluid [143]. Supercritical fluids show property of both liquid and fluids. Supercritical fluids have density nearer to that of liquids and viscosity nearer to that of gases and diffusivity which is more than that of liquids. Because of such unique behaviour the supercritical fluids are probably the very good replacement for the organic solvents. The density of solvent, physical and chemical affinity for the solvent by solute decides the solubility of component in the supercritical fluid [144]. These soluble compounds are separated from the supercritical fluids by decreasing density of supercritical fluid. The density of supercritical fluid can be decreased either by lowering the pressure or by increment in the temperature. Due to these excellent behaviour supercritical fluids are extensively used for extraction of valuable component from various sources, which are then used as a functional ingredient in various food formulations. There are many fluids which can be used as a supercritical fluid but as far as food operation are concerned carbon dioxide is used as a supercritical fluid as its critical temperature and pressure are 31.1 °C and 7.4 MPa respectively. Since temperature and pressure are moderate, supercritical carbon dioxide do not cause harm to food in terms of its sensory and nutrition characteristics. The supercritical fluids also show a beneficial effect in preserving food by reducing microbial load in food. The use of supercritical carbon dioxide lowers the pH and reduces the multiplication of microorganism. The unbound water present in food comes in contact with supercritical carbon dioxide and forms dibasic acids like carbonic acid which further disintegrates in to carbonate ions and form H^+ ions which results in bringing down the pH. This lowering of pH makes microbial cell permeable for carbon dioxide, the supercritical carbon dioxide results in destroying the microbial cells and cell organelles thus resulting in death of microorganism [145]. Supercritical carbon dioxide also results in unfolding of protein structure leading to denaturation of structure which causes reduction or complete loss of enzymatic activity of enzymes responsible for undesirable changes in food [146]. Recently published study by Bertolini et al. [147] on preservation of pomegranate juice showed that SC-CO_2 with 12.7 MPa and temperature 45 °C decreased activity of peroxidases by 69%. The microbial load was below detection level which was 4.3 and 4.2 log CFU/mL. for mesophilic and yeast, moulds respectively in control sample for 28 days of storage. The total phenolic content increased for the supercritical treated juice by 22% but it showed reduction by 15% in control sample. Thus, supercritical treatment shows multiple effect on food like it increases the concentration of bioactive in food with inactivation of microorganisms and enzymes, thus increasing shelf life of food. Similar results were reported for preservation of coconut water [148], Sport drink [149], and liquid food [150]. Supercritical fluids are also used for preservation of ground meat. Yu and Iwahashi [151] treated grounded beef meat with high pressure carbon dioxide at 1 MPa pressure for 26 h and found reduction in the microbial load. Apart from preservation of food supercritical carbon dioxide is employed extensively for selective extraction of bioactives from various sources. Carbon dioxide being non-toxic and easy to separate from the final product is used for extraction as a supercritical fluid. Another reason for using carbon dioxide as a supercritical fluid is that, the working temperature and pressure for CO_2 is very low and at this temperature and pressure there is no chance of loss of volatile bioactive components which are extracted from sources and hence yield of the process increases. Kayathi et al. [152] investigated effect of supercritical carbon dioxide on extraction of polar lipids from mango kernel. The SC-CO_2 resulted in maximum extraction of 3.38% at temperature of 40 °C and pressure 50 MPa. The extraction using supercritical carbon dioxide is common since many years in food processing industry. To achieve more promising effect in terms of inactivation of microorganisms usually supercritical is combined with other non-thermal techniques like ultrasonication or in combination with use of antimicrobial agent [153]. SC-CO_2 have solved the issues related to purity of extracted product. The product has high purity which could not be obtained using conventional methods of extraction. Since SC-CO_2 is a green technology with no harm to environment and non-thermal with no adverse effect on food. SC-CO_2 has proved its potential in food processing, nutraceutical and pharmaceutical industries. Still there is need of exploring supercritical fluid in areas like synthesis of nanomaterials, micro materials, enhancing desirable chemical and physical changes in food.

4.1 Microwave

Microwave is a term which basically refers to the electromagnetic waves with frequency 300 MHz to 300 GHz in the spectrum. In matter these waves travels like light [154]. In microwave operations the effect is achieved by quick interaction of electric field with the food. Dielectric properties of food are responsible for the effect of microwave on food [155]. Microwave processing of food is one of the oldest non thermal technique which is used extensively in food processing industry for cooking, heating, freezing, drying, preservation and microbial inactivation in foods [156, 157]. Microbial inactivation using microwave is well explained by various processes like selective heating in which there is quick heating of microorganisms and thus microorganisms are killed, electroporation in which due to electric field there is leakage in the membranes of microbial cell leading to death of microorganisms, rupturing of cell membranes due to drop in voltage across the membrane or by coupling of magnetic field with the internal cell organelles leading to disruption of internal components of microbial cell causing cell death. Thus, there are various mechanisms through which microorganisms are inactivated in food and shelf life of food is extended up to several days without change in nutritional and sensory characteristics of food. Microwave radiations are also effective against the pathogenic microorganisms. Recently published study by Shankarrao Shirkole et al. [158] showed that combining microwave with infrared is more effective against *Salmonella Typhimurium* with 7.389 log reduction in paprika and also effective against inactivation of *Aspergillus flavus* with 6.182 log reduction. It is also effective against *Clostridium sporogenes* [159], *E. coli* [160], *Listeria innocua* [161], *Bacillus ceres* [162], inactivation of heat sensitive spores [163]. Apart from microbial spoilage there are certain enzymes present on food which are also responsible for the spoilage of food. But this microwave inactivation of enzyme is achieved with the use of thermal operations. Costa et al. [164] investigated microwave heating to be more effective than conventional thermal operations against inactivation of enzymes responsible for spoilage of acai berry pulp. Polyphenol oxidase was more quickly inactivated as compared to peroxidase. Basically the inactivation of enzymes by microwave obeys kinetics of first order [165]. If the microwave heating is more focused than the inactivation can be achieved even at low temperature around 70–80 °C. Thus by more focused effect of microwave the desired inactivation can be achieved and spoilage of fruit juices can be eliminated with little or no change in the fruit juice physiochemical properties [166]. Compared with all other applications microwave drying and microwave cooking are most frequently used in food processing industries. During microwave drying there is heat generated in the food because on radiative heat transfer. Due to this water in food changes to vapours and pressure gradient is set up. The moisture is transported towards surface of food material. Microwaves have good penetrating power because of this there is heating of internal and external surface of food at a time which causes bound and unbound moisture to evaporate from food. Monteiro et al. [167] studied drying of sweet potatoes using microwave vacuum drying at 60 °C. The reduction in moisture content from 4.5 to 0.4 g/g in 50 min of drying time was observed. The treatment gave high quality product with no eye appealing colour and crispy texture. It is also used for microwave convective drying [168], microwave freeze drying [169, 170], microwave air drying [171], microwave vacuum drying [172], microwave assisted fluidizes bed drying [173]. It is also used for freezing but did not show any promising results. Jha et al. [174] showed that the microwave assisted freezing showed good effect on apple and potatoes and did not affect the texture of food. The freezing time and rate of freezing were same for both microwaves assisted freezing and normal freezing process. Well known use of microwave technology is in cooking of food. Since in microwave there is generation of hot spots which increases rate of heat transfer and the process is speeded up [175, 176]. Although microwave is been employed in food industries since long back, there is necessities to strengthen certain areas in microwave treatment, one of the major problems with microwave is non-uniform field in microwave which results in non-uniform processing of food and there is formation of cold and hot points in foods. But all the microwave operations are carried out at temperature which are higher than the ambient temperature used by other non-thermal techniques, hence work need to be done to use microwave operations at lower temperature or ambient temperature to get food with improved qualities. The probable solution to this can be combining microwave operations with other non-thermal techniques to overcome the disadvantages of microwave and to get food with higher sensory and nutritional qualities.

4.2 Irradiation

The process in which food is exposed to the ionizing radiations is referred to as food irradiation. It is one of the non-thermal treatment uses for treating food. As per Codex General Standard for Irradiated Foods the ionising radiations which are safe for treatment on foods are X-rays having 5 MeV energy (or less), accelerated electrons having 10 MeV energy (or less), gamma rays with high energy (^{60}Co and ^{137}Cs) [177]. Ionizing radiations are used in food basically for microbial inactivation and to increase the shelf life of food. The microbial inactivation is achieved as ionizing radiations have an ability to deteriorate the microbial DNA, nucleic acid which prevents the replication of DNA, effects the normal functioning of microbial cell and cell dies thus reducing the microbial load present in food [178]. The inactivation of microorganism is due to irradiations and there is no rise in temperature of food due to radiations and hence the heat sensitive and volatile bioactive and nutritional components of food are not lost. X-rays and Gamma radiation shows high penetrating effect as compared to accelerated electrons which shows less penetrating effect which can penetrate up to 39 mm deep in food with more moisture content. The inactivation of microorganism is also governed by the type of microorganism and total population of microorganism present. Thus, the intensity of radiation may vary from food to food. Yeast and viruses and some fungi are more resistant to radiation as compared with the bacteria [179]. Herbs, spices, dry vegetable are among the food which are treated using irradiation since many days and in many countries. Low dose irradiation is used a preventive measure with dose below 1 kGy. Such low dose irradiations are basically used for delay in sprouting process, delay in maturing of fruits and vegetables, treating of fresh produce, egg sterilization etc. The irradiation dose from 1 to 10 kGy is referred to as medium dose irradiation. Medium dose irradiation are used for inactivation of pathogenic microorganisms and enhance the keeping quality of food [180]. High dose irradiations more than 15 kGy are used for achieving higher inactivation of microorganism in food like meat and meat products, astronaut's food. Irradiation treatment has great potential in enhancing the shelf life of food by controlling the food borne illness [181]. It is also used for treating infant food, one recent study by Jan et al. [182] showed effect of gamma irradiation on various properties of brown rice based infant food. The treatment with 0–10 kGy were applied to brown rice which showed enhances physical, chemical, sensory attributes with enhancement in antioxidant activity, phenolic in treated sample with increase in dose but these decreased with progress in storage time. It is also observed that the irradiation effects are combined to achieve higher degree of safety in food. In one recent study x-ray and gamma irradiations are combined to achieve high degree of inactivation of pathogenic microorganisms. The x-rays (0.75 kGy) with 125 keV energy and gamma radiations with doses of 9.1 kGy are effective against the pathogenic microorganisms including *E. coli*, *Salmonella*, *Listeria* in food [183]. Irradiations are also effective against fungi in fruit juices [184]. But there are certain studies in the literature where it is found that the irradiation of food result in change in colour of food, development of undesirable smell, adverse effect on functional attributes of food. Such effect is majorly seen in meat and meat products, in which the irradiation effects deteriorate myoglobin molecule which changes colour and lipids in meat are oxidises creating unpleasant flavour in food. It also effects whole grains like wheat, rice [185]. Hence the food can be irradiated at low dose coupled with use of anti-microbial agent of irradiation process can be coupled with other non-thermal operations to maximize the synergistic effect of treatment on food with no or minimum effect on the sensory attributes of food [186–188]. Inspite of so many advantages of irradiation on food, there is very low demand for irradiated food in global market because consumer perception of word irradiated is like treating of food with nuclear technology which may incorporate certain harmful radiations in food which may harm human health. There is need to educate consumer regarding irradiated foods and its advantages to humans. Encouraging consumer through marketing, media like television to buy irradiated food can one of the solutions to this drawback. Further there is need to carry out more research of improving adverse effect of irradiation on sensory attributes of food by designing a simple, economical and reliable instrument for treating food. Future of irradiated food is bright and promising, extensive research in the field and designing more reliable equipment will enhance sustainability and will improve its commercial application in food processing industries.

4.3 Pulsed ultraviolet

Ultraviolet is a well-developed non-thermal treatment which is successful in fulfilling the demands of today's consumer for safe and nutritious food with more shelf-life and excellent organoleptic characteristics. In pulsed ultraviolet treatment short pulse white light between 200 and 280 nm is employed for deactivating microorganisms present on the surface of food material [189]. It is one of the economical non thermal treatment in which involves direct exposure of sample to radiations. These radiation are categorized as per their effect as UV-C from 200 to 280 nm, UV-B from 280 to 320 nm, UV-C from 320 to 400 nm [190]. Pulsed ultraviolet is effective against pathogenic and diseases causing bacteria. UV-C is known to show excellent effect against microorganisms. UV light from 200 to 280 nm i.e. with short wavelength are well absorbed by the microbial nucleic acid [189]. The absorbed ultraviolet light results in generation of photoproducts in deoxyribonucleic acid which disturbs the process of replication of DNA and change in the genetic material of microorganism which causes death of microorganism [191]. UV-B also deteriorates nucleic acid to some extend but it is more effective against damage to proteins in microbial cells. UV-A is not absorbed by the microbial DNA but chromophores molecules absorb these radiations and produces reactive oxygen species which damages the membranes of microbial cells and thus the microorganism dies [192]. Countries like USA is one of the country where ultraviolet treatment is used commercially for treating food and food packages to abolish the microbial load present in food and food package [33]. There are new technologies developed where ultraviolet light is used before processing of food. Abadias et al. [193] developed a new and novel method of washing of fruit and vegetable using water washing assisted with ultraviolet lamps. The use of ultraviolet lamps resulted in reduction of pathogenic bacteria like *L. innocua* on the surface of treated sample of tomatoes but it induces turbidity in water. Raeiszadeh and Taghipour [194], developed a technique for maximum inactivation of diseases causing microorganisms like *E. coli* by use of microplasma ultraviolet lamps as a latest developed source of UV-C having extreme photons effect on the genetic material of pathogenic bacterial cell leading to cell death. There are certain bacteria which have ability to form spore in unfavourable conditions and these spores do not undergo any metabolic activity and they are highly resistant to adverse conditions and helps in survival of bacteria. These spores are great concern to food scientist and microbiologist because these spores causes food borne diseases and spoils food [195]. These spores are also present on processing equipment and are resistant to heat and chemical treatment. UV-C photons are found to be effective for inactivating spores. Exposure to ultraviolet-c for 20 min showed reduction of 4 log CFU/mL for *Alicyclobacillus* spp. which are a great concern for fruit processing industries [196]. Apart from increasing shelf life of food by microbial inactivation, ultraviolet treatment of food also has useful effect on the antioxidant activity, total phenolic content, colouring pigent and bioactive present in processed food. Ultraviolet treatment of 40 min to mixed fruit juice showed 2.59 log CFU/mL reduction in bacteria and ultraviolet treatment showed rise in the antioxidant capacity of mixed fruit juice. There was rise in phenolic and colouring pigment. Thus highest level of microbial inactivation is achieved with no loss of nutrients and heat sensitive components from processed food [197]. Ultraviolet-A also shows enhance effect on the physical, chemical, sensory attributes of fruits and vegetables [198]. Wines are fermented beverages in which quality, taste, colour of wine depends on the bioactive, volatiles and pigments extracted in juice. Ultraviolet find good application in this industries also, ultraviolet-B radiations treatment to grapes resulted in higher extraction of volatile and pigment in juice, which gave an eye appealing look and mouth littering aroma and flavour to wine which is not achieved using conventional process [199]. It is extensively used for processing of fluid foods like milk, fruit juice, beverages [200, 201]. There are certain studies reported in literature showing ill effect of ultraviolet on colour and texture of foods [202]. Such undesirable changes in food can be overcame by treating food at lower ultraviolet doses and exposing surface of food to ultraviolet for short time and increasing distance between ultraviolet lamps and the surface of food so that there is minimum or no effect on texture of food. Certain food has uneven or rough surfaces, so damage to texture varies from food to food. It is also noticed that presence of uneven surface may lead to shadow effect i.e. exposure of microorganisms to radiation doses may be prevented which may lead to improper inactivation or non-uniform inactivation of microorganisms in food. Therefore to overcome such drawbacks ultraviolet is coupled with other techniques to achieve higher degree of inactivation and enhanced functional properties with minimum or no effect to nutritional, sensory attributes of food and related products [203–206]. Due to positive effect on bacterial inactivation and food properties, ultraviolet is among the non-thermal treatment which is extensively used for treatment of fluid foods commercially. But combining ultraviolet with other non-thermal technology can greatly increase the positive effects of ultraviolet technology in food processing industries.

5 Conclusion

Non-thermal treatment of food does not expose food to higher temperature and thus it does not pose harm to heat sensitive food constituents and without compromising on the quality of food it increases shelf-life of food by maximum inactivation of microorganisms including pathogenic microorganisms also. In comparison with the thermal technologies, the non-thermal technology expose food to treatment for a shorter time and at ambient temperature which not only keeps food fresh with flavours and aroma intact but also utilizes less energy which saves lot of energy and time. With the critical study of literature, it is seen that all these non-thermal technologies have some limitations of these technologies. With many advantages there always comes limitations. But these limitations can be overcame by synergistic effect of using non-thermal technologies in combination for example treating food with ultrasonication and pulse electric field before dehydration not only reduces dehydration time but also increases quality of food in terms of its appearance, texture and crispiness. Most of these non-thermal technologies are not used in food processing industries due to lack of technical information, unavailability of equipment for bulk processing, skilled professional. The most important drawback which prevents commercialization of these non-thermal technology is awareness in consumer about these technologies. The misconceptions and myths in consumer about food processed through these technologies should be overcame, so that the consumer acceptance increases which will force food processing industries to commercialize non-thermal techniques in food processing sector.

Author contributions HBJ: conceptualization, methodology, investigation, project administration, writing review, and editing review; PC: supervision, conceptualization, data curation, writing original draft, proof reading.

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Declarations

Competing interests The authors confirm that they have no conflicts of interest with respect to the work described in this manuscript.

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