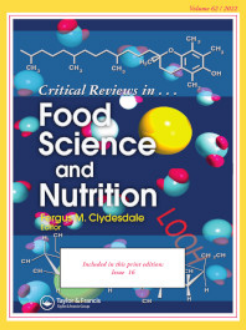

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REVIEW

Ultrasound, infrared and its assisted technology, a promising tool in physical food processing: A review of recent developments

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ABSTRACT

Traditional food processing techniques can no longer meet the ever increasing demand for high quality food across the globe due to its low process efficiency, high energy consumption and low product yield. This review article is focused on the mechanism and application of Infrared (IR) and ultrasound (US) technologies in physical processing of food. We herein present the individual use of IR and US (both mono-frequency and multi-frequency levels) as well as IR and US supported with other thermal and non-thermal technologies to improve their food processing performance. IR and US are recent thermal and non-thermal technologies which have now been successfully used in food industries to solve the demerits of conventional processing technologies. These environmentally-friendly technologies are characterized by low energy consumption, reduced processing time, high mass-transfer rates, better nutrient retention, better product quality, less mechanical damage and improved shelf life. This work could be, with no doubt, useful to the scientific world and food industries by providing insights on recent advances in the use of US and IR technology, which can be applied to improve food processing technologies for better quality and safer products.

KEYWORDS

Inactivation of enzyme; drying; enzymolysis; fermentation; peeling; decontamination

Introduction

Food processing is the transformation of raw plant or animal materials into consumer-ready products, with the aim of stabilizing food products by preventing or reducing negative changes in quality (Hogan, Kelly, and Sun 2005). The knowledge of chemistry, microbiology, and physical composition is paramount for successful processing of food (MacDonald and Reitmeier 2017). Food processing technology has witnessed recent advancements from the normal traditional processing technologies to some novel physical processing technologies due to some contemporary issues; like increase in consumer demand for healthy-hygienic and high quality food, low processing efficiency, low product yield and high energy consumption (Ma et al. 2019). The physical food processing technologies are categorized in three forms; thermal (microwave, radio frequency, infrared, ohmic and high pulse light), non-thermal (magnetic field, electric field, ultra-high pressure and ultrasonic and laser technologies) and rapid detection (electronic nose, artificial vision and electronic tongue) (Ma et al. 2019).

Ultrasound (US), a non-thermal processing technology, is sound waves that have frequencies higher than the threshold of human hearing (>20 kHz). It is usually divided into two types based on the frequency range; low energy (frequencies > 100 kHz and intensity < 1 W/cm^2) and high energy or powers US (frequencies ranging from 20–500 kHz and intensities > 1 W/cm^2) (Rojas et al. 2016; Carrillo-Lopez et al. 2017; Dabbour et al. 2018). It can also be classified based on its intensity into: low intensity US (frequencies between 5–10 MHz, power level less than 1 W/cm^2) and high intensity US (frequencies ranging from 20–100 kHz, power levels ranging from 10–1000 W/cm^2) (Jambrak et al. 2009; Awad et al. 2012). The low energy or low intensity US (Figure 1) is used for diagnostic purposes in food processing, while the high energy or high intensity US technology is used as an alternative to the traditional food processing technology (Jambrak et al. 2009; Rojas et al. 2016; Azam et al. 2020). Some of the processing operations in the food industry, which have witnessed the application of US includes; drying, fermentation, enzymolysis, enzyme inactivation, extraction, filtration, frying, purification, washing, defoaming, emulsification, tenderization, detoxification, viscosity modification, degassing, desalination, and pasteurization. The recent advances in the application of US have covered not only mono frequency, but

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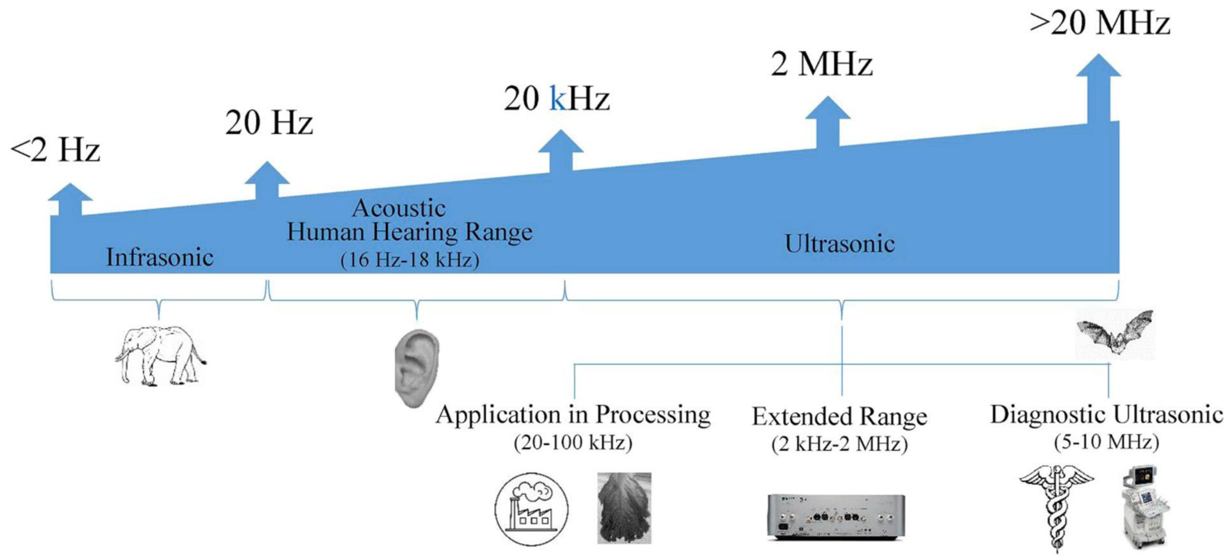

Figure 1. US frequency range and its application. © 2020 S M Roknul Azam et al. All Rights Reserved. Reproduced with permission from Elsevier. (Azam et al. 2020).

multi-frequency modes (Kwaw et al. 2018). US have also been combined with other technologies in form of thermosonication (US + heat), manosonication (US + hydrostatic pressure) and manothermosonication (hydrostatic pressure + heat + US) (Liu et al. 2019). Alenyorege et al. (2019c) investigated the effect of multi-frequency US in washing of fresh Chinese cabbage. They concluded that US-assisted washing improved the greenish leaf appearance and noticeable visual color. Otu et al. (2018) studied the application of dual frequency US technology in the extraction and desalination of *Sorghum bicolor* leaf sheath polysaccharides, higher extraction yield and desalination levels were achieved.

Infrared radiation (IR) heating, a thermal physical processing technology, falls within the wavelength range 0.78–1000 µm (Rastogi 2012). This physical processing technology has many advantages, including high energy efficiency, higher transfer capacity, lower operational costs, instant, uniform and faster heating, fast regulation response, better processing control, lack of heating of the surrounding air, equipment compactness, better retention of vitamins and a lower sample flavor loss. It is also used with other thermal technologies like the microwave in drying, tempering, baking and roasting due to its weak penetration power, fracturing and unwanted swelling after prolonged exposure (Ekezie et al. 2017). IR heating has been utilized in some processing operations like; drying, blanching, roasting, inactivation of microorganisms and enzymes, frying, disinfection, and peeling. Wu et al. (2018a) applied the catalytic IR heating to blanch sweet potato chips prior to frying. They observed that IR treatment reduced 13.79% of the sample oil compared to the conventional method of blanching (hot-water blanching).

There have been many earlier review studies on applying US and IR-heating in physical food processing. For example, Chemat, Zill-e-Huma, and Khan (2011) summarized the importance of ultrasound technology in physical processes like filtration, defoaming, depolymerization, degassing, cooking, cutting, demoulding and extrusion, pickling, thawing, drying, freezing, sterilization, pasteurization, emulsification, tenderization, food preservation, inactivation of enzymes and microorganisms and extraction. Chandrapala et al. (2012) have a review report on the application of US in emulsification, filtration, viscosity modification, diary production, and tenderization. Onwude, Hashim, and Chen (2016) summarized the application of thermal technologies (microwave and IR) in drying of agricultural crops. Azam et al. (2020) have a review study on the application of US in the detoxification (pesticides removal) from fresh vegetables. Bhargava et al. (2021) carried out a review study on the application of US in physical processes like; filtration, freezing and crystallization, thawing, pickling/brining, drying, degassing, depolymerization, foaming, cutting, sterilization/pasteurization, rehydration and extraction.

As noticed, the review reports mentioned above have mostly been focused on the application of the US alone in processing of foods. US food processing combined with other novel technologies like infrared, microwave, pulsed electric field, ultraviolet light, hydrostatic high pressure etc, is covered by these review. Recent review reports of the use of US in the food processing have not covered fermentation, enzymolysis, frying and cleaning which are important food processes. US and IR have recently been combined for food processing operations like drying, frying, inactivation of enzymes, decontamination etc which showed better processing performance. Also, there are no much information on the usage of IR heating devices and some IR-assisted technologies in regard to the physical processing of food. Therefore, this study covers the use of US, IR and other assisted novel technologies in physical processing of food.

Ultrasound as a physical tool in food processing

Acoustic cavitation is a phenomenon that happens as a result of the interaction between a liquid, liquefied gas and

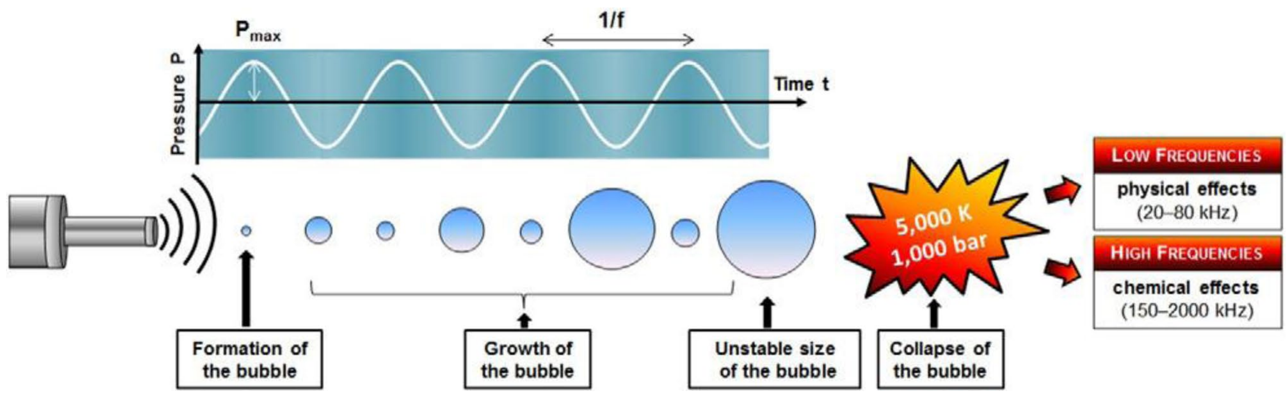

Figure 2. Acoustic cavitation phenomena © 2015. Gregory Chatel et al. All Rights Reserved. Reproduced with permission from Elsevier. (Chatel, Novikova, and Petit 2016).

ultrasonic waves, when the ultrasonic waves travel through the liquid medium (Chandrapala et al. 2012; Yagoub, Ma, and Zhou 2017; Jiang et al. 2020). Two phenomena occur during bubble growth in acoustic cavitation prior to implosion, compression and rarefaction (Qiu et al. 2020). Cavitation is generated as a result of the oscillatory effect produced by compression (positive pressure) and rarefaction (negative pressure) in the ultrasonic wave (Figure 2). The application of power US (a non-thermal technology) in physical food processing normally creates acoustic cavitation and hydrodynamic cavitation, which lead to mechanical, thermal and chemical effects; like growth and collapse of cavities, generation of high local energy densities, high temperature, local pressure, high stress near the bubble wall, strong acoustic streaming, micro jets near the solid surface, and generation of free radicals (Qiu et al. 2019; Cheng et al. 2019; Yu, Tu, et al. 2020). Merone et al. (2020) revealed that the use of US can reduce the total energy consumption of a process by percentages reaching up to 70% and the life cycle analysis by 58–82%. US can be applied in three (3) methods; directly to the product, coupling with a device, and submerging in an ultrasonic bath (Majid, Nayik, and Nanda 2015). Its application also causes desirable chemical reactions like the cross linking of protein during the formation of microcapsules and modification of the functionality of food ingredients which in some cases is not desirable (Chandrapala et al. 2012; Cheng et al. 2019). US has been increasingly used in the food industry for the physical processing and biomass conversion due to the following advantages: low consumption of energy, low cost, reduced processing time, low environmental pollution (i.e. a green energy source), higher mass transfer rates of solvents and raw materials, protection of the nutritional content, low utilization of materials and better quality product with improved shelf life (Arzeni et al. 2012; Oladejo et al. 2018; Ji, Yu, Yagoub, et al. 2020). US have also been used to improve food quality and reduce processing duration in food industries (Kaveh et al. 2018; Fallavena, Ferreira Marczak, and Mercali 2020). Application of multi-frequency US technology in food processing has been increasingly used in recent studies. Researches revealed that both mono-frequency and multi-frequency generates temperatures, pressure or shear forces that affect the functionality of the protein and its structure. But, the multi frequency produces a series of waves that cause a higher cavitational effect on the properties of food than the mono frequency (Cheng et al. 2019; Golly et al. 2020). US have also been used with other thermal (microwave, radio frequency, infrared) and non-thermal (ultra-high pressure and electric field) technologies to further improve the drying performance and quality of the dried product (Guo et al. 2020). One of the key advantages of using US in food processing is that it can be applied to a product at low temperature without affecting the texture of the product (Kaveh et al. 2018) (Figure 3).

Fermentation

Fermentation is a renowned natural means of preserving or safeguarding food and beverages, in order to enhance its nutritional value, destroy undesirable constituents, improve digestibility, and inhibition of undesirable microorganisms (Chaves-López et al. 2020). Food fermentation is a natural method of food preservation; it principally entails chemical alteration or conversion of complex organic compounds into simpler compounds by microorganisms and enzymes (Olaniran and Abiose 2019). Traditionally, production of fermented products like cultured milk, Kimchi, cereal paste is time and energy consuming (Olaniran and Abiose 2018; Olaniran et al. 2020). In recent times, fermentation techniques are being applied in production and extraction of several bioactive compounds for chemical, pharmaceutical and food industries (Galván-D'Alessandro and Carciochi 2018).

In food industry, the use of low-frequency US can increase the rate of fermentation, mass-transfer, wine maturation, aging and other food processing operations (Chandrapala 2015; Khandpur and Gogate 2016). Kwaw et al. (2018) evaluated the US-assisted lactic acid fermentation of mulberry juice. They found that US improved the phytochemical content, volatile profile, odor activity and sensory characteristics of the juice. Low-intensity US serves as a physical tool to analyze physiochemical properties and to monitor changes during food production due to its advantage of exerting little or no physical and chemical modifications in the material. Power US has also been applied to food fermentation to enhance the productivity and process efficiency in the food industry (Guimarães et al. 2019). US

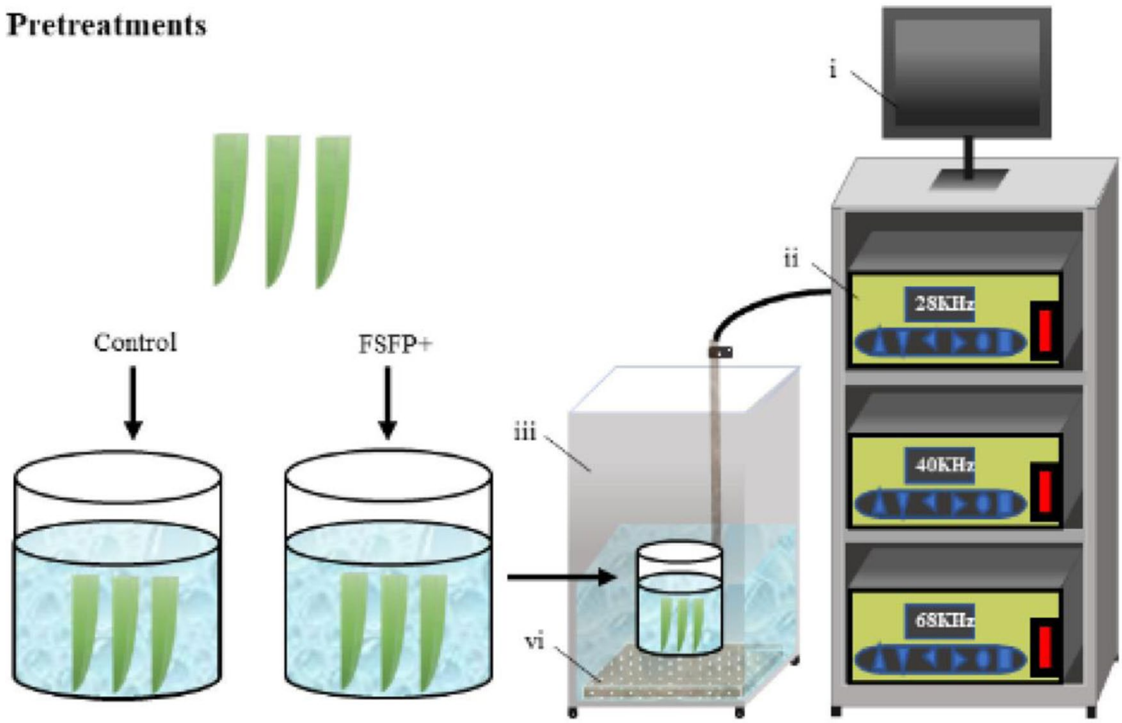

Figure 3. Schematic diagrams of the flat sweep frequency and pulsed ultrasound (FSFPU) device, i. Computer control panel, ii. ultrasound generator, iii. ultrasound bath and iv. ultrasound vibration plate. © 2020 Xin Xu et al. All Rights Reserved. Reproduced with permission from Elsevier. (Xu et al. 2020).

have proven to be a very effective and innovative technology for food processing. It has been used for liquid fermentation by sonolysis to reduce microbial-enzymatic activity (Alenyorege et al. 2019a). US, as emerging non-thermal technology, is extensively used to control some unwanted microorganisms, inactivate certain enzymes, reduce fermentation time, increase cellular growth and its proliferation while stimulating enzyme activities, accelerate acidification and increase the substrate-transfer rate of the fermented milk during processing (Gholamhosseinpour and Hashemi 2019). Fermentation is a very significant step during the steam bread production. In this context, US-aided dough fermentation has been studied by Luo et al. (2018), aiming to improve the quality of the steamed bread, such as hardness, and specific volume, and to extend its shelf life. Ruan et al. (2020) noticed that the application of US accelerated the fermentation process and improved *Saccharomyces cerevisiae* cell growth, thereby facilitating rupturing of probiotic bacteria cells to release intracellular enzymes which promotes the hydrolysis of substrate producing peptides in soybean meal. Sonication has been used to improve flavor of soy sauce, an indispensable fermented seasoning in the cuisines of countries around the world which involves koji and moromi fermentation, resulting in its distinctive aroma and taste (Gao et al. 2019). US-assisted fermentation was used for reducing ethanol production using yeast (*Hanseniaspora sp*) and it showed favorable efficiency in stimulating the biomass growth during production of alcoholic beverages (Al Daccache et al. 2020). The use of a combination of autoclave, US and microwave for the treatment of milk during fermentation significantly increases the viability of *L. acidophilus* (Gholamhosseinpour et al. 2020). Pulsed electric field (PEF) combined with US is quite novel technology with potential for partial or full replacement of conventional heating processes due to its ability to inactivate microorganisms and enzymes with/without a very slight increase in food temperature. Due to its optimistic effects on living cells, applying the PEF and low intensity US technology to fermentation has also received attention at the sub-lethal level (Galván-D'Alessandro and Carciochi 2018).

The use of high-intensity US (HIUS) in fermented-dairy processing can improve viability of probiotics, oligosaccharides concentration, and taste, without the addition of prebiotics, and significantly shorten the processing duration. For example, HIUS accelerates proteolysis and reduces the ripening time during production of cheese, leading to products of enhanced nutritional properties, containing bioactive peptides and having better texture. Also, HIUS can change the structure of prebiotics and facilitates the availability of probiotics depending on the processing parameters, such as processing time, pulse-mode, food composition, etc. (Guimarães et al. 2019). HIUS has been used in yoghurt processing to improve the hydrolysis of lactose, which stimulates growth of probiotic bacteria, thus shortens the fermentation time (Akdeniz and Akalın 2019).

Enzymolysis

Sustainable product development and processes have become very important, because it guarantees environmental protection, safety and continuity (Vanegas et al. 2018; Fakayode et al. 2020; Baah et al. 2021). There is a global look-away from using chemical and emission processes; instead attention has been drawn to green processes and products. Green and sustainability are new terms that are currently being involved in the energy production field (Minutillo, Perna, and Sorce 2020; Armijo and Philibert 2020; Rajendran and Baskar 2021), environmental remediation (Inyinbor, Adekola, and Olatunji 2019; Karri, Sahu, and Meikap 2020; Ji, Jiang, et al. 2020), constructions (Almalkawi, Balchandra, and Soroushian 2019; Javed et al. 2020), agricultural production (Y. Liu et al. 2020; Wei et al. 2021) and various other production and preservation processes (H. Zhang et al. 2020; Mosca et al. 2020; B. Wang et al. 2020; Do and Kim 2020).

Green production and preservation in the food industry is premised on healthy food for consumers, food integrity, process sustainability and environmental protection (Ashaolu and Ashaolu 2020; Ji, Yu, Chen, et al. 2020; Fakayode et al. 2021). Food processing or preservation techniques requiring high temperature, high water consumption and lengthy processes are giving way for new and green technologies (Chemat et al. 2017). For instance, processes utilizing ultrasound (US), microwave, supercritical fluid, pulse electric field, controlled pressure and enzymes may be faster, reduce energy, reduce water consumption and increase food sanctity (Chemat et al. 2017). A multiphase food processing technique such as enzymolysis utilizes enzymes in food extraction, separation and purification (Umego et al. 2021).

Food hydrolysis is carried out by acids (acid hydrolysis) or enzymes (enzymolysis). Huge wastewater generation coupled with complex by-products that accompanied acid hydrolysis has given enzymolysis a huge preference over acid hydrolysis (Jin et al. 2020). Enzymolysis has found great use in various food processing techniques as well as many other extraction and purification processes. Of great importance is the application of enzymolysis in protein extraction, purification and structural modification.

Protein extraction is a preliminary stage in protein quantification (Ippoushi et al. 2020). The protein extraction is a more suitable technique for quantification of plant proteins due to complex constituents of plants. Protein extraction and separation processes, which are well-known techniques, could enhance protein quality and safety as extraction processes affect techno-functional and structural properties of proteins (Hadidi, Ibarz, and Pouramin 2021). Although many methods of extraction exist, enzymolysis comes with unique characteristics such as ensuring that the functional properties and nutritive qualities of a specific protein are not altered (Dabbour et al. 2019). Enzymolysis may also enhance protein digestibility and solubility via development of bioactive peptide having antioxidant characteristics (Braspaiboon et al. 2020). Enzymolysis has a few shortcomings such as a sluggish hydrolysis rate, unexhausted enzyme utilization and protein conversion resulting in inefficient hydrolysis process (Wang et al. 2015). Therefore, various pre- and co-treatments are being introduced into enzymolysis to maximize the process. For instance, Ma et al. (2018) found out that ultrasound pretreatment during the enzymolysis of pectin could bring about a higher level of galactose in pectin hydrolysate. Wang, Meng, et al. (2016) also discovered that the co-treatment during the enzymolysis of rapeseed protein with dual frequency US improved the hydrolysis rate by increasing the surface area of immobilized enzyme, modifying the molecular structure of protein, and enhancing solid solubility. Details of these processes are discussed below.

Localized-enzymolysis, with or without sonication, has been used to modify sunflower protein. Alcalase served as the enzymolytic agent and conditions included variations in the degree of hydrolysis. Various physical properties such as turbidity, color and lightness of both sonicated and unsonicated samples are improved. However, the sonication effect was seen in improved capacity of oil absorption. As it is observed, the hydrolysate from the sunflower protein has a more flexible structure compared with the unhydrolyzed sunflower protein. Peptides obtained from the hydrolyzed sunflower protein have sizes less than or equal to 3 kDa (Dabbour et al. 2020). US with dual frequency slit has been employed to enhance the efficiency of enzymolysis *viz-a-viz* conformational features of gluten from corn meal, which has led to an increase in the solubility rate of the protein. The dual frequency US has also changed the secondary structure of corn gluten, as seen in the decrease in α-helix and an increase in β-sheet (Y. Wang et al. 2020). Dabbour et al. in another study established the possible functionalities and conformational changes as well as antioxidant properties that US-assisted enzymolysis may input unto sunflower protein. Their experimental conditions were designed to involve varied hydrolysis degrees and a dual frequency sonication. Properties such as emulsion stability, foaming properties and solubility are greatly enhanced. They also reported that sonication significantly influenced the structure of both isolates from sunflower meal protein and its hydrolysate derivatives (Dabbour et al. 2019). Ma et al. (2018) explored the application of US in enzymolysis of pectin. They noticed that US improved the enzymolysis efficiency, the pectinase affinity with pectin, and the inhibitory activity of the hydrolysis products against HT-29 colon cancer cells and made the substrate more accessible to the enzyme as well. Enzymolysis supported with dual frequency US has also been used in potato protein hydrolysis. In addition to the US pretreatment, other conditions such as variable temperatures and varying substrate concentrations were employed in their study in order to understand enzymolysis kinetics and thermodynamics. Increased temperature was reported to positively enhance the rate of potato protein hydrolysate formation; however the hydrolysate produced by traditional enzymolysis compared effectively with that produced by US assistance (Cheng et al. 2017). Zhou et al. (2017) used heat and US separately and in combination as a pretreatment prior to the enzymolysis of corn meal gluten. The system pH was maintained constant throughout the entire period of the hydrolysis. Spectroscopy and microscopy analyses were performed to detect changes in the micro-structure and surface morphology of gluten as a result of US and heat pretreatments. The preheating treatment greatly increased the quantity of the hydrolyzed gluten protein, while the heat-US pretreatment gave the best improvement in enzymolysis (Zhou et al. 2017). Enzymolysis aided by a counter-current US was employed to hydrolyze the porcine cerebral protein-isolate. Conditions include variation in substrate concentrations amongst others. The work mainly focused on investigating there action kinetics and thermodynamics. The single frequency counter-current US pretreatment enhanced the hydrolysis reaction speed and the energy required for pretreated samples compared with the traditional enzymolysis. The thermodynamic study indicates that the energy required for US pretreated samples has been greatly reduced (Zou et al. 2016). The work of Wang and his colleagues also reported on the dual-frequency US-assisted enzymolysis of rapeseed protein. They mainly focused on studying the mechanism of enzymolysis; hence the enzyme was immobilized and separated from the system. Scanning electron microscopy analysis was conducted to examine the surface morphology of the enzyme, Alcalase. The degree of hydrolysis was improved at all US frequencies used. Roughness and rupturedness characterized the surface of immobilized enzyme (Wang, Meng, et al. 2016). The structural representation and kinetics of rice protein enzymolysis have also been reported. In their report, US with alkali pretreatments preceded enzymolysis. The structural representation studies include surface hydrophobicity as well as functional group analysis. Fluorescence peaks showed that both US and US-alkali pretreatment increased the rice protein hydrophobicity. Structural changes were reported, proved by shifting in Fourier Transformed Infrared absorption bands (Li, Yang, Zhang, Ma, Qu, et al. 2016). In a similar study, ultrasound and alkali-US pretreatment have been established to enhance the degree of hydrolysis as well as protein eluting characteristics (Li, Yang, Zhang, Ma, Liang, et al. 2016). A multi-frequency ultrasound pretreatment was used in the enzymolysis of wheat germ protein (Yang, Li, Li, Oladejo, Wang, et al. 2017) and rice protein (Yang, Li, Li, Oladejo, Ruan, et al. 2017).

The rice protein was subjected to enzymolysis-irradiation processing in terms to improve its antioxidant activity. A report showed that while enzymolysis increased the amino acid content of rice protein and the amino acid depletion of rice protein hydrolysate was directly proportional to the degree of irradiation. Moreover, the improvement in the antioxidant activity of the rice protein hydrolysate is credited to the electron beam irradiation (Li, Wang, et al. 2019). Pan et al. employed thermal pretreatment to the Lotus seed protein enzymolysis. Their approach followed the optimization of common parameters such as pH, temperature and substrate concentration. Their results indicated that the thermal treatment of such substrate by a temperature greater than 81 °C could result in aggregation of protein, therefore hampering hydrolysis. The degree of hydrolysis of a thermally treated substrate was higher at temperature ranging between 50 °C and 60 °C (Pan et al. 2016). Thermal treatment and/or US have also been used as pretreatment methods for the enzymolysis of hemp seed protein isolate. Antioxidant studies of hydrolysate were studied amongst other things. Moderate US frequency enhanced hydrolysis compared with higher frequency and temperature. Scavenging properties of samples pretreated with low US frequency were also reported to be better than those with thermal pretreatment (S. Wang et al. 2019).

In food processing, residual chemicals could be eliminated by enzymolysis, hence enhance safety of food. Some challenges met with the traditional enzymolysis are being overcome by various pretreatment techniques. However, proper understanding of the possible effect of pretreatment on specie of interest is of great importance. In the thermal treatment, the system temperature should be well controlled to prevent the denaturation and aggregation of the protein, which can affect enzymolysis. In the same vein, enzyme characteristics under the ultrasonic action must be understood.

Drying

Drying is a process of moisture reduction of a product, which occurs as a result of thermodynamic difference between a product and the environment (Kaveh, Abbaspour-Gilandeh, and Chen 2020). Reduction in moisture content decreases microbial activity responsible for food spoilage; also it facilitates handling, transportation and further processing or utilization (Jahanbakhshi, Yeganeh, and Momeny 2020; Huang et al. 2020). It has been regarded as the oldest method of food preservation, which is still very much used even in recent times by the food industry (Abbaspour-Gilandeh, Kaveh, and Jahanbakhshi 2019; Ojediran et al. 2020). In drying of food product, the drying rate, moisture diffusivity, activation energy, heat and mass transfer rates, the total energy consumed by the system and product, and the quality of the dried product is crucial to food industries (H. Wang et al. 2019; Amanor-Atiemoh et al. 2020). Traditional drying of food products has disadvantages: quality mortification, obstreperous ambient conditions, non-uniformity in the dried product, long drying duration, product contamination, and high energy consumption (Dehghannya et al. 2019; Feng, Xu, et al. 2020; Feng, Ping Tan, et al. 2020). Over the years, researchers have developed different drying technology to help improve the drying performance. One of those evolutions is the introduction of US with other assisted technologies, which has tremendously been adopted by food industries (Arvanitoyannis, Kotsanopoulos, and Savva 2017). US applications as a pretreatment measure in drying have witnessed huge advancement (Zhou et al. 2021). The use of US in drying is driven by a phenomenon called "sponge effect," promoting moisture diffusion from the product core to the surface. The intracellular and extracellular cavitation of moisture on food products creates new micro channels, causing reduction of moisture (Bhargava et al. 2021).

Many researchers have studied the benefits and demerits of US assisted dryers for food products. For example, Baeghbali, Ngadi, and Niakousari (2020) studied the drying kinetic and physiochemical properties of okra slices dried by an US and IR-assisted conductive hydro-dryer (USIRCHD), freeze-dryer and oven dryer. The conductive hydro-dryer was used with or without the assistance of US or IR (US + IR+, US + IR-, US-IR-, and US-IR+). US frequency, power and temperature used were 28 kHz, 166 W and 82.5 °C respectively. US + IR + dried okra slices had the lowest color difference as compared to US-IR+, US+IR-, US-IR-, oven and freeze drying. The drying rate increased in the beginning of the drying process for US+IR+and US-IR+, while at the later end US controlled the drying process. The freeze-dried slices had better preserve the microstructure, followed by US+IR-, US+IR+, US-IR+, US-IR- and oven dried slices. US and IR application maintained the rheological properties of the okra. The vitamin C content of US+IR- dried slices was higher as compared to US-IR-, US+IR+, and US-IR+, and comparable with freeze dried sample. Guo et al. (2020) evaluated a US-assisted infrared dryer for moisture reduction of carrot cubes. It was observed that the US assisted dried cubes had higher drying rates, higher rehydration capacity but had no significant effect ($p > 0.05$) on the vitamin C, shrinkage ratio and color of the dried product. Y. Li et al. (2020) explored the use of US-assisted vacuum dryer in drying of hawthorn fruit juice. Four US generators were coupled to the vacuum dryer, intensities used were 15.29, 20.38, 22.93, and 24.46 kW/m^2, frequency (43 kHz) and power (600 W). Results showed that increased US intensity increased the drying rate, retention of total flavonoid content and antioxidant activity, and decreased color degradation. Although, it was noticed that the increase in the US power of the US-assisted heat-pump dryer would cause structural damage and weaken the seed viability (Yang et al. 2020). US-assisted fluidized bed drying reduced the energy consumption, toughness and ultimate compressive strength of grains (Abdoli et al. 2018). In summary, US-assisted dryers can be effectively used in the food industry since it produces better microstructure and rheological properties, color retention, total flavonoid content and antioxidant activity retention, higher drying rate and rehydration potential, reduced energy consumption, reduced toughness and ultimate compressive strength.

Moreover, the influence of sonication and chemical pretreatment (ethanol, glucose, distilled water and other osmotic solution) of food product, dried with non-ultrasonic assisted dryer and ultrasound-assisted dryer have also been investigated by many researchers. Rojas, Silveira, and Augusto (2020) studied the drying of ethanol pretreated rectangular apple slices using an ultrasonically assisted hot air dryer. Ethanol pretreatment was carried out at 25 °C for different duration (0, 10, 20 and 30 min). Drying with the US-assisted hot air-dryer was carried out with or without US at 50 °C and air velocity of 1 m/s. US frequency and power density was 21.77 kHz and 20.5 kW/m^3. Their result revealed an increase in the ethanol pretreatment time combined with the inclusion of US in the course of drying lessened the drying time by 55–70%, increased the mass transfer coefficient (55%) and the moisture diffusivity. The rehydration capacity of the US-dried slices was found to increase with increasing the ethanol pretreatment time, till reached 20 min, and then declined. The antioxidant activity of hot air dried un-pretreated slices was higher compared with the ultrasonically dried ethanol pretreated slices. Application of US to the hot air drying of pretreated slice slightly increased the antioxidant activity. Ethanol pretreatment time decreased the shrinkage level of the slice. Similarly, Li, Zhang, and Wang (2020) explored the pulsed fluidized bed, microwave-freeze drying of Chinese yam pretreated using a sonicated osmotic solution. It was revealed that the increase in the US power levels (1.52, 2.28 and 3.04 W/g) increased the drying and mass transfer rate and reduced the energy consumption during drying. Also, the quality parameters determination showed that the pretreated samples possessed better color and texture, enhanced antioxidant capacity, lessened bitterness and sourness compared with untreated slice. Santos et al. (2021) assessed the convective drying of carrot pretreated with the sonicated ethanol solution. The sample pretreated with the sonicated ethanol showed an improved rehydration capacity, reduced drying time (~50%) and the energy consumption (42–62%), and preserved carotenoid content. Hot air dried glucose sonicated sweet potato cubes showed a higher antioxidant capacity and lower vitamin C degradation, but lower total phenolic and flavonoid content (Rashid et al. 2020). In conclusion, it is noticed that the use of non-sonicated and the sonicated solution as a pretreatment step in the course of drying have been so far successful (higher drying rate, moisture diffusivity, lower shrinkage ratio, better color, texture, less bitterness and sourness, preserved carotenoid content), but the sonicated solution offered enhanced rehydration ratio. Also, some of the demerits include lower total phenolic content and total flavonoid content.

Researchers have also studied the use of single and multi-frequency (dual and tri- sweeping frequencies) US, both as pretreatment measure and as an integral part of most dryers. Xu et al. (2020) pretreated okra slices using a flat sweep-frequency and pulsed ultrasound device (SFPUS) prior to vacuum pulsation drying. Results revealed that okra slices treated with the sweep period (18–180 ms), amplitude (±1 kHz), frequency (40 kHz) and the power density (25 W/L) had the highest water diffusion. Slices treated with SFPUS showed the shortest drying time, higher total phenolic contents, antioxidant capacity, hardness and frangibility but lower chlorophyll degradation, total color change, and no distinct change ($p > 0.05$) on the total flavonoid content. Similarly, Osae et al. (2019) revealed that a sweep-frequency osmosonication pretreatment of ginger slices led to better color, and higher inactivation of enzyme (peroxidase and polyphenol oxidase). Pretreatment of melon with a single frequency US (25 kHz) in an ethanol solution, although lessened the drying time, but reduced the bioactive compounds (da Cunha et al. 2020). Feng et al. (2019) studied the use of tri-frequency (20, 40, and 60 kHz) US assisted osmo-dehydration pretreatment for garlic slices prior to catalytic infrared drying. It resulted in better shrinkage, surface roughness, flavor, color, microbial content but reduced allicin content. The allicin in garlic helps to reduce inflammation and offer antioxidant benefits when consumed. Dual-frequency treated sweet potato slices presented higher drying rate, surface color, enzyme inactivation (Rashid et al. 2019). In summary, the literature showed that applying both single and multi-frequency US reduced the drying time, better color, texture, microbial content, reduced enzymatic browning but only the sweeping frequency application was still able to preserve the bioactive compounds of the food material after drying.

US technology has been combined with other thermal and non-thermal technologies for sample pretreatment. For example, Wiktor et al. (2019) used the US in combination with pulsed-electric field (PEF) pretreatment prior to convective drying of carrot cubes. Different combinations were used, US + PEF and PEF + US. Two methods of sonication were used, namely immersion sonication (iUS) and contact sonication (cUS). The PEF + iUS pretreated sample had a higher water diffusion coefficient, soluble solid loss, total carotenoid, and a shorter drying time, but the total color difference was negatively affected. Strawberries were pretreated with US combined with ultra-high pressure prior to vacuum-freeze drying. Results showed that the pretreated strawberry had a higher value of total anthocyanin, total flavonoid, total phenolic content, diphenylpicrylhydrazyl (% DPPH), hydroxyl (–OH) radical- scavenging assay, redness and hardness. This reveals that the combination of US with other non-thermal technologies had an enhanced effect on the drying kinetic and quality properties of the food except that it affects the color. Xu et al. (2021) studied US-assisted thawing (UST), ultrasound assisted freeze-thawing (FUST) and US-assisted freeze air thawing (FAUST), freeze air thawing (FAT) prior to vacuum freeze-drying of okra. It was observed that FUST and FAUST pretreated samples had shorter drying time and less energy consumption. The UST treated sample retained most of the quality properties (flavor, color, hardness, and frangibility). The UST and FAT showed the best dry matter, lower chlorophyll and higher total phenolics, flavonoids, and pectin, and antioxidant potential.

Frying

Around the world fried foods are very popular arising from their unique organoleptic properties (flavor, color, texture and aroma), affordability and availability (Zhang, Zhang, and Adhikari 2020). Frying is a cooking method where fat or oil is used as the heat-transfer medium, in direct contact with the food (Devi et al. 2020). Frying is a heat- and mass-transfer process causing moisture evaporation from the food product (Figure 4). The formation or absence of a crust determines the mechanism and kinetics of water loss during frying (Sharifimehr, Soltanizadeh, and Goli 2019). Several phenomena take place simultaneously during frying; cooking (thermal reactions induce processes such as gelatinization of starch, denaturation of proteins, hydrolysis, development of flavors, Maillard browning and caramelization), dehydration (moisture loss), and changes in the fat content, texture and the food structure of the food (Dourado et al. 2019).Three basic frying types exist, namely pan frying, stir frying and deep fat frying. The deep fat frying is lately becoming a large-scale industrial operation in the production of products like; French fries, potato chips, etc., due to advantages such as a low cost and ease of operation (Günal-Köroğlu et al. 2019; C. Liu et al. 2020). One of the major disadvantages of deep-fat frying is the high amount of oil uptake of the fried products, which negatively affect its nutritional quality and causes health issues such as cancers, diabetes, cardiovascular diseases, obesity and hypertension (Liberty, Dehghannya, and Ngadi 2019; K. Deng et al. 2019). Deep-fat fried products are usually high in calories, saturated and *trans* fats (Song et al. 2020). The attractive color, captivating fragrance and appealing flavor of fried foods is as a result of Maillard reactions (Zhang et al. 2019; Liu et al. 2019). Maillard reactions are complex physical and chemical relationships between food ingredients and the heating oil (usually above 120 °C) (J. Li et al. 2020). It can also be a channel for the emergence of a possible acrylamide issue. Acrylamide (C_3H_5NO), which is cancerous, is a substance formed when asparagine reacts with reducing sugars at high temperatures (Antunes-Rohling et al. 2018; Schouten et al. 2020).

The oil uptake by fried foods amongst other characteristics has been identified as the major factor causing specific health concerns (Yu, Li, et al. 2020; Pandey, Ravi, and Chauhan 2020). Oil absorption has been noticed by several researchers to be more pronounced during the cooling process of the fried products, which is because of condensation of water vapors in the pores of the food causing ingestion of oil from the surface into the pores (Ayustaningwarno

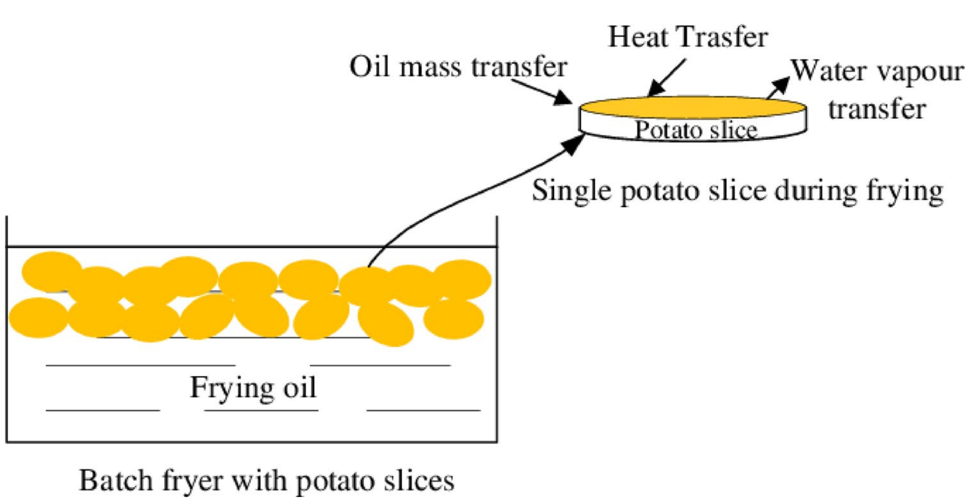

Figure 4. Heat and mass transfer during deep-fat frying.

et al. 2020; Ghaitaranpour et al. 2020). Oil-uptake by fried products can be classified into; surface oil, absorbed oil and structural oil (C. Zhang et al. 2020). Studies have been centered on ways to produce healthy fried products containing less oil by modifying the food surface, frying techniques and the post-frying de-oiling. Some of the non-thermal technologies used so far in the reduction of oil absorption by fried foods includes, US, radio-frequency and pulsed electric field. The US pretreatment was reported by Oladejo et al. (2017) to reduce the oil uptake of potatoes by about 71.47%, Amaral et al. (2017) and Konopacka et al. (2017) suggested that it is a good alternative to reduce or avoid loss of food quality.

US have been applied by researchers in frying basically for modification of the food surface prior to frying and as an integral component of new frying equipment. Su, Zhang, Zhang, et al. (2018) evaluated the energy efficiency and quality of fried potato chips using a vacuum fryer, microwave-vacuum fryer, US-assisted vacuum fryer and US assisted-microwave vacuum fryer. US (300 and 600 W) and microwave (1000 W) power levels were used. Palm oil at a temperature of 90 °C was used for the frying operation. Their result showed that US-assisted microwave-vacuum frying of potato chips reduced the frying time (by 36.4–54.5%), water activity, and volume shrinkage, and improved the moisture diffusivity (by 60.5–144.5%), texture properties, and color due to the increase in the US power from 300 W to 600 W; the energy consumption and oil absorption were respectively reduced by 34.9–48.3% and 27.4–32.3% compared to the vacuum frying alone. Although more porous microstructure was revealed with the use of ultrasound, this is because of the "vibration effect" created. In addition, Islam et al. (2019) also noted that the use of US-assisted microwave vacuum fryer improved significantly ($p < 0.05$) the chlorophyll and vitamin C content of fried edamame as compared to the use of vacuum and microwave vacuum fryer. Al Faruq, Zhang, and Adhikari (2019) observed that the application of US in microwave-vacuum frying of apple slices increased significantly ($p < 0.05$) the rate of moisture evaporation and retards Maillard reaction, which usually serve as an entry-point for acrylamide in fried foods. Su, Zhang, Bhandari, et al. (2018) revealed that the total anthocyanin of the purple-fleshed potato was better retained (about 79.51%) when fried with US-assisted-microwave vacuum fryer at US and microwave power levels of 600 and 800 W. Furthermore, Sun, Zhang, and Fan (2019) studied the effects of both microwave vacuum fryer and US-assisted microwave-vacuum frying on the quality of the oil. They observed that the use of in microwave-vacuum frying delayed the deterioration of the oil. It was concluded by Devi, Zhang, and Law (2018) that ultrasonically fried products usually have the best matrices. Islam, Zhang, and Mujumdar (2019) discovered that the vitamin C and chlorophyll in ultrasonically fried edamame were retained by 72–80% at a storage temperature of 10 °C and by 54–73% at 25 °C.

Ultra-sonication in distilled water, salt solution, citric solution and oil prior to frying has also been investigated. Antunes-Rohling et al. (2018) found that the use of ultra-sonication in water prior to deep frying can reduce the acrylamide content of fried potatoes up to 90% compared to potatoes, fried directly or up to 50% as compared to potatoes blanched in water. D. Su et al. (2020) studied the effects of different pretreatment media (distilled water, salt solution and oil) with the application of US at different power levels. It was observed that potato chips pretreated with US with water and oil as media showed significantly ($p < 0.05$) higher moisture diffusivity, lower oil uptake, hardness, shrinkage, total color change and water activity during microwave-assisted vacuum frying. Ran et al. (2019) found that carrots pretreated with microwave heating at 400 W for 2 min and ultra-sonication in salt solution before frying showed higher dielectric properties and reduced frying time. The US pretreatment also wears away the surface starch granules, reduced the penetration surface oil and structure oil content by about 27.3% (Zhang et al. 2021).

Decontamination

Contamination of food products, especially fruits and vegetables, have posed a major hurdle to food industries, marketers and public health (Paomephan et al. 2018; Alenyorege et al. 2019a). The food borne disease outbreaks in the United States (from 2004–2013) was majorly due to the consumption of fresh and freshly cut produce (Dolan, Bastarrachea, and Tikekar 2018). Food may be contaminated at different stages; on-farm, at harvest, during handling/transport, at storage, or during processing (Kilicli et al. 2019). In food industry, sanitization has been used as a critical food safety measure for reducing food related illness, improving quality and increasing shelf life (Alenyorege et al. 2019a; Alenyorege et al. 2020). Food contaminants mostly include microbes (*Listeria innocua*), bacteria (*Escherichia coli*), fungi (mycotoxins), viruses (Norovirus), dirt and pesticides (like captan) (Chen, Zhang, and Yang 2020). Over the years these foodborne contaminants have been treated and reduced with chemical sanitizers, novel thermal and non-thermal technologies (Dasan, Yildirim, and Boyaci 2018; Mahendran et al. 2019; Owusu-Ansah et al. 2020). Although chemical sanitizers, especially chlorine-based sanitizers, have been noted for their inability to reach portions of the plant harboring the bacterial cells, their reaction with food products can stimulate the production of carcinogenic halogenated disinfection by-products which include; trihalomethanes, haloacetic acids, haloketones and chloropicrin (Alenyorege et al. 2019b). Improper disposal of the used chemical solvents causes environmental hazards (Koubaa, Mhemdi, and Fages 2018). Some of the non-thermal technologies which have been frequently used for decontamination of food products are; US, low intensity electric current, pulsed light, ultraviolet light, pulsed-electric field, non-thermal plasma (like corona discharge plasma and cold plasma), hydrodynamic cavitation, ionizing radiation, ozonation and high hydrostatic pressure processing (Choi, Puligundla, and Mok 2017; Mahendran et al. 2019; Savi et al. 2020).

One of the major advantages of using US in food processing is its ability to initiate physical and chemical changes in food without the application of heat (Salve, Pegu, and Arya 2019). US application in food processing aims at eliminating the negative quality effects caused by the thermal processing like denaturation of protein, degradation of vitamins and lactose, poor sensory attributes, discoloration, etc. (Guimarães et al. 2018; Bahrami et al. 2020). US is a non-toxic and environmentally friendly technology. The inactivation mechanism of US is a result of bursting of the cavitation bubbles induced by changes in pressure created ultrasonic waves (Dolan, Bastarrachea, and Tikekar 2018). Ultra-sonication washing has been used alone for the decontamination of food products by using various levels of intensity (low and high intensity) and frequency modes (mono-frequency, dual-frequency, tri-frequency and sweeping frequency). Alenyorege et al. (2019c) studied the application of multi-frequency US in inactivation of *Escherichia coli* on fresh cabbage. Three treatment conditions were evaluated; sweeping frequency (28 ± 2, 40 ± 2, and 68 ± 2 kHz), fixed frequency (28, 40, and 68 kHz) and combined fixed frequency (28 + 40, 68 + 28 and 40 + 68 kHz). These treatments were conducted at 600 W, water temperature of 20 °C, pulse on and off time of 15 and 5 s, and time of 30 min. The fixed frequency US washing (40 kHz) showed the highest reduction in the population size of *E. coli* (>3 log CFU/g) with an improvement in the product quality. Mono-frequency, dual frequency and tri-frequency US has been explored by Alenyorege et al. (2019c) for inactivation of natural microbiota like total bacteria, yeasts and molds on tomato. They found that the tri-frequency US washing had the highest reduction of the natural microbiota (>1.5 log CFU/g). Alenyorege et al. (2020) reported that the tri-frequency US posed the undesirable changes in the volatile compounds and physicochemical properties of cabbage. Guimarães et al. (2018) evaluated the usefulness of high intensity US (HIUS) at various power levels (0, 200, 400 and 600 W) for the inactivation of aerobic mesophilic heterotrophic bacteria, total and thermotolerant coliforms and yeasts and molds in prebiotic whey beverage. The efficacy of HIUS microbial inactivation at 600 W was similar to high-temperature short-time treatment (75 °C for 15 s), although HIUS enhanced the kinetic stability of whey beverage, decreased the whey protein denaturation and polysaccharides gelation. The use of US-assisted technology for decontamination of food materials has been more pronounced in the food industry due to the inability of US-alone to inactivate some pathogenic bacteria like *Listeria monocytogenes*. A 5-log microbial reduction in 30 s is needed by most food industries (Dolan, Bastarrachea, and Tikekar 2018). Tan, Rahman, and Dykes (2017) explained that a sonication treatment at 20 kHz was able to reduce *Salmonella* Typhimurium ATCC 14028 cells on all plant material surfaces (between 0.5 and 1 logCFU/cm^2) except for bacteria surfaces without pectin and xyloglucan. The synergistic effect of sweeping frequency US (40 ± 2 kHz) and sodium hypochlorite solution (100 mg/L) was discovered to be more effective in the reduction of *Listeria innocua* (about 2.06 logCFU/g more) when compared to the individual treatments (Alenyorege et al. 2020). Dolan, Bastarrachea, and Tikekar (2018) also noted that >5 log CFU/mL of *Listeria innocua* was reduced by the combination of low frequency US (20 kHz) and 40 mM zinc oxide within 8 min, which was an improvement to the individual treatments. The combination of the low-intensity electric current and US reduced the decontamination time of lettuce by 40% (Kilicli et al. 2019). Pesticides like captan, thiamethoxam and metalaxyl residues on tomato have effectively decontaminated by the combination of US and electric current, up to 95.06% (Cengiz et al. 2018). Huang et al. (2018) discovered that the cross-contamination of foods during washing could be reduced by using a combination of US and surfactants. US-assisted washing like US + ultraviolet light and US + ultraviolet + acidic electrolyzed water washing significantly reduced *Listeria monocytogenes* and natural microbiota on salmon fillets, although it affected the color and odor (Mikš-Krajnik et al. 2017). The summary of the review is as presented in Table 1.

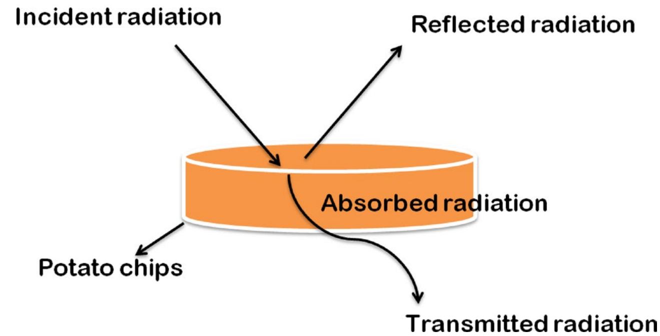

Figure 5. Mechanism of IR radiation rays on food material.

Infrared heating as a physical tool in food processing

IR radiation also known as electromagnetic waves is a form of energy generated from the passage of electrons in atoms and molecules (Rastogi 2012). IR radiation is divided into three (3) sections based on wavelengths; near-infrared (NIR) (0.78–1.4 µm), mid-infrared (MIR) (1.4–3 µm) and far-infrared (FIR) (3–1000 µm) (Rastogi 2012). There are basically two (2) types of IR heating devices; IR heaters fired by gas emitters and electrical lamps (Feng et al. 2018). The gas-fired emitters are usually used for commercial large power source unlike the electrical IR lamps (Wu et al. 2017). During the incidence of IR rays on the surface of food material during physical processing, part of the rays penetrates while the other part is reflected. The penetrated rays are further divided into two categories; absorbed and transmitted rays as presented in Figure 5. The absorbed rays have direct effect on the food material, which activate the molecular movement, leading to a temperature rise. Higher absorptivity reflects higher efficiency in the IR heating process (Lee 2019). IR heating method has been used for wide range of applications in food industry including; drying, peeling, roasting, pasteurization, inactivation of

Table 1. Ultrasound and Ultrasound-assisted technology in decontamination.

Products	Processing conditions	Target contaminants	Significant findings	References
Potato, apple and lettuce	US treatment. Frequency (20 kHz), amplitude (20%), temperature (20 °C), power (750 W) and treatment time (5, 15, 30, 45, 60 and 90 s)	*Salmonella Typhimurium* ATCC 14028 cells	US application has the potential of decreasing *SalmonellaTyphimurium* ATCC 14028 cells attached to fresh produces during processing	Tan, Rahman, and Dykes (2017)
Salmon fillets	Treatments were; acidic electrolyzed water (AEW), ultraviolet light (UV), ultrasound (US), UV + US and UV + US + AEW	*Listeria monocytogenes* and natural microbiota (total viable count, total coliforms, *Escherichia coli*, and yeasts and molds)	UV + US and UV + US + AEW were the best at reducing the populations of contaminants	Mikš-Krajnik et al. (2017)
Cabbage	Treatments conditions were; sweeping frequency (SF), fixed frequency (FF) and combined FF (CFF) US. SF (28, 40, and 68 kHz), FF(28, 40, and 68 kHz), and CFF((28 + 40, 68 + 28 and 40 + 68 kHz), pulse on and off time (15 and 5 s) and temperature (20 °C)	*Escherichia coli*	US washing using FF at 40 kHz showed the highest reduction (>3 log CFU/g) of *Escherichia coli* when compared with water washing	Alenyorege et al. (2019c)
Lettuce	Three treatments type were used; US washing alone, US-assisted washing in sterile water and sterile water washing alone at 20 °C Frequency (42 kHz), power (100 W) and time (10 min)	*Listeria innocua*, *Escherichia coli* O157:H7 and *Pseudomonas fluorescens*	The combination of US and surfactant for washing single or multiple lettuce did not significantly increase the removal of the contaminants (*Listeria innocua* and *Escherichia coli)* when compared to US alone except for *Pseudomonas fluorescens* which showed a higher removal efficacy.	Huang et al. (2018)
Nil	Low frequency US, zinc oxide (ZnO), low frequency US + ZnO. ZnO (20 or 40 mM), US (20 kHz, 43–45 W, 120 µm amplitude) at room temperature for 0–30 min.	*Listeria innocua*	Combined ZnO and US (>5logCFU/mL) showed higher reduction of *Listeria innocua* than the individual treatment (<1 log CFU/mL)	Dolan, Bastarrachea, and Tikekar (2018)
Prebiotic whey beverage	US and high temperature short time (HTST) treatments. US power (0, 200, 400 and 600 W), frequency (19 kHz), sonication temperature (53 °C), sonication time (3 min). HTST at 72 °C for 15 s.	Aerobic mesophilic heterotrophic bacteria (AMHB), total and thermotolerant coliforms and yeasts and molds	US treatment (at 600 W) in inactivation of the contaminants was comparable to HTST treatment, although lower output temperature was reached using US (53 °C).	Guimarães et al. (2018)
Tomato	Low intensity electric current (EC) and ultrasound (US) treatments. EC (200, 800 and 1400 mA), treatment time (2, 4, 6, 8 and10 min) and US (24 and 40 kHz)	Pesticides (captan, thiamethoxam and metalaxyl) residues	Combined treatments of the order; 1400 mA+ 40 kHz, 800 mA +24 kHz and 1400 mA +24 kHz had the highest reductions of captan (94.24 %), thiamethoxam (69.8 %) and metalaxyl (95.06 %)	Cengiz et al. (2018)
Cabbage	Samples were treated with either sweeping frequency US (28 ± 2, 33 ± 2, 40 ± 2 and 68 ± 2 kHz), sodium hypochlorite solution (20, 40, 60, 80 and 100 mg/L) and combination of both.	*Listeria innocua*	Combined sweeping frequency US (40 kHz) and sodium hypochlorite (100 mg/L) treatment showed a higher reduction of *Listeria innocua* than the single treatments	Alenyorege et al. (2019a)
Cabbage	Sweeping frequency US (SFUS), sodium hypochlorite (NaOCl), SFUS + NaOCl. SFUS (28 ± 2, 33 ± 2, 40 ± 2 and 68 ± 2 kHz), NaOCl (20, 40, 60, 80 and 100 mg/L) for 10 min	Natural microbiota	SFUS + NaOCl treatment significantly reduced the mesophilic counts, yeasts and mold when compared with single treatments, also during storage the washed samples using SFUS + NaOCl had the lowest microbial counts	Alenyorege et al. (2019b)
Tomato	Three different US mode were evaluated; Mono-frequency ultrasound (MFU), dual-frequency ultrasound (DFU), and tri-frequency ultrasound (TFU). MFU (20 kHz), DFU (20–40 kHz) and TFU (20–40–60 kHz).	Natural microbiota (Total bacteria, yeast and mold)	TFU showed the highest reduction (> 1.5 log CFU/g) of the natural microbiota followed by DFU and MFU.	Alenyorege et al. (2019c)
Cabbage	Dual frequency US (20–40 kHz; 20–60 kHz; and 40–60 kHz) and tri- frequency US (20–40–60 kHz)	Natural microbiota (total bacteria, yeasts and molds),	The natural microbiota were significantly reduced by triple frequency US than dual frequency US, but triple frequency US treatment diminished the product quality	Alenyorege et al. (2020)

microorganisms etc (Sakare et al. 2020). Food components have varied ranges of absorption intensities at different wavelengths. The incident radiative energy predicts the type of the energy absorption mechanism based on the wavelength range. FIR energy is generally known to be more absorbed by food molecules followed by MIR and NIR. The radiative energy directed on the food surface may cause changes in the electronic, vibration, and rotational states of food molecules (Gani, Quadri, and Ayaz 2018).The absorption of IR is usually through the mechanism of changes in the molecular and vibration state causing radiative heating. Most food materials have high transmissivity and low absorptivity (Krishnamurthy et al. 2008). IR heating relies on the energy spectrum released from the emitters which are at different wavelengths while some part of the radiation relies on the temperature source and the lamp emission. Heat generated by IR energy placed close to the surface of food material is transferred to the inside by either conduction or convection. Thermal and engineering properties of food predict the temperature and the time required for any physical processing operation (Aboud et al. 2019).

Peeling

Peeling is one of the first physical operations in food industry for processing of fruits and vegetables (Kate and Sutar 2020), involves the removal of the outer coat or skin (pericarp). It is an important process operation in food industry for optimal product development particularly in production of canned fruits and vegetables (Eskandari et al. 2018).The nutritive value and taste of the final canned food is affected by peeling operation (Li et al. 2014). Lye and steam peeling method have been most commercialized especially lye peeling due to its higher products yield and better product quality (Rock et al. 2012; Wongsa-Ngasri and Sastry 2015; Wang et al. 2018). Although, the disadvantage such as waste of water resources by steam peeling and environmental pollution by lye peeling has led to the search for more innovative and environmental friendly peeling methods (Gao et al. 2018; Pan et al. 2019). Waste water from lye peeling holds very high salinity (100–200 g/L), Ph, organic loads, and some nutrients content of the food, resulting in negative environmental impacts (Li, Pan, et al. 2014). Recently, there have been the evolvement of other peeling technology such as; enzymatic peeling, freeze-thaw peeling, ohmic peeling, power ultrasound assisted-lye peeling and IR dry peeling. Ohmic, freeze-thaw and power ultrasound assisted-lye peeling still requires a base solution (either water or chemical solution) for its peeling operation, which still remains a concern (Silva-Vera et al. 2020). Enzymatic peeling though is a chemical and water free method but has some disadvantages such as high peeling loss, low production yields, not cost effective and feasibility issues (Andreou et al. 2020).

IR dry peeling has stood out due to following reasons; low penetration depth, uniform and fast surface heating, high heat-transfer rate, reduced processing time and energy consumption, minimum disruption of the edible inner part and texture, improved product quality and safety, improved firmness, lower peeling loss, higher peeling easiness, and peelability. Peels can be used for value-added products (Mohammadi et al. 2019; Vidyarthi et al. 2020).The peeling methods used retards further usage of the peels for production of value added products (Rahmawati et al. 2018). Two types of IR emitters are usually used for dry peeling; electric and catalytic emitter. Catalytic IR emitter uses natural gas which reacts with oxygen in the presence of a catalyst (usually platinum). This type of emitter has lower operational cost since natural gas is cheaper as compared with electricity cost. The major processing parameters which affect IR dry peeling performance are the radiation intensity or power, emitter's distance or gap, heating time and the product size (Wang, Venkitasamy, et al. 2016). IR-peeling has been carried out in three basic methods by researchers; (1) IR-heating followed by manual peeling, (2) a pilot scale IR equipment connecting the separate IR heating unit and the peeling device (abrasive mechanism), (3) the pilot scale IR equipment that combined an IR heater and an abrasive peeling device in one single unit. In the later the IR- heating and peeling operation is carried out simultaneously. For IR-heating followed by manual peeling; Li, Zhang, et al. (2014) studied the effect of catalytic IR heating on the manual peeling performance of clingstone peaches. The surface temperature and the peak-wavelength of the emitter were 500 °C and 3.7 µm, respectively. The processing conditions were heating time (60, 90, 120, 150, and 180 s) and emitters gap (90, 115, and 140 mm). Results showed that IR-peeling out-performed the conventional lye-peeling method. Clingstone peaches processed at the heating time of 180 s and emitter's gap of 90 mm had the highest peelability (84 mm^2/100 mm^2), peeling yield (90 g/100g), lowest surface temperature (<45 °C) at 16 mm deep, uniform and rapid surface heating. Although, the peeled product had similar firmness and color as wet lye-peeling. Wang et al. (2016) evaluated the use of electric IR heating on the manual peeling performance of jujubes. The processing variables were radiation intensities (5.25, 5.66 and 6.07 W/cm^2), emitter's gap (75, 80, and 85 mm) and heating time (40, 50, and 60 s). There results revealed that IR-peeling presented low peeling loss and color change as compared to hot lye-peeling. Radiation intensity of 5.25 W/cm^2, emitter's gap of 75 mm and heating duration of 56 s showed the highest peelability (96%), peeling easiness (3.8), and the lowest moisture loss (1.29%), and surface temperature (115 °C). IR peeling had low peeling loss, and color change as compared to lye-peeling. Lower peeling loss, color change, surface temperature, volatile oil loss and highest peeling efficiency and firmness was also reported by Kate and Sutar (2018) for ginger rhizome. Also IR heating device using four catalytic IR emitters was used by Shen et al. (2020) for pears prior to manual peeling; they found out that IR-heating for 99 s presented the highest product quality, the lowest peeling loss, better peeling easiness, and a relatively thin cooking-ring. In the use of a pilot scale IR equipment consisting of a separate IR heating unit and a peeling device, Eskandari et al. (2018) revealed that the radiation power (1600 W), heating time (3 min), abrasive shaft clearance (4 mm), shaft speed (200 rpm) and the abrasive path (36 cm) led to the best peeling performance for hazelnut. Peeled tomato samples using IR heating produced desirable quality such as firmer product and appealing surface integrity and peels can be used for value-added products (Pan et al. 2015). Mohammadi et al. (2019) used a combined IR-heating and peeling device for kiwi fruit. The processing parameters were radiation power (250–850 W), emitter gap (10–70 mm) and heating time (45–125 s). It was discovered that this peeling method resulted in a significant reduction in the weight loss, surface temperature and the color difference and maintained firmness over the lye peeling.

Decontamination

Decontamination is the process of reducing spoilage microorganisms from the devices, surfaces and the environment, thereby hindering them from possible infection of vulnerable sites (Dasan et al. 2017; T. Wang et al., 2017). The production of food voids of contaminants that is safe for human consumption has been one of the major hurdles faced by food industries. Recent studies have shown that over 2 billion people are exposed to contaminated food and yearly1 out of every 10 people suffer from at least one foodborne illness (Katsigiannis, Bayliss, and Walsh 2021). Fresh produce like lettuce, strawberry, pepper, tomato etc., is normally contaminated with *Listeria monocytogenes, Escherichia coli, Salmonella spp* (Ziuzina et al. 2020). Amongst this various contaminants, *Listeria monocytogenes* is more pronounced in food processing factories since it is transferred to the food material via contact with contaminated processing equipment. This psychotropic microbe grows in aerobic or anaerobic conditions over a wide range of pH (4.1–9.6) and high concentration of salts of about 13% (Horita et al. 2018). Pankaj, Shi, and Keener (2018) also noted that some fungi species belong to genera like Aspergillus, Fusarium and Penicillium, produce toxins contaminating stored food products during storage. Aflatoxins are one of the most widespread contaminants in food crops like maize, tree nuts, dried fruits, spices, and groundnuts, including meat and milk products (Udomkun et al. 2017; A. Liu et al. 2020; Roohi, Hashemi, and Mousavi Khaneghah 2020). They are very toxic, cause quality and nutritional degradation, carcinogenic, and are not degraded by normal food processing techniques (Sen, Onal-Ulusoy, and Mutlu 2019; Shirani, Shahidi, and Mortazavi 2020; Jubeen et al. 2020). Around the globe 28% of liver cancers are associated with the consumption of food crops like maize and peanuts contaminated by aflatoxins (Deng et al. 2020). Lacombe et al. (2017) noted that viruses like Norovirus, which is associated with raw, consumed foods are the leading cause of foodborne outbreaks. Several thermal blanching techniques have been used for decontamination purposes in processed foods. The most commonly used method is the dry- or wet-heat treatment, which is done by heating foods at 71.06 °C for 15 s, followed by drying at 205 °C for 5–6 s. This thermal treatment reduces contaminants and improves the shelf life, but exerts detrimental effects on nutritional content and organoleptic properties (Molnár et al. 2018; Rifna et al. 2019; Lee, Park, and Min 2020). Stratakos and Grant (2018) noted that the thermal treatment was very effective for inactivating *Escherichia coli* and other pathogens.

A set of novel thermal technologies like IR heating, radio frequency heating, microwave heating, ohmic heating and instant control pressure drop have developed to help combat the shortcomings of the conventional heat treatment for decontamination (Mandal, Singh, and Singh 2018). These novel thermal technologies deliver the volumetric heat generated directly to the food without heating the surrounding air. Their inactivation mechanisms are similar to that of microwave heating and ultraviolet light, which is basically relying on the destruction of DNA, RNA, ribosomes, cell envelopes and the protein in the microbial cell (Rifna et al. 2019). IR heating has achieved higher energy efficiency, uniform heating and shorter heating duration for inactivation of microorganism with less quality reduction when compared with other heating methods (Lara et al. 2019). Siciliano et al. (2017) realized that the residual aflatoxin on hazelnut was lower when subjected to infrared heating than hot air. An increase in the IR-heating temperature significantly reduced the formation of *Aspergillus flavus* and *Aspergillus niger* on mung bean by about 5.3 logCFU/g (Meenu, Guha, and Mishra 2017). Bowie et al. (2019) showed that a sample treated with IR heating (at a wavelength of 3.2 μm, emitter-product distance of 110 mm, and a heating time of 30 s) had the highest reduction in amounts of molds (3.11 log CFU/g) and bacteria (1.09 log CFU/g). However, IR-heating has a disadvantage of the low penetration depth, hence becoming less efficient when treating thick food materials (Lao et al. 2019). This shortcoming of infrared-heating alone has been improved by its combination with other assisted novel technologies and tempering conditions. Wang et al. (2014) discovered that infrared heating combined with tempering (60 °C for up to 120 min) reduced *Aspergillus flavus* growing on rough rice (2.5–8.3 logCFU/g). Venkitasamy et al. (2017) and Venkitasamy et al. (2018) applied sequential infrared-hot air drying and tempering condition for the reduction of *Enterococcus faecium* on Pistachios and almond nuts. They found out that the maximum reduction of the shell (6.1 logCFU/g) and kernel (5.41 logCFU/g) was presented at treatments of IR-1 h + tempering-2 h + hot-air drying-5 h and IR-2 h + tempering-1 h + hot air drying-4 h respectively. Wilson et al. (2017) reported that the growth of molds on the shelled corn was significantly reduced by the combination of IR and tempering. IR-heating cum tempering has been found not to affect the product quality. For instance, Fu et al. (2019) noted that grape seeds treated with IR-heating and tempering showed a high oil yield. Similarly, Shavandi, Kashaninejad, et al. (2020) and Shavandi, Taghdir, et al. (2020) observed that IR-heating combined with tempering or holding reduced the growth of *Bacillus cereus* on cardamom seeds and paprika powder, to an acceptable level, without affecting the quality characteristics. Some other novel technologies have been combined with IR-heating to improve its inactivation power and treatment time. Shankarrao Shirkole et al. (2021) stated that the synergistic effect of IR and microwave heating reduced *Salmonella*

Typhimurium (7.389 log) and *Aspergillus flavus* (6.182 log) formed on paprika powder; despite that an increase in the power levels, inhibits the antioxidant capacity and altered the color. The inactivation time of ultraviolet light for *Escherichia coli on* chili flakes was reduced by 50% by the combined treatment of IR and ozone (Watson et al. 2020). The summary of the review is as presented in Table 2.

Inactivation of enzymes

Enzymes are protein molecules present in all living things. They act as biocatalysts regulating the rate at which chemical reactions proceed (Lopes et al. 2018). Blanching is a pre-processing operation used in food industry aiming at inactivation of enzymes, such as peroxidase, polyphenoloxidases, lipase, lipoxygenase, pectin methylesterase, alliinase and γ-glutamyl transpeptidase and phenolase (Xanthakis et al. 2018; Zhao et al. 2020). The main purpose of blanching is to passivate the deteriorative enzymes, remove the air in the food tissue, reduce microbial numbers, modify the cell structure, so as to prevent discoloration, improve texture, increase drying performance and extract phytochemicals (X. Zhang, Shi, et al. 2020; H. Wang, Fang, et al. 2020).

Amongst the numerous inherent enzymes in food, peroxidase (POD) and polyphenol oxidase (PPO) being the most stable and available in high concentrations, are the major cause of food spoilage (Pellicer and Gómez-López 2017; Jamali et al. 2018; Li, Wu, et al. 2019). PPO and POD enzymes degenerate hydrogen peroxide, which is an inhibitor of lipoxygenase, and they generate free radicals in the course of oxidation that can hamper the unsaturated fatty acids and cause oxidative rancidity by advancing oxidation of free fatty acids (Baltacıoğlu, Bayındırlı, and Severcan 2017; Poudel and Rose 2018). The activity of POD and PPO is usually measured as a yardstick for determining the effectiveness of the inactivation method (Huang et al. 2019; Chutia et al. 2019). Inactivation of POD and PPO helps to prevent possible biochemical reactions leading to quality deteriorations in the food; like poor sensory properties, off-flavor generation, poor nutritional quality, poor textural properties and undesirable color changes (Wang et al. 2017c; Akgün and Ünlütürk 2017; Jiang et al. 2018). PPO is the precursor of browning, discoloration and poor sensory quality of food during further processing and storage while POD catalytic reaction produces off-flavor in foods (Chutia et al. 2019; Jiang et al. 2021).

Blanching has been carried out with both thermal (infrared, microwave, roasting, hot-water, steam, radio-frequency, high-humidity hot air impingement) and non-thermal (cold plasma, high-pressure, gamma-irradiation, pulse electric field, ultraviolet light and sonication) technologies for enzyme inactivation (Tolouie et al. 2018; Tian et al. 2018; Chutia et al. 2019). Most of the non-thermal technologies have not been adopted by food industry due to their high cost, complexity and difficulty in scaling up (Pankaj, Misra, and Cullen 2013). Hot water or steam heating medium is the conventionally used wet-blanching method of most food industries, but requires high temperature for excellent enzyme inactivation (L.-Z. Deng et al. 2019; H. Wang, Zhang, et al. 2020). This high temperature could affect the texture, color and the nutritional value of the food (Gong et al. 2019; Y. Su et al. 2020). Also, a large volume of the sample requires longer blanching time, which has an adverse effect on food quality (Ling, Lyng, and Wang 2018). Dry-blanching methods like infrared (IR), microwave and radio frequency heating have been suggested obtaining better blanching efficacy, waste water elimination and better product (Gong et al. 2019).

IR heating is a dry blanching method recently used in the food industry; the energy is transmitted directly to the surface of the sample without heating the surrounding air (Chen et al. 2018). It is a versatile, simple and effective technology which transfers energy by electromagnetic wave to food (Bingol et al. 2014). IR heating reduces the nutrient loss, pigment alterations, and the weight loss better than the conventional hot water and steam blanching methods (Jamali et al. 2018). It has been successfully applied alone or combined with other thermal and non-thermal technologies for inactivation of spoilage enzymes in food products. Feng et al. (2018) compared the influence of catalytic IR heating and hot water blanching method on the inactivation of POD in garlic slices. The processing variables of the IR-heating used were the temperature (95, 115 and 135 °C), emitter to sample distance (10.5, 16.2 and 21.6 cm), slice thickness (3, 5 and 7 mm) and the blanching time (30, 60, 90 and 120 s).The results revealed that increasing the heating temperature and/or reducing the sample thickness during catalytic IR blanching improved the POD inactivation. Also, better garlic quality was obtained from IR heating than hot water blanching. IR heating of potato slices, prior to frying, was completely inactivated PPO in 180 s (Wu et al. 2018). Chen et al. (2018) found out that the IR pretreatment before drying significantly ($p < 0.05$) reduced the POD residual activity. It was reported that the relative-humidity convective drying had higher efficiency in the inactivation of PPO and POD than freeze drying, infrared drying and microwave drying; although, it led to lower quality ginger slices (Osae et al. 2020). In addition, J. Wang et al. (2017) noted that hot water, microwave, infrared and high humidity hot air impingement blanching methods all inactivated PPO and POD (Figure 6), but hot water blanching reduced the quality of red bell pepper. Wu et al. (2018) discovered that inactivation of PPO by IR-heating was faster for thinner potato slices. However, 90% reduction in the activity of PPO and POD in bitter gourd was longer for the IR-heating method (8 min) than hot water and steam (2–3 min) blanching methods; considering that the inactivation of PPO was easier than POD (Nalawade, Sinha, and Hebbar 2018). Introduction of airflow during IR-heating reduced the blanching time required for complete inactivation of PPO on French fries by about 21% when compared with hot water blanching (Bingol et al. 2014). Li, Wu, et al. (2019) also reported that the combination of IR heating and steam blanching showed enhanced inactivation of POD and PPO activity. Hot water blanching was effective for inactivation of pectin methylesterase than IR blanching (Aghajanzadeh, Kashaninejad, and

Table 2. IR and IR-assisted blanching for decontamination of food.

Product	Processing conditions	Target contaminant	Significant findings	References
Rough rice	IR heating at 60 °C for 1 min followed by tempering at 60 °C for 5, 10, 20, 30, 60, or 120 min	*Aspergillus flavus*	IR radiation heating + tempering for 120 min showed the highest *Aspergillus flavus* reduction of 2.5–8.3 logCFU/g.	Wang et al. (2014)
Pistachios nuts	Sequential IR-hot air (HA) drying and tempering (T) conditions were used; HA-6 h, IR-4 h, IR-1h + HA-5 h, IR-2 h + HA-4 h, IR-1 h + T-1 h + HA-5 h, IR-1 h + T-2 h + HA-5 h, IR-2 h + T-1 h + HA-4 h, and IR-2 h + T-2 h + HA-4 h.	*Enterococcus faecium*	The highest reductions in population size of *Enterococcus faecium* on both the shell and the kernel was presented by blanching treatments of IR-1 h + T-2 h + HA-5 h and IR-2 h + T-1 h + HA-4 h respectively	Venkitasamy et al. (2017)
Mung bean	IR intensity (0.299 kW/m^2), heating temperature (50, 60 and 70 °C) and heating time (5 min)	*Aspergillus flavus* and *Aspergillus niger*	IR heating at 70 °C for 5 min showed the highest and significant reduction of the contaminant (5.3 log).	Meenu, Guha, and Mishra (2017)
Shelled corn	Catalytic IR heating to surface temperature of 90 °C and tempering at 50, 70 and 90 °C for 2, 4 and 6 h.	Mold	IR-heating coupled with tempering significantly reduced the microbes on corn	Wilson et al. (2017)
Hazelnuts	IR roasting temperature (140 °C), roasting time (20 and 40 min). Hot air roasting temperature (120–170 °C) and time (20 and 40 min)	*Aspergillus flavus*	Both roasting method at temperature of 140 °C and exposure time of 40 min was effective to detoxification. Although the residual aflatoxins was lower for infrared than hot air	Siciliano et al. (2017)
Almond	Sequential IR and hot air (HA) drying method was used for decontamination in this design; IR-3 h, IR-2 h + HA-1 h, IR-1 h + HA-2 h, and HA-5 h. Tempering time was 2 h.	*Enterococcus faecium*	IR-2 h + HA-1 h and 2 h tempering treatment presented the largest reductions in the population size of *Enterococcus faecium* on the hulls, shells and kernels	Venkitasamy et al. (2018)
Grape seeds	IR-heating temperature (60–135 °C), tempering temperature (60–75 °C) and tempering time (10–60 min)	Aerobic bacteria and mold-yeast	IR-heating at 135 °C and subsequent tempering at 75 °C for 60 min showed the highest reduction in the microbial count.	Fu et al. (2019)
Cardamom seeds	IR power (100, 200, and 300 W), emitter to sample distance (5, 10, and 15 cm) and holding (0-15 min)	*Bacillus cereus*	IR blanching of the seeds reduced the *Bacillus cereus* counts to acceptable levels without affecting its quality.	Shavandi, Kashaninejad, et al. (2020)
Nil	IR and pulsed UV efficacy was compared.	*Escherichia coli*	*Escherichia coli* 0157:H7 with 4par strain was most resistant to IR treatment while 5par strain presented the most resistant to pulsed UV treatment.	Chintagari, Jadeja, and Hung (2019)
Rough rice	IR wavelengths (3.2, 4.5 and 5.8 μm), heating time (10, 20 and 30 s), and emitter to product distance (110, 275 and 440 mm). Tempering was at 60 °C for 4 h	Mold and bacteria	IR-treated sample at wavelength (3.2 μm), emitter to product distance (110 mm), and heating time (30 s) had the highest reduction in mold (3.11 log) and bacteria (1.09 log) count.	Bowie et al. (2019)
Chili flakes	Combined IR, UV and ozone pretreatment was used before fluidized bed drying.	*Escherichia coli*	IR and ozone blanching completely reduced the inoculated *Escherichia coli* in the sample in < 20 min unlike UV which was < 40 min. Combined treatment in the order of UV-IR followed by ozone showed a slightly better performance than ozone assisted by UV-IR.	Watson et al. (2020)
Paprika powder	IR heating power (100, 200 and 300 W), emitter to sample distance (5, 10 and 15 cm) and holding time (0–10 min)	*Bacillus cereus*	IR heating with power (200 W), emitter to sample distance (5 cm) and holding time (1 min) showed the highest reduction in *Bacillus cereus* (2.3 log)	Shavandi, Taghdir, et al. (2020)
Paprika	Combined microwave (MW) and IR heating method was used.	*Salmonella typhimurium* and *Aspergillus flavus*	There was a high reductions in both *Salmonella typhimurium* and *Aspergillus flavus* after MW-IR heating	Shankarrao Shirkole et al. (2021)

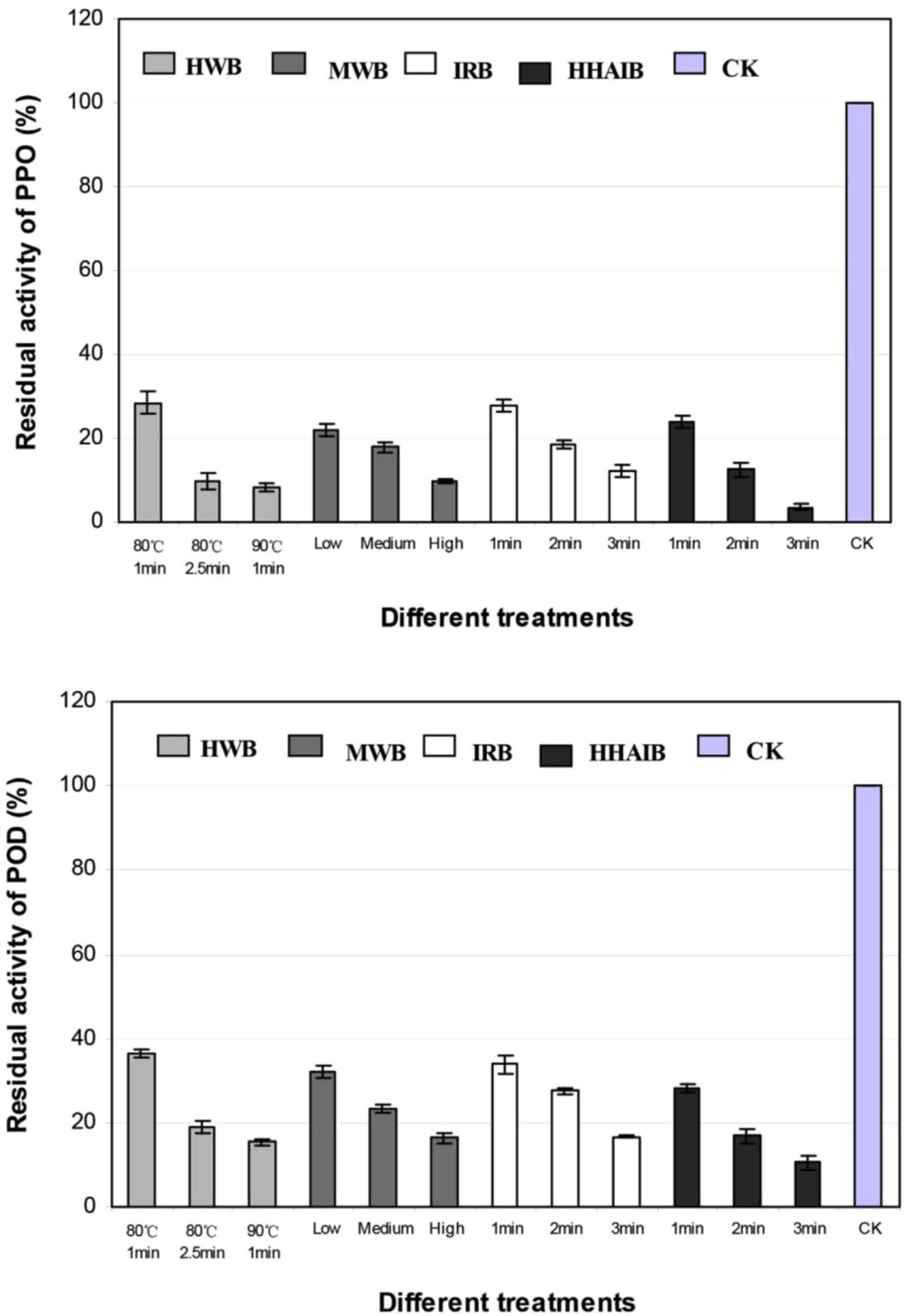

Figure 6. Blanching effects on the inactivation of PPO and POD. HWB: hot water blanching; MWB: microwave blanching; IRB: infrared blanching; HHAIB: high humidity hot-air impingement blanching; CK: without blanching. © 2017 Jun Wang et al. All Rights Reserved. Reproduced with permission from Elsevier. (J. Wang et al. 2017).

Ziaiifar 2016). A summary of the effects of US, IR, and other assisted technologies are shown in Figure 7.

Conclusions

In this overview, the potential use of US (both mono and multi-frequency levels), US-assisted technology, IR and IR-assisted technology in physical processing of food has been elaborated. The following key advantages useful to food industries could be achieved by applying the US and IR to food processing. These advantages include reduced processing time and energy consumption, minimum disruption of food texture, improved product quality, enhanced process efficiency, and improved food safety. There are fewer studies on the combination of IR with other novel thermal or non-thermal technologies in food processing, as some earlier studies observed that it could reduce the blanching time. Also, the development of IR-large scale equipment is still lacking. US supported with other novel technologies improve food processing efficiency, especially when combined with microwave heating. Although, when the processing conditions are not

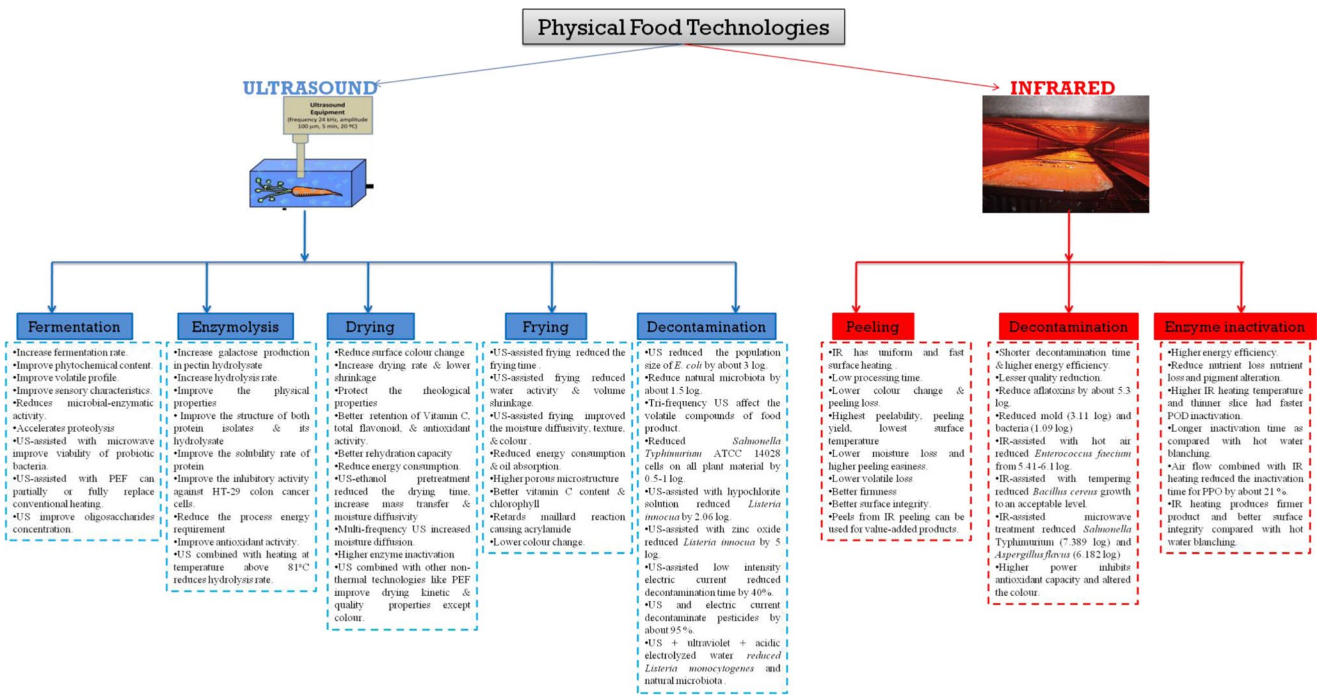

Figure 7. Effects of ultrasound, infrared, and other assisted technologies on food processes.

well monitored it can as well affect the food quality. Since the IR heating technology is characterized by a low penetration depth, it could be combined, in a pilot-scale equipment, with other non-thermal technologies like US to perform physical operations like peeling, blanching, fermentation etc. There is a need for the application of artificial intelligence modeling-approach to better understanding of how several processing variables interact simultaneously; for their easy integration to the industrial large-scale.

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Disclosure statement

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